UNIVERSITÀ DEGLI STUDI DI PALERMO

Ph.D. Program in Health Promotion and Cognitive Sciences

Dipartimento di Scienze Psicologiche, Pedagogiche, dell'Esercizio Fisico e della Formazione Metodi e Didattiche delle Attività sportive (M-EDF/02)

Bench Press Performance, Postural Control, and Motor Adaptation

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CICLO XXXVI

Abstract

The enhancement of athletic performance and injury prevention represents a key focus in the field of sport medicine and exercise sciences. This thesis explores three pivotal areas: strength and conditioning training, postural control and malalignment, and the interplay between motor adaptation and pain. To deepen our understanding of these topics, a combination of systematic reviews and original studies were conducted.

The objectives of Chapter 3 were twofold: first, to identify the specific relative load at which the concentric movement transforms into a purely propulsive action among women, and second, to compare the load-velocity relationships between men and women during the bench press throw. There were significant differences in mean propulsive velocity and the load of propulsive phase between men and women. Women transitioned into a fully propulsive concentric phase at approximately 80% of their 1RM, while men achieved this phase at around 85% of their 1RM. Furthermore, women exhibited reduced velocities when handling lighter relative loads compared to men. Conversely, women demonstrated higher velocities when dealing with loads exceeding 85% of their 1RM in contrast to their male counterparts. . These findings have significant implications for tailoring recommended bench press throw loads for women, which should be distinct from those suggested for men.

The aim of Chapter 4 was to examine the effect of different conditioning activities (concentric-only, isometric, eccentric-only, and eccentric-concentric) on the volume of bench press exercises. The results showed that concentric-only contractions significantly increased the number of repetitions and time under tension compared to the control (without any conditioning activity). Moreover, concentric-only contractions resulted in more repetitions and total work than eccentric-concentric contractions. Additionally, the time under tension was longer for concentric-only contractions than for isometric contractions. These findings indicate that concentric-only conditioning activities may improve the volume of subsequent bench press exercises.

The aim of Chapter 5 was to evaluate the effect of a conditioning activity (CA) using ballistic bench press exercises on subsequent bench press throw performance with different loads. The results demonstrated that the CA enhanced mean velocity for all the loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM). Additionally, peak velocity and peak power showed increases with the CA at the higher loads (70% and 90% of 1RM). The findings suggest that the CA protocol can improve bench press performance with different loads.

In Chapter 6, a systematic review was conducted to understand whether sleep deprivation and circadian rhythm can affect postural control (PC) variables among healthy individuals. Both circadian rhythm and sleep loss had a significant effect on PC, whereas there are inconsistent findings for optimal postural control regarding time of day. In terms of sleep deprivation, all investigations indicated that sleep loss deteriorates postural control.

The aim of Chapter 7 was to compare the lower limb muscle activation pattern in soccer players with and without lumbar hyperlordosis during single-leg squat (SLS) performance. Soccer players with lumbar hyperlordosis had higher muscle activation in gluteus maximus, biceps femoris, and medial gastrocnemius than those with normal lumbar lordosis. By contrast, they had lower gluteus medius, vastus medialis oblique, rectus femoris, soleus, and medial gastrocnemius (only in the final ascent phase of the SLS) muscle activity than the normal group during the SLS. This alteration may negatively affect targeted muscle performance during the SLS.

In Chapter 8,a systematic review was carried out to summarize and critically evaluate studies that examined the influence of experimental pain on motor learning. The results of the review revealed there is no consensus regarding the effect of pain on the skill learning acquisition and retention. However, several studies demonstrated that participants who experienced pain continued to express a changed motor strategy to perform a motor task even one week after training under the pain condition.

Acknowledgments

I would like to express my deepest gratitude to those who have made this journey not only possible but also a memorable and enriching experience.

First and foremost, my sincere thanks go to Prof. Marianna Bellafiore. As my supervisor, Prof. Bellafiore has been a beacon of knowledge, inspiration, and support. Her guidance, patience, and unwavering belief in my abilities have been instrumental in shaping my research and academic growth.

I am also profoundly grateful to Prof. Antonino Bianco for his invaluable assistance throughout my PhD period. His insights, encouragement, and expertise have greatly contributed to my professional development and have been pivotal in the successful completion of my thesis.

A special note of thanks to my Sicilian friends, whose warmth, camaraderie, and unwavering support have provided a comforting sense of home and community. Their presence and encouragement have been a source of joy and motivation during the challenging moments of this academic journey.

To everyone who has been a part of this incredible chapter of my life, I extend my heartfelt appreciation. Your contributions have not only enriched my PhD experience but have also left an indelible mark on my personal and professional life.

International mobility

I had a valuable experience at Professor David Franklin's lab in Munich, where I focused on the role of visual feedback in motor adaptation. This period was crucial for my academic development, introducing me to advanced research methods and data analysis in this field. The collaborative setting in Professor Franklin's lab was key to enhancing my research skills, as I interacted with a diverse group of scholars and peers. This interaction was not just academically enriching but also widened my understanding of global research networks.

My experience in Munich, although not directly included in my thesis, was instrumental in broadening my academic perspective. The project I engaged in at Professor David Franklin's lab involved in-depth experiments and analysis, focusing on the influence of visual feedback on motor learning. This separate research venture was both challenging and rewarding. It bridged theoretical knowledge with practical application, deepening my understanding of the subject. While this work stands distinct from my thesis, the insights gained are invaluable in the context of neurorehabilitation and motor control, potentially contributing to the development of enhanced therapeutic methods for individuals with motor difficulties. This experience has been crucial in my academic journey, enriching my knowledge in the field of motor adaptation and neuroscience and establishing a robust foundation for my ongoing and future research projects.

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List of abbreviations

PAP	post-activation potentiation
CA	conditioning activity
1RM	one-repetition maximum
F-V	force-velocity
LVP	load-velocity profile
LPTs	linear position transducers
LVTs	linear velocity transducers
VBT	velocity-based training
PBT	percentage-based training
MVICs	muscle voluntary isometric contractions
CC	conditioning contractions
Pt	peak torque
CMJ	countermovement jump
ATP	adenosine triphosphate
SJ	squat jump
RT	resistance training
DJ	drop jumps
RFD	rates of force development
PAPE	Postactivation Performance Enhancement
BPT	bench press throw
BP	bench press
HRE	high-resistance exercise
BE	ballistic exercise
MPV	mean propulsive velocity
ISO	isometric

CON-only	concentric-only
ECC-CON	eccentric-concentric
ECC-only	eccentric-only
TUT	time under tension
MV	mean velocity
PV	peak velocity
MP	mean power
PP	peak power
PC	postural control
SD	sleep deprivation
COP	center of pressure
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
AP	anteroposterior
ML	mediolateral
SLS	single leg squat
PROSPERO	International Prospective Register of Systematic Reviews
VAS	visual analogue scale
NRS	numeric rating system

Improving Bench Press Performance: Short-Term Strategies and Optimal Load Prescription

Chapter1: Research context and background literature

To enhance bench press performance, a combination of evidence-based techniques and methods supported by various studies is essential. Factors such as an individual's muscular strength and power, particularly in the chest, shoulder, and triceps muscles, play a crucial role [1]. Proper technique and form, which involve maintaining correct alignment, grip width, and an efficient bar path, significantly optimize force production during the bench press [1]. Additionally, elements like neuromuscular coordination, stability, and core strength contribute to overall performance [2]. Psychological elements, such as concentration, motivation, and confidence, also have an impact [3]. Incorporating exercises like the paused bench press or incline bench press can effectively target specific muscle groups and enhance overall strength [2]. The implementation of periodization, a training method that strategically varies intensity and volume, has demonstrated significant improvements in strength [4]. Furthermore, optimizing recovery strategies through sufficient rest, nutrition, and sleep is vital for muscle repair and growth [5], ultimately resulting in enhanced performance. By comprehensively addressing these factors, individuals can potentially maximize their bench press performance and achieve their desired strength goals.

Although the aforementioned factors play a crucial role in enhancing bench press performance, training programs can also serve as contributing factors that stimulate optimization among athletes [4]. It has been reported that a load-velocity training program is a sophisticated approach to strength training that takes advantage of the intricate relationship between load (weight) and velocity (speed of movement) [6]. The primary objective is to optimize performance outcomes and physiological adaptations by precisely prescribing specific loads and velocities for each exercise within the program. By strategically manipulating the load-velocity continuum, individuals can effectively target a wide range of strength, power, and muscular adaptations. Heavier loads coupled with slower velocities prioritize the development of maximum strength, while lighter loads combined with higher velocities emphasize power and speed [6]. This carefully designed training plan allows individuals to progress at their own pace and closely track their improvements by measuring how fast they can perform at different levels of difficulty. Incorporating load-velocity training into a comprehensive strength program enhances overall performance, triggers substantial muscle growth, and results in comprehensive athletic development [6].

Although there is a significant body of literature examining the assessment of load-velocity relationships in the bench press, there is a dearth of information concerning the load-velocity relationship among female individuals. In the load-velocity relationship, males generally demonstrate higher absolute loads at comparable velocities, reflecting greater maximal strength [7]. These distinctions can be attributed to factors such as hormonal profiles and muscle mass [8]. Specifically, muscle physiology differs between sexes due to variations in hormone levels, influencing muscle fiber composition and size [9]. Males typically have a greater proportion of type II muscle fibers, emphasizing force production, while females often possess a higher proportion of type I muscle fibers, emphasizing endurance capabilities. Hence, muscle strength displays notable sex differences, as males typically demonstrate greater absolute strength attributed to factors such as hormonal profiles and muscle mass. However, when considering relative strength by accounting for body size and composition, females can exhibit comparable levels of strength [9]. In this context, Torrejón and colleagues [7] highlighted significant disparities in the load-velocity relationship between women and men during the bench press exercise. Nonetheless, further research is needed to fully grasp the implications of these variances and their effects on optimizing training and performance for women.

Although the primary emphasis of the bench press exercise lies in developing upper body strength and muscle, it encompasses distinct phases of propulsive force generation and controlled deceleration. Specifically, the concentric phase of movement comprises separate phases of braking and propulsive actions [10]. In the braking phase, the body slows down or counteracts the current motion to prepare for the subsequent propulsive phase. This stage involves eccentric muscle contractions that aid in governing and adjusting the movement's speed and direction. Conversely, the propulsive phase follows the braking phase and involves the generation of force to propel the body or an external load forward. This phase relies on concentric muscle contractions that overcome resistance and facilitate forward movement [11]. During the execution of a bench press with light and medium loads, an additional phase is observed where deceleration exceeds the influence of gravity alone. This occurs as athletes exert force in the opposite direction to the motion of the load. Consequently, the concentric portion of the lift can be further divided into a "propulsive" phase (characterized by positive force) and a "braking" phase (characterized by negative force) [10]. This distinction based on force direction holds practical significance and goes beyond the conventional division based solely on acceleration. In this vein, Sanchez-Medina and colleagues (2009) evaluated the propulsive phases of bench press performance among men and demonstrated the importance of considering the mean mechanical values in relation to the propulsive phase of a lift rather than the entire concentric portion when evaluating strength and muscle power using lighter and moderate loads. The existing knowledge regarding the propulsive and braking phases during the bench press exercise among women is limited. Therefore, it is crucial to conduct further assessments that specifically examine the load-velocity relationships associated with the propulsive and braking phases in women.

Furthermore, bench press performance can be influenced by post-activation potentiation (PAP), i.e., participating in a high-intensity conditioning exercise prior to engaging in athletic endeavors can trigger a temporary elevation in muscle contractility, resulting in enhanced performance for the subsequent task [12]. The improvement in exercise performance following PAP can be attributed to a combination of neural and physiological mechanisms [13]. PAP involves increased muscle contractility through the phosphorylation of myosin regulatory light chains and the heightened calcium sensitivity of contractile proteins [13]. Additionally, PAP can lead to changes in neural activation and recruitment patterns, resulting in enhanced motor unit activation, muscle fiber recruitment, and rate of force development [13]. In this vein, several research studies have investigated the impact of PAP on bench press performance with the goal of optimizing strength gains and power output [14-17]. While the majority of studies reported significant and positive effects of PAP on bench press performance [17], additional research is needed to gain a deeper understanding of how PAP specifically affects bench press performance. This is because numerous factors, including conditioning activity (CA) intensity, recovery time, type of CA, individual variability, training background, exercise volume, exercise order, and warm-up, can impact the result of studies, and the interaction of these factors is intricate, and the optimal combination can vary based on individual characteristics and the specific nature of the performance tasks [18]. Hence, it is imperative to conduct individualized experimentation and closely monitor the outcomes in order to determine the most effective PAP protocols for maximizing performance enhancements.

Previous studies [14-17] have primarily focused on using different types of contractions as CAs to improve power outputs, while neglecting the potential of ballistic activity to enhance performance, particularly in the upper body. The lower threshold for motor unit recruitment in ballistic movements compared to slower contractions suggests that low-load ballistic activity could induce potentiation without excessive fatigue [17]. It has been demonstrated that incorporating a bout of ballistic exercise can improve subsequent explosive activities such as the bench press throw [17]. However, the effectiveness of a CA in potentiating ballistic movements with different loads remains unclear. This is due to the influence of training load on the mechanistic aspects of ballistic movement. Ballistic movements consist of distinct acceleration and braking phases, and the load-velocity relationships observed can vary based on the specific training load used in ballistic bench press exercises [10]. Therefore, exploring the extent to which ballistic bench press performance can be modified with different loads in response to a CA becomes crucial for optimizing exercise prescription strategies.

Despite the wealth of studies exploring the impact of CAs on enhancing force outputs [18], limited research exists regarding their potential to improve subsequent activity volume. However, it has been shown that incorporating heavy-load resistance training (>85% of 1RM) effectively increases the overall volume of subsequent exercises, such as squats and bench presses [19, 20]. The type of contraction employed as a CA can also influence the extent of PAP, resulting in varied outcomes. Different contraction types may elicit distinct mechanisms due to varying levels of neuromuscular fatigue, leading to a diverse range of findings [21]. Dynamic CAs tend to induce more peripheral fatigue and rely on central mechanisms of performance enhancement, while isometric CAs may induce greater central fatigue and predominantly rely on peripheral mechanisms [21]. Although several studies have examined CAs with different contraction types [15, 21, 22], there is limited research directly comparing their effects on PAP. For instance, Rixon et al. (2007) found that isometric conditions elicit greater PAP than dynamic conditions during jump-squat exercises [21]. However, no study to date has investigated the potential influence of contraction types on subsequent activity volume.

The effectiveness and practicality of training theories within any sport require empirical evidence that demonstrates their real-world applicability [23]. Accordingly, the primary objective of this PhD study was to advance the understanding and application of specific strength and conditioning strategies, thus contributing to the evolving body of knowledge in applied performance and physiological aspects of the sport.

Purpose of research

The main objective of this research program is to investigate effective strategies for improving bench press performance, with the ultimate goal of offering practical recommendations for designing training programs.

The specific aims of this part of the dissertation were:

- Determine the specific relative load (i.e., 1RM) at which female athletes can sustain propulsive concentric action during the bench press throw
- Compare the load-velocity characteristics between male and female athletes during the bench press throw
- Assess the impact of a CA utilizing the ballistic bench press exercise on subsequent bench press throw performance with different loads
- Compare the effects of different types of CAs on the volume of bench press exercise

Chapter 2 : Review of Literature
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2.1 Load-velocity training program

2.1.1 Introduction

Enhancing athletic performance through optimal training methods has been a prominent research focus in sports science. Among the various areas of interest, the impact of load-velocity training programs on bench press performance holds significant importance. The bench press exercise is widely acknowledged as a fundamental measure of upper-body strength and power, making it an essential component of athletes' training programs. Investigating the effects of load-velocity training programs designed specifically for the bench press can offer valuable insights for optimizing performance gains in this aspect.

Load-velocity training involves manipulating the load and velocity parameters during resistance exercises to achieve desired outcomes. This approach allows for customization based on individual factors, such as training level, goals, and biomechanical characteristics. Notably, load-velocity training has demonstrated its potential efficacy in enhancing bench press performance, as evidenced by various studies [24, 25]. Understanding the effectiveness of such programs is crucial for athletes and coaches seeking to maximize their performance in the bench press exercise.

Jukic et al. (2021) conducted a systematic review and meta-analysis to examine the effects of load-velocity training on strength and power in different age groups [26]. The findings highlighted the positive impact of load-velocity training interventions, revealing significant improvements in maximum strength and power output. This suggests that manipulating load and velocity parameters can result in improvements in bench press performance.

Moreover, a systematic review and meta-analysis by Harries et al. (2012) focused on resistance training to enhance power and sports performance in adolescent athletes [27]. The analysis indicated that manipulating load-velocity profiles during training resulted in considerable enhancements in power output and sports performance measures. These findings reinforce the notion that load-velocity training programs can effectively contribute to improvements in bench press performance.

While acknowledging the potential benefits of load-velocity training, it is crucial to consider individual variations and implement well-designed programs to ensure safety and maximize results. By customizing load-velocity profiles and continuously monitoring progress, athletes can optimize their training outcomes and work towards achieving their performance goals in the bench press exercise.

2.1.2 Force-Velocity Relationships

Considerable research efforts have been dedicated to unraveling the intricate relationship between force and velocity (F-V) in skeletal muscles, providing insights into how the force generated during muscle contraction is influenced by the speed at which the muscle undergoes shortening. Hill's groundbreaking investigations in 1938 laid the groundwork for comprehending the underlying principles of this association [28]. Recent studies [29-31] have been carried out to explore the F-V relationship across a wide range of domains, including high-performance sports and the everyday activities of older adults, with the objective of enhancing muscle function and optimizing training programs. Analyzing the F-V relationship involves precise measurements of muscle force and velocity under varying conditions, coupled with the application of mathematical models to extract crucial performance parameters such as maximum force, maximum shortening velocity, and maximum power output [32]. Despite the widely recognized significance of the F-V relationship, the precise curvature of the F-V curve and the underlying mechanism are poorly understood. This curvature holds significant implications for muscle power output, thermodynamic efficiency, and the investigation of muscle fatigue.

The observed F-V relationship in vivo is influenced by various factors [32], including neural activation, mechanical properties of elastic components, force transmission between neighboring muscle fibers, muscle architecture, lever arms of joints, coordination of agonist and antagonist muscles, and other factors that are not fully understood. The relationship between muscle moment arm length and torque-velocity has been demonstrated, where a longer moment arm requires greater muscle shortening velocity, leading to a lower region of the F-V relationship [33]. However, these factors do not fully compensate for decreased muscle force during fast joint angular velocities. Despite these complexities, studying the F-V relationship remains important for understanding muscle physiology and guiding training practices [34, 35]. Deviations from the rectangular hyperbola shape are common in vivo F-V relationships, both in single-joint [36, 37] and multi-joint muscle actions [38, 39]. These deviations have been attributed to a central inhibitory mechanism [40]. Recent studies have shown that the F-V relationship can exhibit a double-hyperbolic shape in the high-force/low-velocity region, especially in knee extensor muscles [41, 42]. The shape of the F-V relationship during multi-joint muscle actions has been reported as linear, but this linearity may be a result of limited evaluation in extreme force and velocity regions [32]. Recent evidence suggests that the F-V relationship becomes hyperbolic when low forces or high velocities are evaluated [43]. Joint angle [44] and the influence of the in-series elastic component of the muscle-tendon complex [45] also affect the F-V relationship. Ultrasound studies [46, 47] have shown that tendons lengthen during force development and shorten during force decay, affecting muscle fascicle velocities. It is important to collect F-V data at the point of peak torque to isolate the effects of velocity. The use of modern imaging techniques, such as ultrasound and dynamometry, has advanced the study of the in vivo F-V relationship [32]. However, estimating fascicle force from external joint torque relies on assumptions about constant moment arms, muscle contributions to external force, uniform muscle architecture, and homogeneous fascicle behavior, which may not consistently remain valid [32].

2.1.3 Load-Velocity Relationships

There is a direct relationship between the relative load lifted and the average concentric velocity during submaximal loads (ranging from 35% to 90% of 1RM) [48, 49]. This correlation allows for the evaluation of an athlete's performance across different submaximal loads and provides valuable information for determining the appropriate loads to achieve the desired movement velocity. It also enables the monitoring of adaptive responses to velocity-specific training programs. Additionally, the load-velocity relationship offers coaches the ability to compare the velocity performance of athletes when lifting submaximal loads, even if their strength qualities based on 1RM scores and velocities at 1RM for the bench press exercise appear similar [50].

An intriguing finding from research reveals that the final repetition in sets of bench press and squats, performed until failure, is consistently associated with a particular velocity, regardless of the intensity (e.g., 60%, 65%, 70%, and 75% of 1RM) [51]. This velocity, referred to as the minimal velocity threshold, remains unchanged over time, even when there are improvements in maximum strength or when considering individuals with varying absolute strength levels. Determining an athlete's minimum velocity threshold not only serves as an assessment of residual neuromuscular fatigue but also provides an estimation of their readiness to train [51].

Furthermore, the monitoring of velocity during resistance training provides valuable insights into metabolic stress and neuromuscular fatigue [52]. Sánchez-Medina and González-Badillo [52] conducted a study and found a strong association between decreases in velocity across sets with varying load and repetition schemes, and blood lactate levels during exercises like bench press and squats [52, 53]. Additionally, within a set of resistance exercise, the repetition velocity gradually declines, indicating a progressive decline in neuromuscular function and the onset of fatigue [54]. By effectively tracking repetition velocity, strength coaches can control the level of fatigue that an athlete experiences during resistance exercise. Although further research is needed in this area, incorporating velocity-based endpoints into sets can be an effective strategy. Athletes can be instructed to exert maximum effort during repetitions until a predetermined decrease in concentric velocity is reached [50]. This approach emphasizes the importance of concentric effort and helps manage fatigue.

However, it is important to note that the use of linear position transducers to quantify resistance training through the mentioned methods is still an area of limited research. As a result, the effectiveness of these strategies in monitoring and prescribing resistance training is not fully understood. Furthermore, strength coaches need to consider the relevance of monitoring exercise velocity to their athletes and the specific training goals. For example, athletes focusing on hypertrophy training should prioritize moderate loads with controlled tempo and shorter rest intervals rather than emphasizing explosive movements [55]. This type of training aims to induce metabolic stress for targeted morphological adaptations, resulting in an expected decline in repetition velocity across sets [56]. Thus, monitoring velocity during hypertrophy training may not provide significant benefits. Therefore, strength coaches should take an integrated approach to monitoring resistance training and utilize methods that are most applicable to the training context.

2.1.3.1 Load-velocity characterization

To successfully incorporate monitoring of concentric movement velocity into a resistance training program, it is essential for the practitioner to establish the load-velocity profile (LVP) specific to the athletes involved. The dynamics and mechanics associated with commonly performed compound movements vary, leading to distinct variations in the load-velocity relationship that is observed and reported [6]. In a study conducted by Sánchez-Medina et al. (2013), significant differences were observed in mean propulsive velocity between the prone bench pull and the bench press across various percentages of the 1-RM [57]. The authors proposed that these differences could be attributed to neurophysiological factors, such as variations in muscle activation and movement patterns specific to each exercise. The prone bench pull, involving muscles like the latissimus dorsi, biceps brachii, and brachialis, which have longer muscle fibers and are arranged longitudinally, exhibited faster contraction velocity. On the other hand, the bench press primarily engages muscles like the pectoralis major, triceps brachii, and anterior deltoid, resulting in higher force generation potential but slower concentric velocity [58, 59]. Interestingly, it was demonstrated that were larger reductions in bench press concentric velocity compared to the back squat [53]. Moreover, during repetitions performed at relative loads of 60–75% 1-RM, significantly higher concentric velocity was observed in the back squat compared to the bench press. These findings highlight the existence of distinct differences in LVPs among multi-joint movements. These differences can be attributed to variations in the musculature of primary movers as well as the specific movement phases involved in each exercise [59]. Considering the implications of these findings, it becomes crucial to establish specific LVPs for each exercise before incorporating them into a periodized training program. Relying on more generalized velocity "zones" may not adequately account for the unique characteristics and demands of each movement. Therefore, a thorough understanding of the LVPs associated with different exercises is essential for optimizing training effectiveness and performance outcomes [60] .

The investigation into the optimal approach for deriving the LVP of different movements remains limited in the existing literature. Consequently, contemporary studies employ diverse methodologies to establish LVPs without a definitive consensus on a standardized procedure. These approaches typically involve retrospective analysis, where participants perform maximal-effort lifts at varying loads. The number of repetitions completed is inversely related to mean velocity or relative intensity, gradually increasing the loads until reaching their one-repetition maximum (1-RM). Following data collection, the relative load and corresponding velocity output, often measured as mean concentric or mean propulsive velocity, are graphically plotted. The subsequent step involves fitting a mathematical model, such as a linear or polynomial line, to approximate the relationship between load and velocity. The equation derived from the fitted line is then used to calculate the velocity associated with a given relative percentage. It is important to acknowledge that a margin of error is considered around the fitted line to account for variability in the data and measurement precision. However, further research is warranted to explore and validate the most effective and reliable methodology for establishing LVPs in the context of resistance training. By refining our understanding of LVP determination, we can enhance the accuracy and applicability of load-velocity profiling in practical training settings.

The utilization of these methodologies [51, 57] is widespread in the literature, although their effectiveness has been subject to debate. There are instances where absolute load increments are employed, disregarding the participants' individual 1RM values. In this context, Pallarés and colleagues (2014) reported that the participants achieved 1RM values of 92.2 ± 11.9 kg for the bench press and 100.4 ± 21.8 kg for the back squat. Surprisingly, during the collection of LVP data, load increments of 15 kg were used, resulting in approximately 16% and 15% increases for the bench press and back squat, respectively [61]. However, Sánchez-Medina et al. (2013) employed smaller absolute load increments of 10 kg for LVP establishment. Nevertheless, considering the attained 1-RM values during testing (bench press: 90.3 ± 16.3 kg; prone bench pull: 80.2 ± 11.8 kg), these increments still represented approximately 11% and 12%

for the bench press and prone bench pull, respectively. Notably, both studies initiated the LVP assessment with an initial load of 20 kg, which corresponds to approximately 20–25% of the maximum load lifted.

The discrepancies observed in the chosen load increments highlight the variability in the methodologies utilized for establishing LVPs and raise concerns regarding their suitability. Further investigations are warranted to determine the most appropriate methods for load progression during LVP assessment, ensuring that the selected increments align more closely with the individual capabilities of the participants. By refining these methodologies, we can enhance the reliability and relevance of load-velocity profiling in both research and practical applications, enabling more accurate and personalized training prescriptions.

When taking into account the reduction in absolute load increments based on velocity, it can be observed that participants were typically able to complete only 5–6 sets before the load increments were decreased. In some cases, they reached approximately 90% of their 1RM, specifically for the prone bench pull [57]. It is important to consider that LVPs typically encompass the load-velocity relationship across 15 working sets. However, the limited number of actual data points and their alignment with the proposed 5% zone raise potential concerns regarding the comprehensiveness of the profiles. Consequently, it is worth contemplating an alternative approach that, although more time-consuming, involves recording more sets at smaller increments. This approach would yield a greater number of data points, allowing for a broader and more accurate establishment of LVPs for individual movements. By incorporating a wider range of data, the validity and reliability of the LVPs can be enhanced, leading to a more comprehensive understanding of the load-velocity relationship in resistance training.

2.1.4 Devices for monitoring velocity

The field of strength and conditioning has experienced impressive advancements in both techniques and tools used to control and monitor performance and training variables. Linear positional transducers, accelerometers, and camera systems have gained significant traction within the strength and conditioning environment. Their purpose is to optimize training sessions by manipulating training variables in real-time [51, 62, 63]. As these tools continue to evolve, the ability to modify training sessions based on immediate feedback and the monitoring of training variables has become an integral aspect of modern strength and conditioning approaches.

The field of resistance training has also experienced the development of various devices utilizing diverse technologies and methods to calculate and monitor movement velocity. Traditional approaches involved using three-dimensional high-speed motion capture analysis, which is widely regarded as the "gold standard." However, complicated analysis methods and challenges related to practical application have limited their adoption in modern strength and conditioning settings [64]. As a solution, kinematic systems like linear positional transducers have gained increasing popularity as tools for quantifying multiple performance outputs associated with resistance training.

2.1.4.1 Linear positional transducers and linear velocity transducers

Linear position transducers (LPTs) are hypothesized to serve as a practical and cost-effective substitute for quantifying velocity, power, and force variables in practical work environments [64]. They have gained prominence as the most widely utilized LTs in the scientific and practical domains. The LPT comprises an isoinertial dynamometer equipped with a cable that is typically connected to the bar. It directly measures the vertical displacement of the cable and derives displacement over time using the inverse dynamics approach to determine velocity [65]. In addition to LPTs, linear velocity transducers (LVTs) have emerged as recent developments that directly provide velocity measurements by detecting electrical signals proportional to cable extension velocity [66]. It is crucial to validate these devices across a wide range of exercises, execution models, and load variations.

2.1.4.1.1 Reliability and validity of LPTs

LPT technology has been recognized as a suitable means for evaluating motion in non-plyometric resistance exercises, irrespective of the load range (20–90% 1RM) or exercise type (e.g., back squat, bench press, prone bench pull, power clean, bent-over row, deadlift). Nonetheless, the accuracy of LPT measurements may depend on the transition to the concentric contraction phase, which is a critical factor to consider [64].

Valid linear position transducers (LPTs) for non-plyometric exercises with isometric pauses of 0.5–1.5 seconds prior to each concentric muscle action include Chronojump, GymAware, Tendo Weightlifting Analyser System, and FitroDyne (Tendo) [67-69]. These LPTs demonstrated high consistency with the proposed gold standard, such as Raptor 3D Motion Capture, Rapture-E 3D, 3D Eagle Motion, Vicon 3D, Qualysis Motion Capture System, and TrioOptiTrack [68, 70-72].

However, when used without isometric pauses or eccentric controlled phases, GymAware, FitroDyne, Tendo Weightlifting Analyser System, Chronojump, and Speed4Lift LPT devices provided less accurate velocity values [71, 72]. This discrepancy could be attributed to the greater sampling frequencies of these LTs, which impact the identification of the actual start of the push phase [64]. Higher sampling frequencies result in more time points integrated into the calculation runs, leading to increased measurement errors [64].

Therefore, coaches should pay attention when selecting LT sampling frequencies. Lower sampling frequencies may offer greater validity for assessments involving plyometric exercises, multiple planes of motion, and exercises without isometric pauses prior to the concentric muscle action. However, further research is needed to determine the most appropriate sampling frequency, similar to investigations conducted with other technologies [73].

Reliability of movement in non-plyometric exercises, including back squat, bench press, deadlift, prone bench pull, biceps curl, bent-over row, and power clean, has been demonstrated using LPTs [64]. These evaluations encompassed the entire investigated load range, which was below 90% of 1RM. However, it is important to note that the observed variations were sensitive to the execution mode of the movement and the dimensionality of the plane (2D or 3D) in which the exercise was performed. The LPTs' reliability was influenced by these factors [64].

LPT devices such as GymAware, FitroDyne, Chronojump, and Speed4Lift have shown reliability in monitoring non-plyometric exercises. They exhibit consistent results within and between devices. However, variations and measurement errors occur in different protocols, with smaller errors observed in protocols with isometric pauses and larger errors in protocols without both eccentric and concentric phases [64]. Mean variables tend to have higher errors compared to peak variables. LPTs are also sensitive to displacement in different planes, with greater variations and errors observed in free-weight exercises compared to exercises using the Smith machine. These variations may be influenced by joint moments, angular velocities, and changes in bar kinematics due to the applied load. Plyometric exercises additionally increase errors. Overall, the reliability of LPT devices depends on the execution method and plane of the exercise [64].

2.1.4.1.2 Reliability and validity of LVTs

The validity of LVT devices has been found to be satisfactory for measuring velocity in both plyometric exercises (such as jump squats) and non-plyometric exercises (such as back squats and bench presses) across a range of loads from 25% to 100% of 1RM [64]. However, the validity values are influenced by various exercise characteristics, including the presence of an isometric pause, plyometric nature, or non-plyometric nature, which can affect the accuracy of the measurements [64].

T-Force, a LVT device with a sample rate of 1000 Hz, has been found to be valid for measuring velocity in non-plyometric exercises that do not involve an isometric pause or controlled eccentric phase [71, 74]. It showed good agreement with gold standard measurements (Vicon 3D and TrioOptitrack) in velocity variables [74]. However, its precision decreased during plyometric exercises [75]. The limitation of accurately detecting the start of the propulsion phase may contribute to these measurement errors, which are more pronounced in plyometric exercises and particularly when there is no isometric pause before the concentric action [64]. While the high sample rate of T-Force may introduce some measurement errors, direct velocity measurement by LVTs can help mitigate these errors compared to other data manipulation methods. Future research should investigate the validity of LVTs with different sampling frequencies and the impact of incorporating pauses between contractions to minimize errors. In conclusion, T-Force, and LVTs in general, can be considered valid devices for monitoring velocity in plyometric and non-plyometric exercises, although precision errors increase notably in plyometric exercises, especially without an isometric pause prior to each concentric action [64].

LVTs have demonstrated reliability in assessing both plyometric exercises (such as jump squat) and non-plyometric exercises (including back squat, bench press, and prone bench pull) across a load spectrum of 25–100% 1RM [71, 74, 75]. T-Force and SmartCoach were reliable for both plyometric and non-plyometric exercises, regardless of the presence or absence of an isometric pause, with high inter-device consistency and moderate to low variability in velocity variables [64]. However, T-Force exhibited slightly higher variations and measurement errors in plyometric exercises compared to non-plyometric exercises. The use of a 14-bit resolution analog-to-digital data acquisition board and a low-pass Butterworth digital filter with a cut-off frequency of 10 Hz contributed to minimizing technological errors [64]. Future research should explore the impact of the absence of a pause between contraction regimes and the performance of exercises with free weights on LVT reliability. In conclusion, LVTs appear to be reliable tools for evaluating both plyometric and non-plyometric exercises, with higher reliability values observed in non-plyometric exercises performed in a Smith machine [64].

2.1.5 Velocity as an essential training variable

Linear velocity transducers, such as the T-Force, possess the capacity to simultaneously capture and analyze multiple variables throughout a single repetition [76]. This encompasses the acquisition of eccentric and concentric velocities, as well as peak, mean, and propulsive velocities. While mean and peak velocities are commonly integrated into strength and conditioning practices, propulsive velocity, which represents the average value between the initiation of the movement and the point where acceleration falls below gravity, remains relatively unfamiliar. Despite potential changes in 1RM following periodized training, it was demonstrated that the mean propulsive velocity associated with a specific relative percentage remains stable [10]. This finding is supported by comparable research, indicating that athletes maintain a consistent relative load-velocity relationship throughout their training and that individual load-velocity profiles are comparable within a group of similarly trained athletes [57].

The effective use of velocity as a monitoring tool for relative load requires individuals to exert maximal effort during the concentric phase, as emphasized by González-Badillo and Sánchez-Medina (2010). Previous studies suggested that the voluntary intention to move a load was just as important as the achieved velocity, implying that the willingness to exert maximal effort influences observed adaptations regardless of relative load [77]. However, recent literature highlights the value of velocity-based movements, which yield increased peak and mean velocity output while maintaining comparable force and power production at the same load as slower contractions [78]. Therefore, both an individual's intent to lift and the achieved concentric velocity during a lift are critical factors for producing desirable neuro-physiological adaptations, ultimately leading to enhanced strength and power. Consequently, when aiming to improve neuromuscular strength and power, it is advisable to prioritize maximal concentric velocity during appropriately loaded movements rather than solely focusing on maximal relative loading.

The measurement of mean concentric velocity (MCV) is considered a more reliable indicator of the relationship between relative load and individual effort when assessing velocity in simple, non-ballistic compound movements like the back squat, bench press, and bench pull [49]. Recent research by Banyard et al. (2017) confirmed that this holds true across a range of training loads (20–90% 1RM). However, when working at 100% of 1RM, concentric peak velocity exhibits greater stability compared to both concentric mean velocity and concentric mean propulsive velocity. Although this finding is significant, it is worth noting that individuals are unlikely to lift at their 1RM during a typical training program. As a result, MCV remains widely utilized in the literature [79-81].

In an effort to eliminate the impact of the braking phase, researchers have opted for mean propulsive velocity instead of mean velocity in certain instances. The braking phase, as defined by Sánchez-Medina et al. (2013), occurs during the concentric phase when deceleration exceeds that caused by gravity alone. It indicates the point at which athletes actively decelerate before completing the movement repetition. The duration of the braking phase has been found to be inversely correlated with relative load and movement velocity, with lighter external loads necessitating a longer braking phase [57, 61]. This phenomenon is attributed to the requirement of maintaining technical control regardless of the relative load, prompting athletes to actively decelerate to prevent the release of the bar. However, in some cases, as the relative load surpasses a specific threshold (e.g., bench press load ≥ 80% 1RM), the braking phase disappears since athletes no longer need to actively decelerate during repetitions performed with maximal intent [57].

Despite numerous researchers highlighting the importance of considering the braking phase during maximal concentric lifting [57, 61], investigations by Banyard et al. (2017) and García-Ramos and colleagues (2018) have demonstrated no significant difference in linearity between mean velocity and mean propulsive velocity concerning relative load. Consequently, although both mean velocity outputs yield similar relationships with relative load, the ease of calculating mean velocity has resulted in its greater emphasis in recent studies [78, 82, 83].

As movements transition into a more ballistic nature, as well as jumping actions, studies have revealed that concentric peak velocity demonstrates greater consistency across repeated trials [84]. This consistency has been attributed to the specific movement patterns associated with these actions, where not every phase of the movement aims for maximum velocity. Including such data would skew the mean outcome, thereby impacting the effectiveness of using mean or mean propulsive velocity as performance measures. Conversely, recent research by García-Ramos et al. (2018) highlighted that mean velocity proved to be the most reliable predictor of relative load during explosive bench throws. While peak velocity exhibited lower coefficients of variation between visits, both mean velocity and mean propulsive velocity demonstrated stronger linearity in relation to relative load and greater accuracy, as evidenced by the lower standard error of the estimate. It should be noted that although the ballistic nature of explosive bench throws might suggest monitoring peak velocity, the completion of the entire movement with maximal voluntary intent mitigates the issues associated with movements like Olympic weightlifting.

2.1.5.1 Velocity feedback

The increasing adoption of linear velocity transducers has led to the evolution of associated software, providing expanded functionalities for strength and conditioning practitioners. These advancements now facilitate real-time monitoring and instantaneous feedback on performance variables, including movement velocity and force, which have become commonplace [65]. The availability of such feedback has consistently demonstrated its capacity to enhance kinematic outputs and reinforce participant motivation levels [82, 83, 85]. A study by Argus et al. (2011) underscored the significance of verbal kinematic feedback in mitigating performance declines during explosive bench throws across multiple repetitions and sets. The findings revealed that the provision of feedback resulted in marginal but standardized improvements in peak power and velocity when averaged over sets, compared to scenarios where feedback was denied. Although the observed acute adaptations were relatively modest, this can be attributed to the participants' high training status. The authors concluded that the integration of verbal kinematic feedback holds the potential to yield immediate enhancements in power, thereby optimizing the overall training quality. It is important to acknowledge that the findings related to verbal kinematic feedback presented in Weakley et al. (2019) (6.6%) demonstrate a noticeable increase compared to previously reported values in Argus et al. (2011) (1.3%). This difference may be attributed to various factors, including the athletes' training status (elite vs. sub-elite), the specific compound movement assessed (bench throw vs. back squat), and the variable measured (peak vs. mean velocity). Nonetheless, the compilation of data presented offers sufficient evidence to support the notion that feedback is a valuable addition to resistance training, particularly in the context of velocity-based training (VBT). While further research is needed to determine the optimal method of delivering feedback, it has been demonstrated that providing feedback effectively mitigates the decline in concentric velocity and power that typically occurs during sets and repetitions.

2.1.6 Incorporating velocity tracking in resistance training for fatigue management

In current scientific literature, there is substantial evidence that establishes a strong correlation between isoinertial resistance training, concentric movement velocity, and neuromuscular fatigue [86, 87]. The concept of fatigue encompasses various definitions, but a common observation is the decline in muscular force production and subsequent reduction in movement velocity following exercise [52, 88]. As the capacity for generating muscle force diminishes, the ability to sustain optimal performance becomes progressively more difficult, ultimately leading to task failure if prolonged. Consequently, it becomes crucial to implement effective fatigue monitoring strategies during resistance training to optimize training outcomes and minimize the risk of performance deterioration.

The decline in muscular force-generating capacity is accompanied by a noticeable decrease in concentric contraction velocity, which is attributed to the accumulation of metabolic by-products within the muscles [52]. This gradual reduction in repetition velocity is commonly interpreted as an indication of impaired neuromuscular function [89]. Under conditions of fatigue, continued repetitions disrupt cellular homeostasis, leading to a significant increase in blood ammonia levels. This elevation in ammonia indicates an accelerated depletion of purine nucleotides in the muscles, concurrent with an increase in lactate levels. These metabolic changes ultimately result in reduced performance and prolonged recovery periods [52, 87]. Consequently, the monitoring of concentric velocity has been proposed as a method to objectively manage training-induced fatigue. By adjusting the prescribed repetitions based on observed velocity output, trainers can optimize training interventions and effectively mitigate fatigue [78]. By incorporating velocity monitoring into training programs, fatigue can be better accommodated, leading to improved performance outcomes and facilitating the recovery process.

In current research, novel strategies such as incorporating specific velocity zones or velocity stops have gained recognition as effective means of optimizing training outcomes [78]. Velocity zones refer to predetermined ranges that indicate the relative load of an exercise, guiding athletes to perform repetitions within these ranges to target specific performance goals [60, 84]. Conversely, velocity stops set minimum velocity thresholds for each repetition, requiring athletes to maintain velocities above these thresholds to minimize fatigue [87].

The combined use of velocity zones and stops can potentially enhance muscular strength and power adaptations while simultaneously reducing neuromuscular fatigue [87]. By integrating these strategies, athletes gain a comprehensive approach to training, allowing them to effectively regulate movement velocities. Through careful monitoring and adjustment of velocities within the designated zones or above the prescribed stops, athletes can optimize the training stimulus and minimize the accumulation of excessive fatigue. It is important to consider that the effectiveness of velocity zones and stops may vary depending on individual characteristics, training objectives, and exercise selection. Therefore, athletes and coaches should carefully consider these factors and implement personalized approaches when incorporating velocity-based strategies. By doing so, athletes can maximize the benefits derived from monitoring and manipulating movement velocities within their resistance training programs.

Incorporating the monitoring of concentric velocity in resistance training has been advocated as a practical approach to gauge training intensity and make timely adjustments before the onset of fatigue [86, 87]. These VBT methods have shown promising results, with similar or even greater increases in power output and no significant reduction in maximal strength or force output compared to traditional percentage-based approaches [78].

However, it is important to acknowledge that VBT methods have yet to be directly compared to specific maximal strength training programs. Traditional strength training typically involves performing repetitions close to failure with near maximal loads (> 85% 1RM) to optimize the recruitment of high-threshold motor units and stimulate maximal strength gains [90]. Given that VBT methods aim to mitigate fatigue accumulation [87], concerns arise regarding their effectiveness in providing an optimal stimulus for maximal strength development. However, it is essential to note that VBT achieves fatigue limitation by optimizing loading and repetitions rather than reducing the workload imposed on athletes. Additionally, until direct comparisons between VBT and traditional methods are explored, the relationship between these approaches remains speculative.

To fully understand the efficacy and potential trade-offs of VBT in relation to maximal strength training, further research is warranted. By investigating the interplay between these methodologies, a more comprehensive understanding can be obtained, leading to evidence-based recommendations for athletes and coaches to optimize strength and performance outcomes.

2.1.7 Velocity-based training

Recent research has revealed the crucial role of optimal movement velocity in the development of effective periodized resistance training programs [52, 87]. This concept emphasizes the prescription of specific velocities that exert maximum influence on neural and muscular mechanisms, thereby optimizing functional strength and power [77]. Furthermore, it has been observed that aligning resistance training with the movement patterns and velocity profiles associated with successful sporting performance leads to greater transferable strength and power adaptations in athletes. As a result, athletes are encouraged to use resistance loads that enable replication of these specific movement patterns, particularly during the later stages of the preparatory phase, which includes sport-specific physical training and the competitive phase [86]. By incorporating velocity-based approaches into training protocols, athletes have the potential to surpass the outcomes achieved with traditional methods, as these approaches align with established training concepts. This suggests that integrating optimal movement velocity can effectively enhance the adaptive responses derived from resistance training programs.

The effects of incorporating velocity into training interventions have been explored in several studies, focusing on two types of muscle actions: isokinetic (constant velocity) and isoinertial (constant mass). Isokinetic dynamometry is commonly used in research to accurately measure movement velocity and is considered a valid and reliable tool [91, 92]. However, the applicability of these actions to actual sporting movements is often questioned, raising concerns about the transferability of findings to practical settings [51]. Moreover, the labor- and resource-intensive nature of isokinetic protocols presents challenges when implementing them in strength and conditioning programs [93]. On the other hand, isoinertial resistance training, which involves constant mass, is widely used in applied settings due to its ability to engage and coordinate various muscle groups simultaneously, making it more relevant to sporting performance [94]. This, coupled with the development of kinematic measuring systems like LVTs, provides researchers and practitioners with a means to quantitatively assess velocity outputs during traditional training methods. By examining the integration of velocity in training through these different approaches, researchers and coaches can gain valuable insights into the suitability and practicality of each method for optimizing athletic performance.

Comparatively limited research has been dedicated to examining the effects of isoinertial VBT. The majority of studies have focused on comparing maximal concentric velocity movements to various other training methods. These comparisons include deliberate half-velocity movements, soccer-specific training, high-intensity/low-velocity training, or the absence of a comparative training method altogether. For example, an early study conducted by Delecluse et al. (1995) investigated the effects of nine weeks (18 sessions) of high-velocity training in relation to high-intensity training. The results showed that the high-velocity group exhibited significant improvements in overall sprint time and all assessed phases of the sprint, including initial acceleration, build-up to maximum speed, and maintaining maximum speed [95]. Conversely, the high-intensity group only demonstrated a significant improvement in the initial acceleration phase. Further research is necessary to explore the specific implications of isoinertial VBT across different training contexts and performance outcomes.

González-Badillo et al. (2014) conducted a study to explore the impact of maximal velocity isoinertial training on maximal strength in comparison to deliberate half-velocity training. Over a period of six weeks, participants engaged in Smith machine bench press training for a total of 18 sessions following a traditional linear progressive design. The results of the study provided compelling evidence in favor of maximal velocity training, showing significantly greater improvements in 1RM (18.2% vs. 9.7%) when compared to deliberate half-velocity training. Additionally, the mean velocity at both light and heavy loads demonstrated substantial enhancements (11.5% vs. 4.5% and 36.2% vs. 17.3%, respectively) in favor of maximal velocity training. Similarly, Pareja-Blanco et al. (2014) conducted a comparable study, investigating the effects of six weeks (18 sessions) of maximal velocity training versus deliberate half-velocity training on Smith machine back squat 1RM. The findings of this study further reinforced the advantages of maximal velocity training, revealing significant improvements in 1RM when participants focused on maximal propulsive velocity during full back squat exercises. While no significant interaction was observed between the groups, larger effect sizes were evident following maximum velocity training compared to half-velocity training (0.94 vs. 0.54, respectively). These results indicate that maximal velocity training may offer a more effective training stimulus for enhancing maximal strength when compared to slower velocity training approaches. In summary, both studies provide substantial evidence supporting the incorporation of maximal velocity isoinertial training in resistance training programs. By emphasizing maximal propulsive velocity, individuals not only achieved greater gains in 1RM but also experienced improvements in mean velocity across various load levels. These findings contribute to the existing body of knowledge, affirming the efficacy of maximal velocity training in optimizing strength development.

González-Badillo et al. (2015) and Negra et al. (2016) conducted studies to examine the effects of high-velocity resistance training in comparison to conventional soccer training. The focus was on assessing various performance measures, including jump assessments, maximal strength, and linear speed at distances of 5m, 10m, 20m, and 30m. The experimental groups engaged in high-velocity resistance training sessions in addition to their regular soccer training, while the control groups solely participated in soccer training. The results from both studies demonstrated the benefits of incorporating high-velocity resistance training alongside soccer training. The combined training approach led to significant improvements in maximal strength, vertical and horizontal jumps, and short-distance sprint performance. These findings emphasize the value of integrating high-velocity resistance training into soccer training programs to enhance overall performance. Additionally, Ramírez et al. (2015) conducted further research on VBT and its effects on power, force, and velocity output [96]. The study involved 18 participants who completed a 10-week training program consisting of 20 sessions of high-velocity half-squat training with a fixed load equivalent to approximately 65% of their 1RM. The outcomes indicated that VBT had a positive impact on absolute and relative power outputs. However, it is important to consider that the absence of a comparative group limits the interpretation of the results. Collectively, these studies underscore the advantages of incorporating high-velocity resistance training into soccer training regimens. The findings suggest that such training methods contribute to improvements in strength, power, and various performance indicators. Nevertheless, further research comparing these training approaches to traditional methods would enhance our understanding and provide more conclusive insights.

Limited research has been conducted to compare VBT with the more traditional percentage-based training (PBT) approach. Banyard et al. (2018) aimed to address this gap by investigating the effects of integrating velocity monitoring into traditional resistance training, specifically focusing on the free-weight back squat. The study involved participants completing a 1RM test to determine their maximum strength. Subsequently, they performed four training sessions under different conditions. The PBT group completed five sets of five repetitions at 80% of their 1RM, while the velocity-based loading group also performed five sets of five repetitions at 80% 1RM, with the intensity based on their individual load-velocity profile. Two additional conditions were included: fixed set velocity and variable set velocity. In the fixed set velocity condition, participants performed repetitions for five sets at 80% 1RM until their mean velocity dropped 20% below a predetermined threshold or completed five repetitions. In the variable set velocity condition, participants completed a total of 25 repetitions at 80% 1RM, aiming to perform as many repetitions as possible per set until their mean velocity dropped 20% below the predetermined threshold. The study measured various parameters, including force, velocity, power, time under tension, and session work and load. The findings revealed that the velocity-based loading condition resulted in significantly higher peak and mean velocities throughout the session compared to the PBT group. Importantly, there were no further differences observed between the conditions. These results demonstrate the benefits of using a predetermined load-velocity profile to dictate load selection in resistance training. The velocity-based loading approach allowed participants to achieve and sustain higher movement velocities while reducing time under tension and mechanical stress. Notably, this approach did not compromise force and power outputs compared to the traditional PBT method. In conclusion, integrating velocity monitoring into resistance training, as demonstrated in this study, offers a promising approach to optimizing training outcomes. By utilizing individual load-velocity profiles, individuals can train at higher velocities while minimizing mechanical stress. Further research is necessary to fully explore the implications and potential advantages of velocity-based training compared to traditional percentage-based training.

The incorporation of velocity monitoring into isoinertial resistance-based interventions remains limited, leading to a lack of comprehensive understanding regarding the relationship between VBT and its impact on strength and power adaptations. Evidence suggests potential effectiveness of these methodologies; however, inconsistencies in research design decrease the reliability of the findings. Issues such as inadequate control of training variables, variations in training stimuli across groups, participants' disparate training experience, utilization of Smith Machines versus free-weight exercises, undisclosed maturation status of young athletes, absence of comparative control groups, and unreliable velocity measurement methods persist throughout the existing studies [86, 97, 98]. Moreover, no research to date has explored the use of high-velocity resistance training as a means to enhance strength and power performance in comparison to traditional heavy PBT. Given the current state of evidence, it remains challenging to provide definitive recommendations regarding optimal movement velocities or specific VBT training designs that can maximize sport-specific strength and power performance. Consequently, further research endeavors are warranted to address these limitations, improve study design, and yield more conclusive findings in this domain.

2.2 Performance Improvements: Exploring the Significance of Postactivation Potentiation

2.2.1 Introduction

The performance of skeletal muscle in response to contraction is influenced by its previous contractile history. Repetitive contractile stimulation leads to fatigue, which causes a decrease in performance. However, alongside the onset of fatigue, there is also the occurrence of postactivation potentiation (PAP) [99, 100]. PAP is the phenomenon whereby the acute muscle force output is heightened as a result of its contractile history. It has been suggested that performing heavy resistance exercises prior to explosive movements, such as vertical or horizontal jumps, can enhance jumping performance [101-104].

The principal mechanism of PAP is considered to be the phosphorylation of myosin regulatory light chains, which makes the interaction between actin and myosin more responsive to the release of calcium from the sarcoplasmic reticulum [105]. This increased sensitivity to calcium has its most significant impact during twitch and low-frequency tetanic contractions when the myoplasmic calcium levels are low. Conversely, this heightened sensitivity to calcium has minimal or no effect during high-frequency tetanic contractions when calcium levels are already saturated. As a result, PAP selectively enhances the force-frequency relationship in the low-frequency portion while having little impact on the high-frequency portion [100, 106]. Interestingly, the conditioning activity (e.g., 10-second maximum voluntary contraction) can concurrently enhance (through PAP) and diminish (due to fatigue) the force produced during low- and high-frequency contractions, respectively [100].

PAP has been observed to enhance performance in both the upper and lower body. Specifically, a significant 2.39% improvement in vertical-jumping ability was found after the application of PAP compared to the pre-stimulus condition [103]. To investigate this further, participants were instructed to perform 5 sets of half squats, consisting of 2 repetitions each, at varying intensities of 20, 40, 60, 80, and 90% of their

1RM. Additionally, the researchers discovered that individuals with greater maximal strength experienced more substantial enhancements in vertical-jump ability. It was also demonstrated that PAP can lead to a 4.5% increase in power output following a 6RM bench press performed at 65% of 1RM [107], in which power output was assessed by conducting bench press throws with a resistance of 50 kg. Furthermore, Chiu and colleagues (2003) conducted a study where they compared explosive jumps before and after 5 sets of 1-repetition back squats at 90% of 1RM [102]. Although initially no significant improvement in performance was found, when the subjects were divided into a trained power group and a recreationally active group, significant differences emerged. However, the comparison focused on the percentage difference in potentiation between the groups rather than the specific change in jump performance. Lastly, French et al. [101] assessed various dynamic exercises following a sequence of leg extension MVICs involving 3 repetitions at either a 3-second or 5-second duration. The study reported significant increases in jump height, maximal force, and acceleration impulse during drop jumps, as well as significant increases in knee extension maximal torque following a PAP protocol.

Although the impact of PAP on performance has been established, it is crucial to acknowledge the multitude of factors that can influence performance in response to PAP. Subsequent sections will delve into these factors that can affect performance when PAP is applied, along with providing insights into the effects of PAP on bench press performance.

2.2.2. The Type of Conditioning Contraction

The degree of potentiation achieved through PAP is likely correlated with the type of contraction used, although any type of contraction can activate the mechanisms of PAP to some extent [108]. The utilization of different contraction types, such as isometric or dynamic contractions, has contributed to inconsistent findings in previous studies [101, 109].

Studies investigating the effects of isometric maximum voluntary contractions (MVCs) on subsequent explosive activities have produced mixed results [101, 109]. While some studies reported performance enhancements [101, 109], others found no significant changes [13, 110, 111]. Similarly, studies employing dynamic maximal or near-maximal contractions to induce PAP have yielded conflicting outcomes, with some [16, 112] observing potentiation and others reporting no significant effects [113, 114]. The relationship between contraction type (isometric vs. dynamic) and the response to PAP remains unclear, as evidenced by the varying results in the literature [108].

The fatigue response associated with different contraction types is another factor that may influence the mechanisms of PAP [108]. Isometric contractions tend to induce greater central fatigue, while dynamic contractions may lead to greater peripheral fatigue [108, 115]. These contrasting fatigue patterns may be attributed to differences in muscle metabolite accumulation and blood flow during contractions [108, 115].

Future studies should explore the effects of contraction type on the mechanisms of PAP and fatigue while standardizing the volume and recovery period of contractions [108]. Additionally, it is crucial to determine whether any specific contractile condition offers superior benefits compared to conventional warm-up methods [108]. Although one study suggested the superiority of contractile conditions, the findings were specific to the individuals and protocols examined [116]. Hence, conducting comprehensive comparisons between contractile conditions and conventional warm-up techniques is necessary to obtain more conclusive evidence.

In summary, comprehending the factors influencing PAP and its effects on performance is essential. Different types of contractions can elicit diverse responses in terms of fatigue and activate distinct mechanisms of PAP. Further research is warranted to unravel these mechanisms and determine the optimal volume and recovery period required for effective potentiation. Conducting comparisons between contractile conditions and conventional warm-up techniques would provide valuable insights for practical applications [108].

2.2.3 The Volume of Conditioning Contraction

The interaction between PAP and fatigue is influenced by the volume of conditioning contractions (CC), as emphasized in a particular study. Hamada and colleagues (2003) conducted an experiment using a fatiguing protocol involving 16 sets of 5-second isometric maximum voluntary contractions (MVCs) for knee extensions, with 3-second rest intervals between each MVC [117]. They observed that PAP dominated over fatigue in the initial three MVCs when the volume was small, leading to a gradual increase in twitch peak torque (Pt) by 127% from baseline values. However, as the MVC volume increased, fatigue became more prominent, resulting in a progressive decrease in twitch Pt. By the sixteenth MVC, twitch Pt measured 32% below baseline values. During the recovery period, fatigue dispersed faster than PAP, resulting in a potentiation of twitch Pt after 30–120 seconds of recovery (+32% compared to baseline). Another study [118] supported these findings by examining twitch tension in the dorsiflexors before and after different durations of isometric MVCs. They found that the highest PAP occurred after a 10-second MVC, with twitch Pt increasing by +43% to +142% depending on the MVC duration. The effect of CC volume on subsequent voluntary explosive activities was also investigated. French et al. (2003) reported a significant increase in isovelocity knee-extension Pt immediately after three sets of 3-second isometric MVCs, while a significant decrease was observed after three sets of 5-second MVCs. In contrast, Behm et al. (2004) measured isometric MVC peak force after one, two, and three sets of 10-second MVCs and observed a decrease in peak force only after three sets of MVCs. However, Behm et al.'s study focused on maximal force rather than other performance measures. It is important to note that the varying CC volumes used in these studies may have contributed to different levels of fatigue accumulation. The results from these studies [101, 111, 117, 118] demonstrate the impact of CC volume on the PAP-fatigue relationship. They suggest that PAP develops quickly with a low CC volume, but as the volume increases, fatigue becomes more dominant, necessitating a recovery period before PAP can be fully realized. The specific duration of the recovery period required for different CC volumes remains uncertain, and the lack of standardized methodologies makes it difficult to compare the results across studies.

2.2.4 Subject Characteristics

Several subject characteristics have been proposed to impact an individual's response to PAP fatigue. These include factors like muscular strength, distribution of fiber types, training level, and the power-strength ratio, which are discussed in detail in the following.

2.2.4.1 Muscular Strength

The PAP response following a conditioning contraction may be partly influenced by an individual's muscular strength, as supported by existing evidence. It was demonstrated that subjects capable of squatting loads exceeding 160 kg experienced a significant 4% increase in countermovement jump (CMJ) height [103]. In contrast, subjects unable to squat heavy loads showed only a slight 0.4% increase in CMJ height. Similarly, the result of another study [16] demonstrated a correlation between muscular strength (both absolute and relative) and CMJ peak power potentiation 12 minutes after a back squat session with a load equivalent to 3RM. These findings may be linked to the distribution of muscle fiber types in the subjects. Previous research has consistently demonstrated a positive linear relationship between muscular strength and the percentage of type II muscle fibers [119, 120]. Notably, type II muscle fibers exhibit the most substantial increase in RLC phosphorylation following a CC [121]. Furthermore, individuals with a higher proportion of type II muscle fibers are likely to have a greater number of higher-order motor units available for activation. Consequently, the combination of increased RLC phosphorylation and enhanced recruitment of higher-order motor units may predispose individuals with a higher percentage of type II muscle fibers to exhibit a more pronounced PAP response. In light of these findings, it can be speculated that the stronger subjects in the aforementioned studies [16, 103] possessed a greater proportion of fast-twitch muscle fibers, which likely contributed to their heightened PAP response.

2.2.4.2 Distribution of Fiber Types

The relationship between fiber-type distribution and PAP was explored by Hamada and colleagues [117], providing substantial evidence. They categorized participants into two groups based on their predominant muscle fiber types: one group comprised individuals with predominantly fast-twitch (type II) muscle fibers, and the other group consisted of individuals with predominantly slow-twitch (type I) muscle fibers. Notably, the T-II group exhibited a significantly higher Pt response during a 3-second isometric maximum voluntary contraction (MVC) compared to the T-I group. Additionally, when subjected to a fatigue protocol involving 16 sets of 5-second isometric MVCs targeting the knee extensors, the T-II group demonstrated significantly greater twitch tension potentiation in the early stages of the protocol. However, as the fatigue protocol progressed, the T-II group experienced a more pronounced decline in both twitch Pt and MVC Pt. These findings suggest that individuals with a higher proportion of type II muscle fibers exhibit an enhanced PAP response but also a heightened fatigue response following a high-volume CC protocol.

Several factors may contribute to the observed increased fatigue response in the T-II group, as reported by Hamada et al. (2003). Firstly, it is important to note that the T-II group demonstrated higher Pt production during the initial stages of the fatigue protocol, in line with the force-fatigue relationship [122]. Additionally, a negative correlation has been observed between initial glycolytic rate and fatigue during intermittent exercise [123]. The specific task employed by Hamada et al. (2003), involving 16 sets of 5-second isometric MVCs with short rest intervals, predominantly relies on a high anaerobic adenosine triphosphate (ATP) turnover rate, particularly in individuals with a greater proportion of type II muscle fibers [124, 125]. Consequently, individuals with a higher percentage of type II muscle fibers are expected to exhibit increased MVC Pt due to a higher initial anaerobic ATP turnover rate. However, they are also more likely to experience greater Pt decrements due to elevated depletion of anaerobic energy stores and the production of fatigue-related metabolites [126].

2.2.4.3 Training Level

Consideration should be given to how an individual's level of training may influence the fatigue responses and PAP that occur following a conditioning activity. In the study conducted by Chiu et al. (2003), a sample of 24 participants was divided into two distinct groups: athletes engaged in national and/or international-level sports training and participation (NIT) and individuals involved in recreational resistance training (RT). The NIT group experienced a 1-3% increase in both countermovement jump (CMJ) and squat jump (SJ) height after completing five sets of back squats at 90% of their 1RM, followed by a recovery period of 5–7 minutes. Conversely, the RT group exhibited a 1-4% decrease in CMJ and SJ height under identical conditions. According to Chiu et al. (2003), it is postulated that individuals who engage in higher levels of resistance training are likely to develop resistance to fatigue as an adaptive response to their intensive training routines, thereby increasing their likelihood of experiencing PAP. However, it is important to note that Chiu and colleagues (2003) did not assess the distribution of muscle fiber types, which leaves room for the possibility that the observed effects in this study may have also been influenced by a higher proportion of fast-twitch muscle fibers in the RT group [102].

2.2.4.4 Power-Strength Ratio

The findings further imply that the ability to convert strength into power plays a crucial role in determining the effectiveness of PAP. Subjects with a lower power-strength ratio, indicating a relatively weaker power output compared to their strength, exhibited a greater potential for PAP benefits. On the other hand, individuals with a higher power-strength ratio did not show a significant association between the ratio and peak power potentiation [127]. These results suggest that the efficiency of power conversion is a key factor in unlocking the benefits of PAP. It highlights the importance of optimizing power output relative to an individual's strength level. Therefore, understanding and enhancing the power-strength ratio may be a valuable strategy for athletes and strength-trained individuals seeking to maximize the effects of PAP in their training programs [108].

2.2.5 Type of Subsequent Activity

The diverse range of subsequent explosive activities employed to assess the immediate effects of post-PAP can be a contributing factor that may result in inconsistent outcomes reported in prior studies [108]. Previous investigations [109, 111, 128] have utilized different approaches, such as isometric maximum voluntary contractions (MVCs), isolated dynamic contractions (e.g., isovelocity knee extensions [110]), and compound ballistic activities (e.g., countermovement jumps (CMJ) and drop jumps (DJ)) [103, 109, 116, 129]. It is evident that the impact of a specific competitive challenge may vary depending on the particular explosive activity under investigation. Therefore, it is crucial to consider the unique characteristics and demands of the subsequent activity in order to gain a comprehensive understanding of the effects of PAP.

When comparing isometric and dynamic explosive contractions, there have been moderate to strong correlations observed in rates of force development (RFD) and peak force [130]. However, it is important to note that despite these associations, there are significant differences in the underlying neural and mechanical processes between the two types of contractions. Isometric contractions follow the size principle, where motor units are recruited in a hierarchical order, whereas dynamic contractions exhibit a distinct recruitment pattern based on joint angle and position [108]. Moreover, dynamic contractions involve eccentric movements and elicit afferent input from muscle spindles, setting them apart from isometric contractions [131]. The utilization of elastic strain energy and the involvement of the stretch-shortening cycle, absent in isometric contractions, significantly contribute to the performance of dynamic movements [132]. Understanding these distinctions is essential for a comprehensive grasp of how PAP impacts muscle function.

The findings from studies examining the effects of PAP on various activities emphasize the importance of aligning the kinematics and characteristics of the competitive contest with the subsequent explosive activity [109]. For instance, a study by French et al. (2003) investigated knee extension, CMJ, DJ, and 5-second cycle sprint performance before and after MVC knee extensions. Significant improvements were observed in DJ height, DJ rate of force development, and knee extension peak torque. However, no significant effects were observed in the other activities. These results suggest that the duration of muscle activation and the involvement of specific muscle groups play a pivotal role in determining the effectiveness of PAP. Therefore, it is crucial to carefully match the kinematics of the competitive contest with those of the subsequent explosive activity to optimize the recruitment of higher-order motor units and achieve performance enhancements [108].

2.2.6 Postactivation Performance Enhancement (PAPE)

Recent research has been dedicated to investigating the potential impact of PAP on improving voluntary muscle force production in humans. Specifically, studies have focused on movements that require maximal muscle activations, such as vertical jumping, sprint running, cycling, and swimming. Several notable studies, including those by Güllich and Schmidtbleicher (1996), Gossen and Sale (2000), French et al. (2003), McBride et al. (2005), Yetter and Moir (2008), Winwood et al. (2016), Munro et al. (2017), and Hancock et al. (2015), have explored the effects of PAP on enhancing maximal voluntary muscle contractions during these activities [101, 109, 110, 133-137]. While investigating the mechanisms underlying PAP, researchers have examined its potential to improve the RFD during MVC and submaximal force output. It is hypothesized that brief PAP protocols may enhance RFD and subsequently enhance performance at specific points in movements where maximal forces are yet to be produced. However, some studies evaluating muscular performance following the dissipation of PAP have not incorporated evaluations of its presence using electrically evoked twitches or low-frequency tetanic stimulations during voluntary muscle testing [138]. Consequently, it remains unclear whether the observed performance enhancements can be solely attributed to "classic" PAP. As a result, researchers have suggested that both peripheral and central factors may contribute to the increased performance seen in maximal voluntary exercise. To differentiate between voluntary and electrically evoked force production, Cuenca-Fernandez et al. (2017) proposed the term "post-activation performance enhancement" (PAPE), which refers to improvements in voluntary force following high-intensity conditioning contractions [139]. While this term has yet to gain widespread acceptance in the scientific and clinical communities, it serves as a useful distinction between the effects of twitch force and voluntary force in such circumstances.

2.2.7 Study Design Considerations for PAPE/PAP

Recognizing the substantial divergence between PAP and PAPE, as well as the dissimilar assessment methods employed (e.g., muscular twitches versus voluntary contractions), results suggest a significant conclusion: a narrow range of studies have effectively employed the suitable methodology to reconcile PAP and PAPE. To establish a connection between these phenomena, it becomes imperative to consider vital aspects pertaining to study design [138, 140]. As previously deliberated, the evaluation of muscular twitch force measurements is widely regarded as reflective of PAP's magnitude, enabling the comprehensive examination of its intensity and temporal progression in relation to PAPE. To ensure standardization, a comprehensive set of guidelines, proposed by MacIntosh et al. (2012), can be utilized as an invaluable framework.

These guidelines encompass several essential focal points that demand careful consideration when undertaking studies that investigate PAP, PAPE, or both. Foremost, a comparative analysis involving a minimum of two conditions is paramount, encompassing a non-exercising control condition alongside an unrelated exercise condition. Such a comparison aids in discerning whether the conditioning activity possesses a distinctive capability to elicit a response or purely serves as an additional element of warm-up. Secondly, the introduction of participant familiarization with the performance task is crucial to mitigating potential learning effects that could influence the outcomes. Randomization of conditions on separate days further reinforces the integrity of the results, minimizing potential order effects or biases. Moreover, the implementation of blinding techniques, such as single blinding (researcher) or double blinding (participant and researcher), significantly reduces bias and enhances the objectivity of the study.

In addition to these considerations, strict control of factors that could impact the results is imperative. Researchers should strongly emphasize the control of variables such as muscle temperature, time of day, dietary and hydration practices, physical activity undertaken in the days preceding the testing, and the potential usage of performance-enhancing substances. These factors exert a substantial influence on the outcomes and should be accurately regulated to ensure accurate interpretations. By addressing these critical considerations in study design, researchers can enhance the reliability and comparability of findings pertaining to PAP and PAPE [138].

A recent investigation conducted by Cuenca-Fernandez et al. (2017) revealed the repercussions of these considerations. The study highlighted notable increases in squat jump height following a non-exercising control condition, raising the possibility of a PAP/PAPE effect. However, it was also observed that these increments could potentially be ascribed to a warm-up effect stemming from the completion of baseline tests. Furthermore, the study underscored the potential influence of a learning effect associated with the warm-up. The absence of control conditions, wherein participants abstain from engaging in conditioning activities immediately prior to testing, impedes the ability to solely attribute performance alterations to the conditioning activity. Consequently, incorporating suitable control conditions becomes pivotal in accurately appraising the effects of PAP and PAPE [138].

To avoid potential confounding factors, researchers have explored the utilization of torque generated during maximum voluntary contractions as a control condition [141]. This approach aids in accounting for warm-up effects, encompassing enhancements in muscle activation or temperature. Nonetheless, it should be noted that increases in peak isometric force may not exhibit significant temperature sensitivity [142]. In situations where the measurement of twitch force is impractical, the comparison of maximal voluntary force with force produced in ultra-brief, rapid contractions can provide valuable insights into the extent of PAP. Nonetheless, further research is warranted to ascertain whether improvements in the rate of force development or muscle power beyond maximal voluntary torque correlate with the magnitude of PAP. Additionally, ensuring blinding in the study design, encompassing both the intervention (conditioning activity) and the participants' knowledge of study outcomes, assumes the best consequence in minimizing bias and increasing the validity of the results.

2.2.8 PAPE in Bench Press

A recent meta-analysis by Krzysztofik and colleagues (2021) demonstrated that conducting a condition activity can lead to improvements in the following bench press throw (BPT) performance among resistance-trained men, which in turn revealed that optimal enhancement of BPT performance can be achieved within a length of 5-7 minutes after performing a single set of the BP exercise at a moderate intensity (60–84% 1RM) [17]. specifically, it can be inferred that performing the BP exercise at a moderate intensity (60–84% 1RM) as the CA yields slightly better results compared to ballistic-plyometric exercises (e.g., BPT at 30% 1RM or body weight plyometric push-ups) and the BP exercise at high and supramaximal intensities enhances subsequent BPT performance. Conversely, the concentric-only BP exercise seems to be the least effective [17]. These findings align with the research conducted by Maloney et al. (2014), who suggested that high-intensity resistance exercises are more effective in inducing the PAPE effect than ballistic exercises, in which the authors highlighted that ballistic CA can lead to performance improvements ranging from 2 to 5% [143]. The enhancement of performance following ballistic-plyometric CA may be attributed to the recruitment of motor units at lower thresholds compared to slower, gradual contractions [144], as well as reduced fatigue compared to traditional heavy-loaded resistance exercises [18]. Moreover, the advantage of ballistic-plyometric CA lies in its minimal equipment requirements, making it suitable for inclusion in warm-up routines before competitions [20].

The data obtained from the study of Krzysztofik and colleagues (2021) revealed a little difference between the effects of single and multiple sets of the CA. Notably, previous meta-analyses conducted by Wilson et al. (2013) and Seitz and Haff (2016) reported significant disparities in CA volume when comparing single sets to multiple sets. However, Seitz and Haff (2016) specifically highlighted that individuals with higher levels of strength tend to experience a more pronounced effect after a single set rather than multiple sets of the CA. Despite the potential for multiple sets of the CA to induce greater fatigue, this finding may not be applicable to stronger individuals who exhibit a higher resistance to fatigue [102]. Moreover, it appears that multiple sets do not confer additional benefits compared to a single set of the CA, as the latter seems sufficient to elicit similar enhancements in BPT performance among individuals with higher strength levels.

The effects of the rest interval within the CA exhibit intriguing patterns, irrespective of the intensity employed [17]. Notably, the most pronounced impact was observed after a rest interval of 5-7 minutes, suggesting its optimal duration. Specifically, when considering intensities below 85% 1RM, the greatest effect was seen after 5-7 minutes, followed by 0.15–4 minutes, while a slightly smaller effect was noted after rest intervals of ≥8 minutes. Interestingly, for intensities above 85% 1RM, comparable effects were observed after 5-7 minutes and ≥8 minutes of intra-complex rest intervals. In contrast, a negative effect emerged when the rest interval fell within 0.15–4 minutes [17]. These findings align with Seitz and Haff's (2016) observations, who similarly reported the greatest PAPE effect with intra-complex rest intervals lasting 5-7 minutes. The presence of concurrent fatigue and potentiation induced by the CA offers a plausible explanation for these outcomes. In conclusion, a 5-7 minute intra-complex rest interval is considered optimal for enhancing explosive performance [145]. It is worth noting that the lack of improvement within the 0.15–4 minute rest interval following the CA at intensities above 85% 1RM may be attributed to the overwhelming fatigue surpassing the potentiation. Conversely, in the case of the CA performed at intensities below 85% 1RM, an opposite scenario may unfold. Furthermore, these findings may be associated with the rapid increase in muscle temperature and blood flow within 3-5 minutes, reaching a plateau, while longer intra-complex rest intervals could potentially reduce these factors. Additionally, the elevation in muscle temperature may particularly benefit type II fibers, leading to heightened power outputs [145].

Table 1. Overview of studies investigating PAPE in bench press

Article	Training Experience	Strength Level	Exercise	Volume and load	Intra-complex rest intervals	Potentiated exercise
Brandenburg (2005)	>1 year	1.46 kg/bw	Bench press	(a) 1 set of 5 repetitions at 100% 5RM (b) 1 set of 5 repetitions at 75% 5RM (c) 1 set of 5 repetitions at 50% 5RM	4 min	Concentric-only bench press throw at 45% 1RM
Bevan et al. (2009)	>2 years	1.35 kg/bw	Bench press	3 sets of 3 repetitions at 87% 1RM with 4 min rest	15 s, 4, 8, 12, 16, 20, 24 min	Bench press throw at 40% 1RM
Esformes et al. (2011)	>2 years	1.14 kg/bw	Bench press	(a) 7 s isometric (b) 1 set of 3 concentric repetitions at 3RM (c) 1 set of 3 eccentric repetitions at 3RM (d) 1 set of 3 eccentric–concentric repetitions at 3RM	12 min	Bench press throw at 40% 1RM
Farup and Sørensen (2010)	>1 year	1.4 kg/bw	Bench press	5 sets of 1RM with 5 min inter-set rest period	1–21 min	Bench press throw at 30% 1RM
Kilduff et al. (2007)	>3 years	1.27 kg/bw	Bench press	1 set of 3RM	15 s, 4, 8, 12, 16, 20 min	Bench press throw at 40% 1RM
Krzysztofik et al. (2020b)	>3 years	1.54 kg/bw	Bench press	(a) 2 sets of 2 eccentric repetitions at 90% 1RM (b) 2 sets of 2 concentric repetitions at 90% 1RM (c) 2 sets of 2 eccentric repetitions at 110% 1RM (d) 2 sets of 2 eccentric repetitions at 130% 1RM	5 min	Bench press throw at 30% 1RM
Liossis et al. (2013)	>6 months	1.09 kg/bw	Bench press	(a) 5 repetitions at 65% 1RM (b) 5 repetitions at 85% 1RM	4 and 8 min	Bench press throw at 30% 1RM
Tsoukos et al. (2019)	**>3 years**	**1.26 kg/bw**	**Bench press**	**(a) 40% 1RM until mean velocity dropped to 90% of the peak attained (b) 40% 1RM until mean velocity dropped to 70% of the peak attained (c) 60% 1RM until mean velocity dropped to 90% of the peak attained (d) 60% 1RM until mean velocity dropped to 70% of the peak attained (e) Control in which participants did not perform any CA**	**45 s, 2, 4, 6, 8, 10, 12 min**	**Bench press throw at 30% 1RM**

Source: adapted from the study by [17]

2.2.9 Ballistic Exercises as a Conditioning Activity

Ballistic exercise is characterized by its focus on maximal velocity and the acceleration of a mass throughout the entire movement [146]. It involves actions such as jumping or throwing, which eliminate the deceleration phase seen in traditional resistance exercises. While some studies have argued its effects, ballistic exercise has consistently shown to generate greater power outputs compared to non-ballistic approaches. Newton et al. (1996) have suggested that the extended duration of positive acceleration during ballistic exercise facilitates increased force production and muscle activation. However, the viewpoints expressed by Frost et al. (2008) and Lake et al. (2012) challenge these assertions, highlighting the ongoing debate surrounding the efficacy of ballistic training. Nevertheless, the unique qualities of ballistic exercise make it a compelling option for enhancing power performance [147, 148].

One key advantage of ballistic exercise is its ability to recruit motor units more efficiently compared to slower contractions [149]. This reduction in recruitment threshold plays a significant role in facilitating PAP [143]. By employing ballistic contractions, the excitatory drive stimulates the activation of the entire motor-neuron pool within milliseconds [150]. This rapid recruitment of motor units enables a strong and immediate response, potentially enhancing subsequent performance. It is important to note that while the recruitment threshold is lower during ballistic contractions, the principle of contraction size and the absence of selective recruitment of faster motor units are still preserved [151]. These findings support the notion that ballistic exercise can effectively harness the neuromuscular system to promote enhanced performance outcomes [151].

Although ballistic exercises can promote PAP when used as a conditioning activity, several factors can influence performance outcomes. The subsequent section delves into the intricate details of the factors that influence performance, namely loading, recovery, and physical characteristics [143].

2.2.9.1 Loading

Research findings suggest that ballistic exercises employing heavier loadings tend to induce more favorable acute adaptations compared to lower-intensity protocols [143]. When incorporating ballistic exercises, the choice of loading becomes a critical consideration. This includes selecting the appropriate plyometric intensity or incorporating external loading methods such as weighted jumps or variations of Olympic weightlifting movements [143].

For example, studies have demonstrated that depth jumps, categorized as higher-intensity exercises, can lead to significant improvements in performance measures. Notably, depth jumps have been shown to elicit enhancements in various areas, including increased power production during counter-movement jumps (CMJ), improved shot throw distance, and enhanced vertical jump height. Surprisingly, exercises classified as lower-intensity, such as tuck jumps, have exhibited minimal effects on performance [152-154].

To advance the understanding of plyometric exercise and its impact on performance, future research should aim to compare different types of exercises and evaluate the specific kinetic variables that are affected [143]. Since individual exercises exhibit distinct kinetic profiles, it is possible that different mechanisms contribute to the observed enhancements in performance outcomes. Additionally, exploring optimal loading strategies and their effects on performance measures in ballistic exercise protocols would further enhance our knowledge in this field [143, 155, 156].

2.2.9.2 Recovery

In studies examining recovery duration following high-resistance exercise (HRE), a consensus has been reached regarding the initial impairment of performance, followed by the realization of PAP in an inverted U-shaped pattern [16, 157]. However, in the context of ballistic exercise (BE), there is no agreement on the recovery effects [143]. Some findings suggest a similar recovery profile between drop jumps and HRE [158], while others demonstrate a negative association between recovery and PAP [159]. The impact of recovery duration on BE outcomes remains uncertain, although shorter durations (e.g., 60 seconds to 3 minutes) have shown potential [143]. Further research is needed to determine the optimal recovery period for BE, considering protocol intensity and volume.

2.2.9.3 Physical Characteristics

Extensive research has been conducted to explore the impact of individual differences on PAP responses, primarily focusing on HRE. Athletes' strength levels emerge as the crucial factor, as athletically trained males and females experience a potentiation effect, while recreationally trained individuals exhibit decreased performance following HRE [143]. This disparity is attributed to greater muscle activation in the athletically trained population. Similar findings are supported by other studies [102, 103]. Moderate to strong correlations have been observed between strength and PAP responses in strength-trained athletes, both for HRE and BE [160]. However, when categorizing athletes based on strength levels, no significant effect has been reported [153]. The role of type II muscle fibers in the PAP response and their relationship with strength further explains the positive effect of HRE on stronger athletes [161]. Additionally, it is suggested that stronger individuals require less recovery time to benefit from PAP, indicating a higher training experience and tolerance level [162]. Sex also plays a significant role, with PAP occurring to a greater extent in untrained or recreationally trained males compared to females [21]. Similar results have been observed in resistance-trained male and female athletes [163]. However, there are varying views on inter-sex differences following BE. Further research is necessary to fully understand these factors and optimize training protocols accordingly.

Table 2. Overview of studies exploring the impact of ballistic pre-activation approaches on performance

Article	Pre-activation stimulus	Volume	Recovery before testing	Performance test	outcome
Masamoto et al.	Depth jump	2 reps * 1 set	30 s	1RM back squat	3.5 % (4.9 kg) increase from pre-test (P\0.05; ES 0.16; 90 % CI 0.9–8.9 kg
	Tuck jump	3 reps * 1 set	30 s	1RM back squat	No effect
Burkett et al.	DB loaded box jump w/ 10 % BW (0.64 m box)	5 reps * 1 set	2 min	CMJ height	3.3 % (2.28 cm) increase over control (P\0.01; ES 0.38; 90 % CI 0.9–3.7 cm)
	CMJ at 75 % intensity	5 reps * 1 set	2 min	CMJ height	No effect
Mc Bride et al	BS w/ 90 % 1RM	3 reps * 1 set	4 min	40 m sprint	0.87 % (0.05 s) faster than control (P = 0.018; ES 0.16; 90 % CI 0.02–0.08 s)
	Smith machine CMJ w/ 30 % of 1RM BS	3 reps * 1 set	4 min	40 m sprint	No effect
Faigenbaum et al.	WV loaded DWU w/ 2 % BW	NR	2 min	CMJ height, LJ distance MB throw, 10 yard sprint, CMJ height, LJ distance, Medicine ball throw,	No effect, 7 % increase over control (estimated from figures; P value NR)
	WV loaded DWU w/ 6 % BW	NR	2 min		No effect
Hilfiker et al	Modified DJ from 0.6 m	5 reps * 1 set	1 min	CMJ height, CMJ power	No effect, 2.2% (1.21 W kg-1) increase over control (P\0.05; ES 0.27; 90 % CI 0.2–2.2 W kg-1)
Thompsen et al	DWU w/ 10 % BW WV for last 4 exercises	NR	2 min	SJ height, SJ power, CMJ height, LJ distance	No effect, no effect, no effect, 2.5 % (4.6 cm) increase over control (P B 0.05; ES 0.24; 90 % CI 0.8–8.4 cm)
Tahayori	WV loaded CMJ w/ 15 % BW	3 reps * 5 sets (0.5 min recovery)	2 min	CMJ height	2.1 % (1.48 cm) increase over control (P B 0.05; SD NR; 90 % CI 0.3–2.7 cm) in males No effect in females
Terzis et al.	DJ from 0.4 m	5 reps * 1 set	20 s	Underhand front shot distance	4.6 % (0.38 m) increase from pre-test (P \0.01; ES 0.32; 90 % CI 0.2–0.6 m) [1.5 % (0.11 m) increase in females (ns; ES 0.14); 7.4 % (0.64

					m) increase in males (P \0.01; ES 0.69; 90 % CI 0.3–1.0 m)]
			4–6 min, 7–9 min		
Till and Cooke	Deadlift w/ 5RM	5 reps * 1 set	4–6 min, 7–9 min	20 m sprint, CMJ height	No effect
	Tuck jump	5 reps * 1 set	4–6 min, 7–9 min	20 m sprint, CMJ height	
	Isometric MVC (3 s)	5 reps * 1 set		20 m sprint, CMJ height	
Chattong et al.	Box jump (box at knee height)	5 reps * 1 set	2 min	CMJ height	No effect
McCann and Flanagan	Hang clean w/ 5RM BS w/ 5RM	5 reps * 1 set	4 min	CMJ height	No effect
Andrews et al.	Hang clean w/ 60 % 1RM	3 reps * 3 sets	3 min after each set	CMJ height	No effect of gender
Lima et al	DJ from 0.75 m	5 reps * 2 sets	5 min 10 min 15 min	CMJ height, 50 m sprint	No effect for 5 min and 10 min CMJ height, 2.4 % (0.16 s) faster than control (P\0.05; ES 0.66; 90 % CI 0.03–0.3 s), 5.5 % (2.4 cm) increase over control (P\0.01; ES 3.16; 90 % CI 1.0–3.8 cm, 2.7 % (0.17 s) faster than control (P\0.05; ES 0.69; 90 % CI 0.03–0.3 s)
Tsolakis et al.	Isometric leg press at 90 degree knee flexion (3 s)	3 reps * 1 set	8 min 12 min	CMJ power	No effect overall [7.5 % decrease in males (P \0.01; ES 0.53)], No effect overall [8.7 % decrease in males (P \0.01; ES 0.65)]
Chiu and Salem	Snatch pull	8 reps * 2 sets	3 min after each set	CMJ height	5.8 % increase from pre-test (P = 0.001; ES 1.62; mean figures NR)
West et al.	Bench press w/ 87 % 1RM	3 reps * 3 sets (recovery NR)	8 min	Ballistic bench throw power w/ 30 % of 1RM bench press	4.3 % (38 W) increase from pre-test (P \0.001; ES 0.35; 90 % CI 21–55 W)
Chen et al.	DJ from 0.6 m	5 reps *1 set	2 min 6 min 12 min	CMJ height	Increase from pre-test when combined w/ 2 set condition (P = 0.008; mean figures NR), no effect, no effect

Read et al	CMJ	3 reps * 1 set	1 min	Golf clubhead speed	2.2 % (2.25 mph) increase over control (P \0.05; ES 0.16; 90 % CI 0.4–4.1 mph)
Tobin and Delahunt	Ankle hops	10 reps * 2 sets	1 min	CMJ height	4.8 % (2.09 cm) increase from pre-test (P \0.001; ES 0.39; 90 % CI 1.2–3.0 cm)
	Hurdle hops,	5 reps * 3 sets	3 min		3.9 % (1.72 cm) increase from pre-test (P \0.001; ES 0.31; 90 % CI 1.0–2.5 cm)
	DJ from 0.5 m	5 reps * 1 set	5 min		3.5 % (1.53 cm) increase from pre-test (P \0.001; ES 0.27; 90 % CI 0.9–2.2 cm)

Source: adapted from the study by [143].

Chapter 3: Sex Differences in the Determination of Prescribed Load in Ballistic Bench Press

3.1 Introduction

Since athletes need to improve their performance through exercise, strength and conditioning coaches have focused on various techniques and training programs that can enhance athletic performance. One of the most common exercises is the bench press, which in turn helps athletes develop neuromuscular qualities and subsequently improve skills-related athletic performance [10]. In this context, bench press throw is widely used to improve power-related capacities among athletes [164]. Specifically, subjects need to accelerate the load throughout the movement from the beginning until the end of projection. Hence, since a variety of motions in athletic movements are required explosive motor actions, ballistic bench press exercise can assist athletes by maintaining velocity while improving strength, which in turn can enhance power-related capacities [165].

Previous studies [164, 166, 167] demonstrated that prescribed training loads affect different aspects of muscle performance, in which very heavy weights (90–95% 1RM) are employed to boost maximal strength [164], high loads (approximately 80% 1RM) are associated with muscle strength and hypertrophy improvements [166], and lighter loads (40%–60% 1RM) are used to enhance characteristics such as the rate of force development (RFD) and power-related qualities [167]. Whereas ballistic bench press exercise can help improve athletic performance, there is still a concern related to prescribed loads. That is, an increase in load can lead to a decrease in velocity, such that if athletes tend to train in the presence of a high load (e.g., 80% 1RM), they cannot maintain propulsive acceleration throughout the concentric activation of exercise, which means movement velocity is too low. It is, therefore, impractical to project a loaded barbell into the air. In this vein, a recent study [168] demonstrated that mean propulsive acceleration is close to zero during bench press throw after 80% 1RM, which suggests athletes cannot project a loaded barbell into the air. It was, therefore, proposed that strength and conditioning coaches prescribe any load below 80% 1RM if they tend to maintain the characteristics of ballistic exercise.

Given the substantial body of literature addressing sex differences in neuromuscular characteristics, including strength [169] and fatigability [170, 171], it is expected women demonstrate different responses compared to men in relation to ballistic bench press exercise. In particular, previous studies demonstrated that men with comparable training backgrounds exhibit a steeper slope in the load-velocity relationship compared to women [7, 172, 173]. Thus, general equations that were formerly published to detect the propulsive phase of the concentric contraction might not be well-suited for women [174]. Conducting research is essential to determining the appropriate load to maintain velocity in female athletes during a bench press throw. To the best of our knowledge, no study has been carried out to ascertain the specific relative loads at which women reach the point where the concentric action transforms into a purely propulsive phase during a bench press throw, meaning athletes are unable to project the load into the air. Therefore, the primary objective of the current study was to identify the specific relative load, represented as a percentage of 1RM, at which the concentric motion shifts into a purely propulsive action among women during the bench press. Additionally, to gain a deeper understanding of the differences between sexes in terms of the recommended load, we aimed to compare load-velocity relationships between men and women during the bench press throw. We hypothesized that female athletes would exhibit a different threshold load in the achievement of the pure propulsive phase during concentric action when compared to their male counterparts. It is also hypothesized that the change in velocity for a specific change in %1RM would be greater among men.

3.2 Methods

3.2.1 Subjects

While previous power analyses [175] suggested that differences in mechanical variables (velocity, force, and power) could be detected with sample sizes as low as 3 to 9 participants, we conservatively enrolled 14 male collegiate athletes (age = 28.78 ± 3.19 years; body mass = 76 ± 6.23 kg; body height = 177.78 ± 4.99 cm) and 14 female collegiate athletes (age = 27.71 ± 2.33 years; body mass = 51.21 ± 8.91kg; body height = 166.92 ± 3.33 cm) in the current study. The athletes possessed a range of 3 to 6 years of experience in weight training and were actively engaged in training, with 3 sessions per week, during the time of measurement for the study. These athletes had no history of musculoskeletal injuries in the past six months and any physical limitations that could affect the result of the study. Subjects were informed about the type of test and how to perform the bench press throw; however, were not informed regarding the outcomes of any their evaluations. Participants signed the informed consent before performing the test, and the present study was approved by the Institutional Review Board at the University of Palermo.

3.2.2 Procedures

Participants started to perform 1 RM test after a 10-min standardized warm-up, which consisted of jogging on a treadmill, stretching and upper-body joint mobilization exercises, and 1 set of 5 repetitions of bench press with a load of 8 kg (the weight of the Smith machine barbell). To perform the 1 RM test, the initial load was set at 8 kg for both male and female athletes. The external load was progressively increased by 10 and 5 kg for male and female athletes, respectively, until the achieved mean propulsive velocity (MPV) was less than 0.5 m.s^{-1}. Then, the load was increased by 5–1 kg to attain the precise estimation of 1RM bench press, such that 1RM was determined when an athlete could lift the heaviest load with the full extension of his/her elbow. Three, two, and one repetitions were executed for the lighter (MPV > 1 m.s^{-1}), medium (0.65 m.s^{-1} ≤ MPV ≤ 1 m.s^{-1}), and heaviest loads (MPV < 0.65 m.s^{-1}), respectively. The rest period was 3 min for lighter and medium loads, while it was 5 min for the heaviest loads. The rest period between the repetitions executed with the same load was also 10 sec [10].

Subjects performed the bench press throw in accordance with the method, which was extensively described in previous studies [10, 170]. The participants were first asked to execute the eccentric phase with control, holding a static position for at least one second at the end of this phase, ensuring that the bar lightly touched the chest. This was done to reduce the influence of the rebound effect and enhance measurement consistency. Following this, they were instructed to perform the concentric action with maximal effort. To provide safety for participants and give them feedback to keep their maximum velocity, two trained spotters were present on both sides of the barbell.

A Smith machine (JK Fitness Equipment) along with a dynamic measurement system (i.e., a linear velocity transducer that was sampled at a frequency of 1000 Hz (T-Force System, Ergotech, Murcia, Spain)) was used to measure the MPV of the barbell during bench press throw. MPV was assessed throughout the concentric phase of the BP; in particular, the propulsive phase was determined as the portion of the concentric phase in which the acceleration of the movement was greater than the acceleration caused by gravity (i.e., g = 9.81 m.s^{-2}). The validity and reliability of the T-Force system were reported in previous studies [10, 176].

3.2.3 Statistical Analysis

Data were assessed for normality and homogeneity of variance using the Shapiro-Wilks test and Levene's test, respectively. Linear regression models were employed to elucidate the association between load (%1RM) and MPV, as well as load (%1RM) and the propulsive phase (% of total concentric time). ANCOVA was utilized, with load as a covariate, to assess the sex-related differences in linear regression models. To better comprehend the distinctions between sexes in relation to dependent variables, we examined Cohen's effect size (ES) along with its 95% confidence interval. This analysis was conducted across 5% increments, ranging from 20% 1RM to 100% 1RM. The criteria for interpreting the ES magnitude encompassed the following categories: trivial (2.0), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), and extremely large (>2.0) [177]. Independent t-tests were also used to compare 1RM strength with respect to sex. Analyses were conducted using SPSS software version 26, and the level of significance was set at $P < .05$.

3.3 Results

The 1RM strength was significantly different between men and women ($p< 0.001$; ES = 4.47; men = 88.71 ± 14.12 kg; women = 40.57 ± 5.63 kg).

Table 1 displays the breakdown of concentric time into propulsive and braking phases at various percentages (from 20% to 100%) of 1RM for both men and women. The results from our linear regression models reveal a strong correlation between the load (1RM%) and the relative contribution of the propulsive phase to the total duration of the concentric lift for men ($R^2 = 0.817$, $p < 0.001$) and women ($R^2 = 0.644$, $p < 0.001$), as illustrated in Figure 1. A. The results of the ANCOVA analysis reveal significant differences between men and women concerning the relative contribution of the propulsive phase to the total duration of the concentric bench press throw (F = 43.431, $p < 0.001$). Specifically, at 20% 1RM, men accounted for 69% of the concentric time in the propulsive phase, whereas women demonstrated an 87% contribution to the propulsive phase at the same relative load. Notably, men reached a full propulsive phase at 85% 1RM, while women achieved the total propulsive phase at 80% 1RM, as detailed in Table 1. The effect size, along with its 95% confidence intervals, for the relative contribution of the propulsive phase to the total duration, is visually represented in Figure 2A.

The data analysis revealed a robust relationship between load (1RM%) and MPV in both men (R^2=0.939, $p < 0.001$) and women (R^2=0.855, $p < 0.001$), as depicted in Figure 1B. Furthermore, the results from the ANCOVA indicated significant differences between men and women regarding MPV (F = 19.745, $p < 0.001$). A comprehensive representation of MPV across various loads (ranging from 20 to 100% 1RM) can be found in Table 1. Additionally, Figure 2B visually illustrates the effect size of MPV, along with its corresponding 95% confidence intervals.

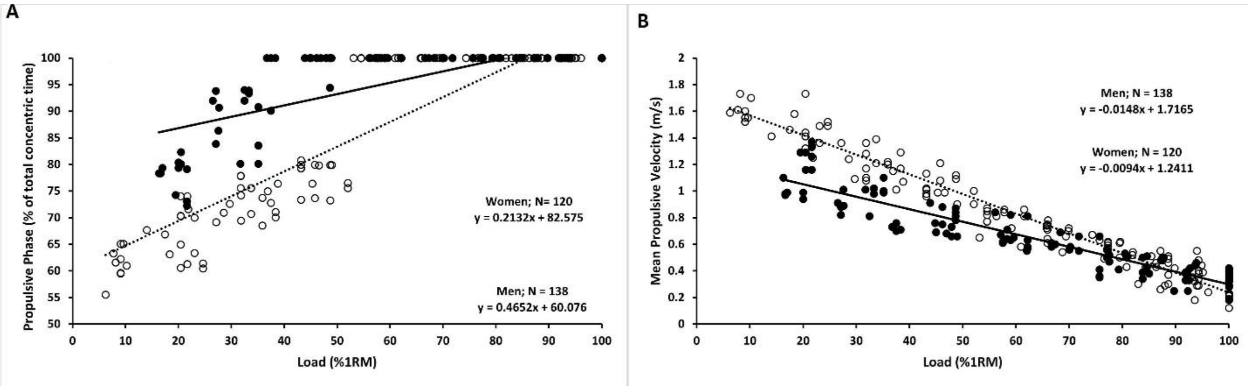

Figure 1. (A): Relationships between relative load (% 1RM) and Propulsive Phase for men (open dots and dashed line) and women (filled dots and solid line); (B): Relationships between relative load (% 1RM) and MPV for men (open dots and dashed line) and women (filled dots and solid line)

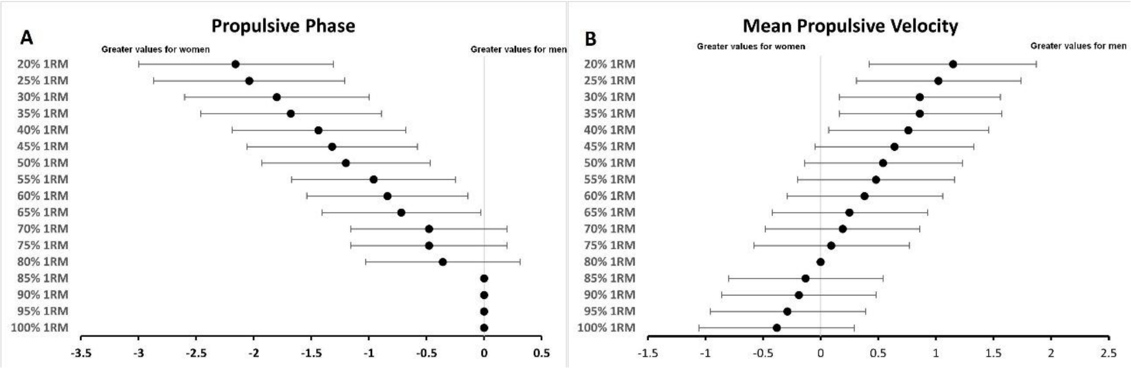

Figure 2. Effect size and its 95% confidence interval, represented as horizontal lines, are depicted in (A) for the Propulsive Phase and in (B) for the Mean Propulsive Velocity. Positive numbers indicate great values for men.

Table 1. sex differences in mean propulsive velocity (in meters per second) corresponding to various loads (as a percentage of 1RM) and the proportion of the propulsive phase's contribution to the overall concentric duration

Load (%1RM)	Men (n=14)		Women (n=14)	
	Propulsive Phase (%)	MPV (m.s^{-1})	Propulsive Phase (%)	MPV (m.s^{-1})
20	69	1.42	87	1.06
25	71	1.34	88	1.02
30	74	1.27	89	1
35	76	1.20	90	0.93
40	79	1.12	91	0.88
45	81	1.04	92	0.84
50	83	0.97	93	0.80
55	86	0.90	94	0.75
60	88	0.82	95	0.70
65	90	0.74	96	0.66
70	93	0.67	97	0.61
75	95	0.60	99	0.57
80	97	0.52	100	0.52
85	100	0.44	100	0.48
90	100	0.37	100	0.43
95	100	0.30	100	0.39
100	100	0.22	100	0.34

MPV = mean propulsive velocity

3.4 Discussion

The aim of this study was to investigate the threshold loads at which women exhibit a solely propulsive phase during the bench press throw and to compare the load-velocity relationship between men and women. Our results revealed that, at approximately 80% of their 1RM, women transitioned into a completely propulsive concentric phase. In contrast, men exhibited this purely propulsive phase at around 85% of their 1RM. Furthermore, we observed a significant difference in the load-velocity relationship between men and women. Specifically, women displayed lower velocities when handling lighter relative loads compared to men. Conversely, women exhibited higher velocities when dealing with loads exceeding 85% of their 1RM, in comparison to their male counterparts.

In theory, ballistic exercises such as the bench press throw, which involve high-velocity movements, have the potential to enhance athletes' power-related attributes, thereby elevating their performance in sports and competitive events [168]. However, it is important to note that the effectiveness of ballistic exercises in improving athletes' performance can be influenced by the prescribed load, which alters their kinematics and kinetics. Specifically, heavier loads result in reduced velocity, ultimately negating the benefits of these exercises by preventing the effective projection of the load into the air. In this vein, prior studies [10, 168, 178] have shown that when male athletes lift loads surpassing approximately 75-80% of their 1RM, they are unable to harness the benefits of the ballistic bench press. This is because, at these specified loads, the concentric phase of the exercise primarily becomes propulsive, preventing athletes from effectively launching the loaded barbell into the air. In other words, the concentric contraction comprises both propulsive and braking phases. When lifting lighter loads (resulting in higher velocity), there is a prolonged braking phase during which acceleration exceeds that of gravity. However, when handling heavier loads (resulting in lower velocities), the braking phase diminishes, and acceleration falls below that of gravity [10]. Consequently, athletes are unable to propel the barbell into the air. According to our data, women displayed a distinct propulsive phase at 80% of their 1RM, whereas men exhibited this phase at 85% of their 1RM. To delve deeper, when lifting at 20% 1RM, women demonstrated a significantly larger propulsive phase compared to men (87% for women and 69% for men). Interestingly, women exhibited an 87% propulsive phase even at just 20% of their 1RM, and from 35% to 75% of their 1RM, the propulsive phase ranged from 90% to 99%. This suggests that propelling the barbell into the air during this phase becomes particularly challenging. In line with prior research (García-Ramos et al., 2021; Nieto-Acevedo et al., 2023; Torrejón et al., 2019) advocating for the use of a specific equation to predict load-velocity relationships in women, our findings confirmed that women exhibited a higher value for the propulsive phase of concentric contraction than men.

In our current study, we observed a significant difference in the load-velocity relationship between men and women. This finding aligns with previous research (García-Ramos et al., 2021; Torrejón et al., 2019), which has consistently shown that women tend to exhibit lower velocities at lower relative loads compared to men. However, at higher relative loads (~80% 1RM), women demonstrate higher velocities compared to men. While a limited number of studies have investigated load-velocity differences based on sex, these studies have utilized mean velocity and mean propulsive velocity as key variables in developing their models [172]. It is worth noting that while there is some variability among individuals, a clear pattern emerges when the movement becomes purely propulsive: both mean mechanical and mean propulsive variables converge, becoming indistinguishable. However, during phases that are not entirely propulsive, mean propulsive variables surpass mean mechanical variables in magnitude [10]. Our data revealed that men demonstrated lower velocities compared to women when the bench press throw became entirely propulsive. The difference between the sexes may result from variations in muscle fiber types between men and women [7]. Specifically, the higher prevalence of slow muscle fibers in women compared to men might contribute to their reduced speed when handling lighter relative loads [169]. It can also stem from range of motion (ROM) [172]. In this vein, since men are taller and have longer limbs compared to women, prior studies [25, 179] have demonstrated that variations in ROM can affect RFD, activation, and synchronization of motor units. However, further research is needed to identify the mechanisms underlying these sex differences and to determine whether they are attributed to muscle fiber types and ROM.

The findings of the present study must be interpreted in light of certain limitations. Firstly, the athletes in our study were not engaged in supervised weight training at the time of data collection. Additionally, due to the inherent constraints associated with cross-sectional studies, it is imperative that the results of our study are validated through future research. Lastly, as our study exclusively involved athletes with prior resistance training experience, it is important to note that the findings may not apply to different athletic groups. Therefore, it is recommended to investigate the relative loads at which a concentric contraction shifts entirely to a propulsive phase among women participating in diverse sports disciplines.

Practical Applications

In the process of executing a proper barbell throw, athletes are required to maintain a persistent net positive force over an extended portion of the lift, thereby creating a more pronounced acceleration path throughout the upward phase of the motion. Furthermore, athletes need to decelerate the barbell to bring it to a complete stop during the concentric phase. The absence of a braking phase in this context renders it impossible to project the barbell into the air, as is typically the case in the traditional bench press [168]. As soon as the acceleration phase becomes entirely propulsive, it becomes unfeasible to project the barbell into the air. This point can be regarded as the 1RM for the bench press throw [168]. Therefore, coaches are advised to consider 80% of bench press-1RM for women and 85% of bench press-1RM for men as bench press throw-1RM when prescribing loads to athletes. In other words, 85% of bench press-1RM is equivalent to bench press throw-1RM. This approach aims to maintain the mechanical characteristics of ballistic exercises and optimize their performance.

3.5 Conclusion

Our research revealed that women transitioned into a fully propulsive concentric phase at roughly 80% of their 1RM, while men achieved this entirely propulsive phase at approximately 85% of their 1RM. Additionally, a significant disparity emerged in the load-velocity relationship between men and women. To elaborate, women exhibited reduced velocities when handling lighter relative loads in contrast to men. Conversely, women demonstrated higher velocities when dealing with loads exceeding 85% of their 1RM, as compared to their male counterparts. These findings hold notable implications for prescribing bench press throw loads for women, which should differ from those recommended for men. Further studies are necessary to validate the efficacy of the proposed load recommendations.

Chapter 4: Assessing the Influence of Various Types of Muscle Contractions on Subsequent Bench Press Performance Volume

4.1 Introduction

An acute enhancement of performance following maximal or sub-maximal muscle activity, induced by a conditioning activity (CA), is attributed to a phenomenon known as post-activation potentiation (PAP) [180]. It has been proposed that two primary mechanisms contribute to PAP: the phosphorylation of myosin regulatory light chains and an increased recruitment of higher motor units [18, 180]. While the application of PAP has been extensively used in human performance studies, including its impact on enhancing power-related activities in athletes, the mechanism that triggers this improvement in athletic performance remains poorly understood [180]. To address this, Prieske and colleagues (2020) suggested using the term "post-activation performance enhancement" (PAPE) instead of PAP. This recommendation arises from the fact that electrically-evoked twitch properties are necessary to comprehend the mechanisms underlying PAP, whereas studies in sports sciences apply a CA to assess performance related to PAP [180].

Previous research has extensively explored the potential of using a CA to enhance various athletically-related activities, such as swimming [137], sprinting [181], and strength and conditioning exercises like squats [182] and bench presses [20]. It is generally established that engaging in maximal or sub-maximal intensity contractions through different types of CAs can lead to improvements in PAPE [18, 180]. While numerous studies have focused on the benefits of CAs for increasing force output [15, 181, 183], there has been limited investigation [19, 20] into whether CAs can also positively impact the volume of subsequent activities. Notably, it has been demonstrated that engaging in heavy-load (>85% 1RM) resistance training can enhance the overall volume of subsequent activities, including squats [182] and bench presses [19].

Although any contraction type utilized in a CA can induce PAPE, the degree of potentiation may be influenced by the specific type of contraction employed [108]. Consequently, one can expect varying outcomes when applying CAs with different contraction types. Specifically, it is hypothesized that distinct neuromuscular fatigue resulting from various contraction types may activate different mechanisms, leading to a variety of results [108]. Dynamic CAs are more likely to induce peripheral fatigue but primarily rely on central mechanisms for PAPE [108]. Conversely, isometric CAs may generate greater central fatigue but are more likely to depend on peripheral mechanisms for PAPE [108]. Despite the use of various contraction types in numerous studies [19, 20, 182], there is limited research comparing CAs using different contraction types in the context of PAPE. For instance, a study by Rixon and colleagues (2007) found that isometric conditions led to more significant PAPE compared to dynamic conditions during jump squats [21]. However, there is currently no study that investigates whether contraction types can affect the volume of subsequent activities.

Since it has been reported that a CA can lead to improved performance during a resistance training session [19, 20], enhancing our knowledge regarding PAPE can lead to optimizing resistance training programs. To our knowledge, there is no study to demonstrate whether the contraction types of CAs can affect the volume of subsequent resistance exercise; hence, the aim of the current study is to compare the PAPE influence of various types of CAs (concentric-only, isometric, eccentric-only, and eccentric-concentric) on the volume of bench press exercise. It was hypothesized that the volume of bench press exercises would be impacted differently by various types of CAs.

4.2 Methods

4.2.1 Subjects

We performed a sample size estimation using G*Power (version 3.1.9.4) software. The analysis type chosen was repeated-measures analysis of variance (ANOVA), with the following parameters defined: a target power level of 0.80, a significance level (alpha) of 0.05, a correlation of r = 0.5 between repeated measures, and an effect size (ES) of 0.4. The ES value was derived from a meta-analysis conducted by Wilson and colleagues [184], investigating the impact of conditioning exercises on muscle performance. Based on the power analysis results, a minimum of nine subjects is necessary to detect statistically significant effects.

Ten male collegiate athletes (age = 26.5 ± 1.27 years; body mass = 76.8 ± 4.96 kg; body height = 177.7 ± 2.26 cm; 1RM = 92 ± 14.1 kg) with 3 to 6 years of weight training experience who had experience in resistance training for at least three years, on average three times a week, and at least 1.5 hours in each session, participated in the present study. Subjects were free from any musculoskeletal injuries that could impact the findings of the study and were informed regarding the type of test and how to perform various conditioning activities; nevertheless, they were not informed concerning the outcomes of their assessments. All athletes signed the consent forms prior to conducting the study, and the present study was approved by the Institutional Review Board at the University of X.

4.2.2 Procedures

Subjects attended the strength and conditioning lab at the University of Palermo for six separate days to complete the measurements. In particular, on the first session, height, weight, and 1RM were evaluated such that participants were asked to perform the bench press to reach 1RM after a 10-minute standardized warm-up procedure that consisted of jogging on a treadmill, the mobilization and flexibility of the upper body, and one set of five repetitions of the bench press with a load of 8 kg (the weight of the Smith machine barbell). To execute the 1RM test, the initial load was set at 8 kg, and the weight was gradually increased by 10 kg until the attained mean propulsive velocity (MPV) was below 0.5 m/s. After that, the external loads were added by 5–1 kg to the point when participants could completely extend their elbows, with the heaviest load considered 1RM. Bench press was repeated one, two, and three times for heavy (MPV < 0.65 m.s^{-1}), medium (0.65 m.s^{-1} ≤ MPV ≤ 1 m.s^{-1}), and light (MPV > 1 m.s^{-1}) loads, respectively. The rest time for light, medium, and heavy loads was 3 min, 4 min, and 5 min, respectively. The rest time between repetitions was also 10 seconds [10].

On the other days, following a standardized warm-up, participants completed three sets of bench press exercises using 75% of their 1RM, continuing until reaching concentric failure [19]. This was done either after one of the four types of contraction activations or without any CA (CONT), with the order being counterbalanced and randomized across different days (i.e., all subjects attended the lab at 48-hour intervals and approximately at the same time of day). The four types of contraction activations included isometric (ISO), concentric-only (CON-only), eccentric-concentric (ECC-CON), and eccentric-only (ECC-only) contractions. More specifically, the CAs were a 7-second isometric contraction with the elbow joint angle at 110 degrees, one set of three repetitions of concentric-only contraction with 90% 1RM, one set of three repetitions of eccentric-concentric contraction with 90% 1RM, and one set of three repetitions of eccentric-only contraction with 120% 1RM [15]. The rest period between the CA and the test was 10 minutes, and there was a 4-minute break between each set. The test procedure and all CAs were performed on a Smith machine (JK Fitness Equipment), and two spotters attended to ensure safety for participants, along with lifting or lowering the bar for concentric-only and eccentric-only contractions, allowing athletes to execute only concentric and eccentric contractions.

The performance was measured through time under tension (TUT), the number of repetitions, and total work (i.e., the number of repetitions completed was multiplied by the workload in kilograms), which represent training volume variables. The T-Force system (T-Force System, Ergotech, Murcia, Spain), with its cable attached to the bar, was used to measure TUT.

4.2.3 Statistical Analysis

Data were presented as the mean ± SD, and all variables exhibited a normal distribution as determined by the Shapiro-Wilk test. A two-way analysis of variance (ANOVA) with repeated measures, employing a 5×3 design (condition × set), was applied, with a mean confidence interval of 95% (IC), to compare differences in the number of repetitions, time under tension, and total work among various conditions. In cases where it was required, we conducted post hoc testing through multiple comparisons, applying Bonferroni's correction. The determination of effect sizes (ESs) for main effects and interactions was based on the values of partial eta-squared (η^2). These values were categorized into three levels: small (0.01–0.059), moderate (0.06–0.137), and large (> 0.137). The ES for pairwise comparisons was measured using Hedges' g, where it was categorized as small (<0.3), medium (0.3–0.8), and large (>0.8). The analyses were carried out utilizing SPSS software version 26, and the level of significance was set at $P < .05$.

4.3 Results

The two-way repeated measures ANOVA did not reveal a significant main interaction effect (conditions × set) for the number of repetitions ($F = 0.85$, $P > 0.05$, $\eta^2 = 0.08$), TUT ($F = 0.97$, $P > 0.05$, $\eta^2 = 0.07$), or total work ($F = 0.79$, $P > 0.05$, $\eta^2 = 0.08$). Nevertheless, a significant difference was observed regarding the impact of different conditions on the number of repetitions ($F = 10.38$, $P < 0.001$, $\eta^2 = 0.53$). The mean and standard deviations for the number of repetitions, TUT, and total work are presented in Table 1.

Post-hoc analysis indicated that the total number of repetitions was notably higher in the CON-only condition compared to the control condition ($P = 0.037$, Hedges' $g = 0.80$), and it was also significantly greater in the CON-only condition compared to the ECC-CON condition ($P = 0.013$, Hedges' $g = 0.99$).

Moreover, TUT was significantly increased in the CON-only condition in comparison to the control condition (P = 0.47, Hedges' g = 0.72), and it was notably higher in the CON-only condition compared to the ISO condition (P = 0.43, Hedges' g = 0.46). Lastly, the total work across three sets was significantly greater in the CON-only condition in comparison to the ECC-CON condition (P = 0.23, Hedges' g = 0.40). Furthermore, the number of repetitions did not exhibit significant differences among the following conditions: control and ECC-CON (P = 1), control and ISO (P = 1), control and ECC (P = 0.52), ECC-CON and ISO (P = 1), ECC-CON and ECC (P = 0.18), CON-only and ISO (P = 0.06), CON-only and ECC (P = 0.22), and ISO and ECC (P = 0.24). There were also no significant differences in TUT between the following conditions: control and ECC-CON (P = 1), control and ISO (P = 0.57), control and ECC (P = 0.19), ECC-CON and CON-only (P = 0.11), ECC-CON and ISO (P = 0.61), ECC-CON and ECC (P = 0.41), CON-only and ECC (P = 0.30), and ISO and ECC (P = 0.58). Total work exhibited no significant differences among the following conditions: control and ECC-CON (P = 1), control and CON-only (P = 0.052), control and ISO (P = 0.36), ECC-CON and ISO (P = 1), ECC-CON and ECC (P = 0.19), CON-only and ISO (P = 0.057), CON-only and ECC (P = 0.35), and ISO and ECC (P = 0.17). No significant differences were observed in the number of repetitions between set 1 and set 2 (P = 0.28), set 1 and set 3 (P = 1), and set 2 and set 3 (P = 0.18). Similarly, TUT did not show significant variations between set 1 and set 2 (P = 0.52), set 1 and set 3 (P = 0.57), and set 2 and set 3 (P = 1). Additionally, there were no significant differences in total work between set 1 and set 2 (P = 0.3), set 1 and set 3 (1), and set 2 and set 3 (P = 0.19).

Table 1. Performance variables for four different types of contractions in the bench press exercise for each set (mean ± SD)

Conditions	**CON**			**ECC-CON**			**CON-ONLY**			**ISO**			**ECC**		
Variables	Set1	Set 2	Set 3	Set 1	Set2	Set3	Set1	Set2	Set3	Set1	Set2	Set3	Set1	Set2	Set3
REP (n)	12.40 ± 0.96	12.90 ± 0.87	12.10 ±1.19	12 ± 0.94	12.60 ± 0.96	12.40 ±0.84	13.30 ± 0.82	13.40 ±0.96	13.10 ± 1.10	12 ± 1.05	12.80 ±0.91	12 ± 1.49	12.50 ± 0.84	12.70 ± 0.82	12.70 ±1.15
TUT (s)	9.79 ±1.43	10.31 ± 2.05	9.71 ±1.81	9.40 ± 1.68	9.27 ± 3.36	10.14 ± 1.79	10.81 ±1.13	11.57 ± 1.65	11.01 ± 1.86	10.07 ± 1.17	10.70 ± 1.91	10.4 ± 1.68	10.39 ± 1.59	10.78 ± 2.13	10.83 ±1.79
TW (kg)	**863.70 ± 170.27**	**899 ± 179.40**	**841.40 ± 159.15**	**836 ± 163.62**	**879.10 ± 182.10**	**859.80 ± 138.47**	**923.10 ± 149.81**	**933.90 ± 178.99**	**907.40 ± 145.13**	**834.60 ± 155.59**	**887.50 ± 143.53**	**839.50 ± 198.65**	**871.20 ± 169.99**	**885.70 ± 177.06**	**886 ± 181.37**

REP: the number of performed repetitions, TUT: time under tension, TW: total work, CON: control condition, ECC-CON: eccentric-concentric contraction, CON-only: concentric-only contraction, ISO: isometric contraction, ECC: eccentric contraction

4.4 Discussion

The objective of the present study was to assess the PAPE effects resulting from various muscle contraction types, including eccentric-concentric (ECC-CON), concentric-only (CON-only), isometric (ISO), and eccentric-only (ECC-only), on the subsequent volume of bench press exercise. Our findings indicate that con-only contraction significantly enhances both the number of repetitions and the TUT during bench press performance compared to the control condition. Furthermore, it was observed that the number of repetitions and total work are greater in the CON-only contraction than in the ECC-CON contraction. Additionally, time under tension is also higher in the CON-only contraction compared to the ISO contraction.

To the best of our knowledge, this is the first study to compare PAPE effects stemming from various muscle contractions on the subsequent bench press exercise volume. Previous studies [88, 185] indicated that dynamic contractions, both CON and ECC, may lead to more significant potentiation than ISO contractions. Specifically, ECC contractions could result in even more potentiation than the other types, given that the torque produced during an ECC contraction typically exceeds that of CON and ISO contractions [185]. This is significant since the degree of PAP is believed to be linked to the force level achieved during the conditioning voluntary contraction [185]. However, our findings demonstrated that CON-only contractions significantly enhanced the number of repetitions performed when compared to the control condition. While no notable differences were found when comparing the PAPE effects of the other types of muscle contractions to the control condition, CON-only contractions also significantly increased the number of repetitions performed in bench press exercise compared to ECC-CON conditioning activity. These observations are consistent with the research conducted by Alves et al. (2020), which showed an increase in the number of repetitions performed in bench press exercises as a result of the PAPE effect. However, it is important to note that their protocol employed ECC-CON muscle contractions. Contrary to our findings, Krzysztofik et al. (2020) did not observe an increase in the number of repetitions performed during bench press exercises when applying ECC-CON contractions. The results of the present study are inconsistent with the previous investigations [15, 21, 183] comparing the PAPE effects of various muscle contraction types on the counter movement jump and power out performances, which observed that ISO muscle contractions induce effective PAPE compared to dynamic muscle contractions (ECC and CON). The contradictory results may stem from a complex interplay of factors, including the intensity and type of conditioning activity, the duration of recovery periods, individual differences, training background, the order of exercises, and warm-up procedures [18]. Furthermore, the perfect combination of these elements may vary based on personal characteristics and the specific requirements of the given performance tasks [18].

TUT is another critical variable used to evaluate training volume. Burd and colleagues (2012) revealed that prolonged time under tension during muscle contraction results in an elevated synthesis rate of myofibrillar proteins following a recovery period of 24–30 hours [186]. Additionally, this increase is linked to heightened phosphorylation levels of proteins that signal anabolic activity. Hence, extended periods of muscle tension may increase muscle protein synthesis post-resistance training [186]. Our observations indicate that TUT significantly increases during CON-only conditioning contractions compared to the control condition. Furthermore, TUT shows a significantly greater increase during CON-only conditioning activities compared to ISO conditioning contractions. The findings of the current study align with those from the investigation by Krzysztofik et al. (2020), which indicated a significant increase in TUT in response to PAPE effects during bench press exercises carried out until volitional failure. However, while they employed ECC-CON conditioning contractions to induce PAPE, our study did not observe a significant increase in TUT following ECC-CON conditioning contractions.

The conclusions of the current study should be considered within the context of its specific limitations. During data collection, the athletes were not participating in supervised resistance training. Also, the results should be approached with caution due to the typical restrictions of cross-order research, and further studies are required for validation. Our evaluation was limited to male athletes with experience in resistance training; therefore, the results of this study cannot be generalized to female athletes or other demographic groups. The present study did not include an examination of physiological changes or electromyography recordings, which could have provided an explanation for the results observed. Due to the lack of data on the causes behind the increase in TUT and the number of repetitions in the CON-only activity condition, there is a clear need for further research to investigate the underlying physiological and mechanical variables.

4.5 Conclusion

Our research revealed that, in comparison to a control condition, concentric-only conditioning contractions in bench press exercises performed to volitional failure result in a significant increase in the number of repetitions and time under tension. Other muscle contraction types did not trigger a PAPE effect. Furthermore, concentric-only conditioning activities notably increased the number of repetitions and total work when compared to eccentric-concentric conditioning contractions. Additionally, time under tension was also greater in concentric-only contractions than in isometric conditioning contractions.

Chapter 5: Bench press throw performance with different loads in response to the execution of a conditioning activity

5.1 Introduction

Post-activation performance enhancement (PAPE) has been defined as an acute improvement in muscle performance following a conditioning activity (CA), the exercise of maximal, or sub-maximal, muscle contraction [108]. This phenomenon, characterized by the phosphorylation of myosin regulatory light chains and increased recruitment of higher-order motor units, was previously described by Tillin and Bishop (2009). In this context, contradictory findings have been reported regarding the influence of a CA on the acute performance of the subsequent activity. The inconsistent results can stem from various contributory factors, including the type of explosive activity, recovery time, and subject characteristics [18]. For instance, it was demonstrated that the execution of an isometric MVC compared to a maximal dynamic contraction can result in a better improvement in the squat jump performance [21].

High resistance exercise, typically around 85% of one repetition maximum (1RM), is often used to induce PAPE [143]. However, the practicality of applying heavy loads before a performance is challenging. This is because heavy loads require specific equipment and space, which may not be available to athletes before competitions, rendering it impractical to use heavy loads as a CA to enhance performance [143]. While previous studies [21, 102, 187] have applied different types of contractions as a CA to increase power outputs, there has been less focus on the use of ballistic activities for potentiating performance, particularly for the upper body. Ballistic movements have a lower motor unit recruitment threshold compared to slower contractions, suggesting that they could induce potentiation with lower loads, thereby minimizing fatigue potentially caused by CA [143, 150]. This makes ballistic exercises a feasible option for athletes to perform prior to competitions. In this vein, it was demonstrated that performing a bout of ballistic exercise can improve the following explosive activity, including bench press throw [188].

While mechanical variables can be affected by a CA during ballistic exercises, it remains unclear whether applying a CA can potentiate the subsequent ballistic movement with various loads due to the influence of the training load on the mechanistic characteristics of ballistic movements. From a mechanical perspective, the necessity of projecting the barbell into the air during ballistic movements compels the application of a net positive force throughout the acceleration phase, consequently increasing the vertical force required. However, this increase in force diminishes when heavier loads are used [178]. Markovic et al. (2008) investigated to understand the load-specific acute effects of a CA using high-resistance exercises on the throwing speed of medicine balls. Although it was shown that maximum speed could be specific to the load in response to the acute effects of high-resistance exercise, they utilized two medicine balls weighing 0.55 kg and 4 kg, which are relatively light [189]. The question remains as to whether ballistic exercises can produce an acute effect on subsequent bench press throws with various loads. Therefore, it is crucial to determine whether bench press throw performance with different loads can be modified in response to a CA using ballistic exercises, which could optimize exercise prescription. The purpose of the current study was to evaluate the effect of a CA using ballistic bench press exercises on subsequent bench press throw performance with different loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM). It was hypothesized that bench press throw performance under heavier loads would not be affected by the CA, as opposed to performance under lighter loads

5.2 Methods

5.2.1 Subjects

The power analysis demonstrated that a minimum sample size of 10 subjects is required. This value was calculated through G*Power (version 3.1.9.4) software. Consequently, 10 male collegiate athletes (height = 177.7 ± 2.26 cm; age = 26.5 ± 1.27 years; body mass = 76.8 ± 4.96 kg; 1RM = 92 ± 14.1 kg) volunteered to participate in the present study. None of the participants had a history of musculoskeletal injury and physical limitation, which could affect the result of the study, in the past six months. These participants had 3 to 6 years of experience in resistance training, practicing at least twice a week. Athletes were informed about the test procedure and how to perform a conditioning activity; nevertheless, they were not informed about the outcome of the test. All subjects signed the consent forms before the initiation of the evaluations. The study was also approved by the Institutional Review Board at the University of Palermo.

5.2.2 Procedures

Participants attended our laboratory in five separate days to accomplish the assessments. Height, weight, and 1RM were evaluated on the first session; in particular, subjects executed 1RM test after a standardized warm-up protocol, consisting of jogging on a treadmill, the flexibility of the upper body, and one set of four repetitions of bench press with the barbell (the weight of barbell was 8 kg). To conduct the 1RM test, the starting weight was set at 8 kg and progressively increased by 10 kg until the mean propulsive velocity (MPV) dropped below 0.5 $m.s^{-1}$. Subsequently, additional weights in increments of 5 to 1 kg were applied until the participants were able to fully straighten their elbows, identifying the heaviest weight as the 1RM. Depending on the load's intensity, the bench press was performed once for heavy loads (MPV < 0.65 $m.s^{-}$

^{1}), twice for medium loads (0.65 $m.s^{-1} \leq MPV \leq 1$ $m.s^{-1}$), and three times for light loads ($MPV > 1$ $m.s^{-1}$), with corresponding rest periods of 5 minutes for heavy, and 3 minutes for both medium and light loads. Moreover, a 10-second rest interval was maintained between each repetition [10].

To measure the effect of CAs on bench press throw performance, athletes performed bench press with one of the loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM), as a baseline, after conducting the standardized warm-up. Following 5 min rest, participants executed a CA consisted of bench press with 60% 1RM with maximum velocity until mean velocity dropped by 30% (i.e., to the 70% of the highest achieved mean velocity). After 5 min rest, subjects executed the same test that was done as a baseline. Each participant performed bench press throw with all four loads but at different days in a randomize and counterbalanced order. All tests were performed on Smith machine (JK Fitness Equipment) and two spotters were present to make safety for athletes during the test.

Mean velocity (MV), peak velocity (PV), mean power (MP), and peak power (PP) were measured by a linear velocity transducer at a sampling rate of 1000 Hz (T-Force System, Ergotech, Murcia, Spain). Previous studies indicated that the T-Force system is highly reliable and valid for assessing movement velocity and calculating power in strength and conditioning exercises [10, 176].

5.2.3 Statistical analysis

Normality of data and homogeneity of variance were assessed through the Shapiro-Wilk test and Levene's test, respectively. Repeated measures univariate analysis of variance (ANOVA) were used to compare differences in mean velocity, peak velocity, mean power, and peak power with respect to various loads (2×4 ANOVA; time × loads). To further understand the differences in variables in cases where significant main effects or interactions were found, Bonferroni post hoc tests were performed. The values of partial eta-squared (η^2) were used to describe effect sizes (ESs) for main effects and interactions, classifying them as small (0.01–0.059), moderate (0.06–0.137), and large (> 0.137). Hedges' g was also applied to quantify the ES for pairwise comparisons, categorized as small (<0.3), medium (0.3–0.8), and large (>0.8). All statistical analyses were performed using SPSS software version 26, and the level of significance was accepted at $P < .05$.

5.3 Results

The results of repeated measures ANOVA indicated that there were no significant main interaction effects (time × load) for MV ($F = 1.09$, $P = 0.36$, $\eta^2 = 0.08$), PV ($F = 0.69$, $P = 0.56$, $\eta^2 = 0.05$), MP ($F = 1.86$, $P = 0.15$, $\eta^2 = 0.13$), and PP ($F = 2.12$, $P = 0.11$, $\eta^2 = 0.15$). However, MV ($F = 77$, $P < 0.001$, $\eta^2 = 0.68$), PV ($F = 27.80$, $P < 0.001$, $\eta^2 = 0.43$), and PP ($F = 18.83$, $P = 0.001$, $\eta^2 = 0.34$) were significantly different with respects to time (pre-test and post-test). The means and standard deviations for MV, PV, MP, and PP for each load in regard to time condition are represented in Table 1.

Post hoc analysis demonstrated that MV was significantly different for 30% 1RM ($P = 0.001$, Hedges' $g = 0.68$), 50% 1RM ($P = 0.045$, Hedges' $g = 0.69$), 70% 1RM ($P < 0.001$, Hedges' $g = 0.79$), and 90% 1RM ($P < 0.001$, Hedges' $g = 0.66$) between pre-test and post-test. PV was also significantly different for 70% 1RM ($P = 0.001$, Hedges' $g = 0.71$) and 90% 1RM ($P < 0.001$, Hedges' $g = 0.68$), whereas there were not significant differences for 30% 1RM ($P = 0.12$) and 50% 1RM ($P = 0.13$) between pre-test and post-test. Similarly, PP exhibited significant differences for 70% 1RM ($P < 0.001$, Hedges' $g = 0.45$), 90% 1RM ($P < 0.001$, Hedges' $g = 0.52$), while there were no significant differences for 30% 1RM ($P = 0.95$) and 50% 1RM ($P = 0.11$) between pre-test and post-test.

Table 1. Performance variables for four different loads in the bench press exercise (mean ± SD)

Conditions	**30% 1RM**		**50% 1RM**		**70% 1RM**		**90% 1RM**	
Variables	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
MV ($m.s^{-1}$)	1.11 ± 0.11	1.20 ± 0.15	0.88 ± 0.07	0.93 ± 0.07	0.64 ± 0.11	0.72 ±0.10	0.39 ±0.12	0.46 ±0.11
PV ($m.s^{-1}$)	1.83±0.19	1.94 ± 0.33	1.43 ± 0.16	1.49 ± 0.20	0.99 ±0.18	1.13 ± 0.21	0.63 ± 0.15	0.73 ± 0.17
MP (w)	293.86 ± 122.10	277.23 ± 118.55	386.63 ± 101.75	396.83 ± 99.02	426.40 ± 66	443.83 ± 66.33	324.50 ± 95.72	354.17 ± 93.37
PP (w)	717.63 ± 283.24	719.43 ± 251.90	773.31 ± 211.20	827.66 ± 205.71	733.23 ± 141.91	797.41 ± 144	536.20 ±144.03	614.05 ± 151.27

MV: mean velocity, PV: peak velocity, MP: mean power, PP: peak power

5.4 Discussion

The aim of the present study was to assess the effect of a CA using ballistic bench press on the following bench press throw performance at various loads. Our results demonstrated that the CA enhanced MV for all the loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM). Additionally, PV and PP showed increases with the CA at the higher loads (70% and 90% of 1RM).

Velocity-based exercises have been extensively applied to monitor and quantify training volume, allowing for the control of fatigue, which in turn leads to optimized performance [12]. Previous studies [10, 190] indicated that recording the velocity drop from the first to the last repetitions can be considered an indicator of neuromuscular fatigue. We utilized a CA protocol consisting of bench presses at 60% of 1RM with maximum velocity until the mean velocity dropped by 30% to induce PAPE. Our results revealed a positive acute effect of the protocol on the mechanical variables, including MV, PV, and PP, of the bench press throw with different loads. These results are consistent with similar protocols that used velocity-based training with low (40% 1RM), moderate (60% of 1RM), and heavy (80% of 1RM) loads [12, 191]. While other studies [12, 191] have applied bench press throws with 30% of 1RM as a baseline, we considered 30%, 50%, 70%, and 90% of 1RM. Specifically, we observed the protocol increased MV at all tested loads, while PV only increased at loads of 70% and 90% of 1RM in response to the CA. Although prior research [192, 193] suggests mean values are more reliable than peak values, the application of peak values has been recommended due to their stronger correlation with jump performance [193]. In our study, PP values were significantly different at loads of 70% and 90% of 1RM, yet no significant differences were detected for MP values following the protocol. García-Ramos et al. (2016) also noted that measuring mean values poses more challenges due to the arbitrary decisions involved in determining the start and end points of the concentric phase [74].

Markovic et al. (2008) reported that the acute effect of a CA on subsequent ballistic throws is load-specific. However, we observed an increase in MV at all loads in response to the CA, while PV and PP were only significantly higher at 70% and 90% of 1RM compared to their baselines. Their protocol and the test were completely different from the method of our study. Specifically, high-resistance exercise was applied to induce the PAPE effect prior to throwing medicine balls with two different loads (0.55 kg and 4 kg). Although previous studies [194, 195] have indicated that high-resistance exercises can lead to greater potentiation through the activation of motor units comprising type II muscle fibers, heavy loads may also cause fatigue concurrent with neuromuscular activation [143]. If the fatigue outweighs the potentiation, performance will decrease. In our study, a linear velocity transducer was used to monitor the drop in velocity from the first to the last repetitions, considered an indicator of fatigue [52, 190]. This allowed for a reduction in fatigue while still potentiating the muscles. Moreover, the loads used in the study by Markovic and colleagues (2008) were relatively low, which makes it difficult to conclude that the PAPE effect is load-specific. However, we applied four different loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM) to determine whether the CA could potentiate across a spectrum of loads. Chiu et al. (2003) also demonstrated that a protocol of high-resistance exercise could significantly influence jump squat performance at three different loads (30% 1RM, 50% 1RM, and 70% 1RM) among athletes. However, they only observed a significant negative response to their protocol at 30% 1RM when both athletes and recreationally trained subjects were analyzed together. Seitz and Haff (2015) reported in a meta-analysis that stronger individuals could further improve their performance in response to a CA compared to their weaker counterparts. This may be due to a higher percentage of type II muscle fibers and increased phosphorylation of the myosin light chain, resulting in a higher level of PAP [18]. It is also reported that stronger individuals develop greater fatigue resistance to heavier loads than their weaker counterparts, which in turn leads to improved performance [18]. In this context, resistance-trained individuals who participated in our study were consistent with the subjects from the study by Chiu et al. (2003). The discrepancies between the findings of Markovic et al. (2008), Chiu et al. (2003), and our study may be due to the varying levels of resistance training experience among the subjects. However, as previously stated, the protocols and load weights from their study are not directly comparable to ours.

The results of the current study should be considered with the following limitations: It is important to interpret the findings cautiously due to the inherent limitations of cross-sectional research, and further research is necessary for validation. This study exclusively focused on male athletes experienced in resistance training; thus, its findings might not be applicable to female athletes or other demographic groups. We applied a CA protocol consisting of a ballistic bench press with maximum velocity until the mean velocity dropped by 30% to induce PAPE. Further research is required to demonstrate whether velocity-based training protocols can lead to non-load-specific results when using ballistic bench press exercises until mean velocity drops by 10%. This is because it is expected that individuals experience less fatigue when they reach 90 percent of their highest velocity, compared to our protocol.

5.5 Conclusion

Our results reveal that a conditioning activity protocol using ballistic exercise can lead to a PAPE effect and improve bench press throw performance with different loads. Specifically, the CA protocol enhanced mean velocity for all the loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM). Additionally, peak velocity and peak power showed increases with the CA at the higher loads (70% and 90% of 1RM).

Postural Control Evaluation and Postural Malalignment

Chapter6: The effect of time-of-day and sleep deprivation on postural control

6.1 Introduction

Postural control (PC) measurement is used among various researchers and clinicians as a way to detect deficits in the neuromuscular system that impair balance. PC data help to qualify factors related to decreasing postural stability and those who are susceptible to injury (e.g., identify those at risk of falls) [196]. Importantly, neurophysiological performance can fluctuate based on circadian rhythm [197, 198]. That is, cognitive performance and metabolic function, which can influence mental and physical performance, including strength and flexibility [199], fluctuate during a 24-hour period, whereby several human functions can be expected to act optimally when the aforementioned variables are at a high value [197, 200]. In this context, it has been suggested that PC can be varied at different times of the day [201, 202]. However, several studies have not demonstrated any significant differences between PC and time of day [203-205].

Another factor that can influence PC by alterations in cognitive performance is sleep deprivation (SD) [198, 206, 207]. In other words, changes in a normal sleep and wake cycle may impair visual, vestibular, and somatosensory integration resulting in poor muscle function and postural orientation [208-210]. Despite a growing body of literature demonstrating that SD leads to postural imbalance and subsequent injuries [208, 209, 211, 212], the underlying mechanism is poorly understood. One such explanation, however, may be that sleepiness results in mental fatigue and reduced vigilance, which may alter postural sway [213, 214]. As such, several researchers [213, 214] have suggested that objective PC evaluation can assist in detecting those who experience SD, whereby it can result in preventing occupational and traffic accidents that can arise from sleepiness. This is because a reduction in vigilance level that may be the result of mental fatigue, which can be stem from sleepiness, may lead to postural sway alterations [215].

Since both sleep homeostatic (i.e., tendency to sleep that is affected by time of wakefulness) and circadian rhythm processes that may result in deficiency in performance are closely linked [5], it has been suggested that both factors can concurrently lead to deteriorating PC [212, 216]. Notably, several investigators [212, 216, 217] have evaluated PC during different times of day after disrupted sleep. The results of such studies have demonstrated the significant, negative effect of SD on PC [207, 208]. There have also been reported differences in center of pressure (COP) sway with respect to diurnal variations. This means some research indicated an increase in COP sway after SD [206, 218, 219], while several studies reported reduced COP sway in regard to various times of the day [207, 208].

While a growing number of studies have focused on the combined effect of SD and time of day on PC, there has been no study to critically review the literature to provide a better understanding of such impact. Since a large number of people experience disrupted sleep, it is necessary to understand the influence of disrupted sleep on PC. This knowledge will help develop better prevention strategies for the musculoskeletal injuries or falls that may result from sleep disruption-induced postural impairments. Hence, the aim of the current study was to systematically review the research that examined the effect of time-of-day and SD on PC variables among healthy individuals.

6.2 Methods

This study was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [220].

6.2.1 Search strategy

Four electronic databases (Embase, PubMed, Scopus, and Web of Science) were used to identify relevant studies for this systematic review. Combinations of the following keywords were searched until March 2021 and detailed search strategies are provided in Supplementary material: “postural control”, “postural balance”, “postur*”, “postural stability”, “dynamic balance”, “balance control”, “center of pressure”, “postural sway”, “postural steadiness”, “posturogra*”, “time-of-day”, “circadian rhythm*”, “diurnal variation*”, “circadian variation*”, “daily fluctuation”, “diurnal fluctuations”, “daily variation”, “clock gene”, “circadian clock”, “biological rhythm”, “sleep depriv*”, “sleep loss”, “sleep restriction”, “sleep curtailment”, “sleep”. References of the included studies were also hand-searched to ascertain the identification of related research.

6.2.2 Eligibility criteria

All studies which met the following criteria were included in the current systematic review: (1) original research that was published through the peer review process in any language without publication date limitations; (2) research was done to understand the effect of sleep deprivation (SD) and/or time of day (TOD) on postural control (PC); (3) participants were healthy humans; (4) SD was described as any type of sleep insufficiency (i.e. complete SD (total lack of sleep) or sleep restriction (decrease in the normal amount of sleep)), other than chronic SD and sleepiness that may arise from sleep apnea and other sleep disorders; and (5) authors reported at least one quantitative variable of PC or postural orientation or the results of objective evaluation of PC (e.g. star excursion balance test). All study designs with the exception of any kind of reviews, letter to editors, and meta-analysis were included. Finally, investigations that were designed to understand the effect of sleep quality using subjective assessment (e.g., Pittsburgh Sleep Quality Index), on PC, were excluded.

6.2.3 Study selection

After removing duplicates, titles and abstracts were independently screened by two reviewers. Next, retrieved studies were separately evaluated by the reviewers in accordance with the inclusion and exclusion criteria. Any disparities between the authors were discussed with a third reviewer until consensus was reached.

6.2.4 Quality Assessment

The modified version of the Downs and Black index [221, 222], which was scored out of 17, was applied to evaluate the risk of bias of the included studies. This modified checklist includes the following sub-scales: reporting (items 1, 2, 3, 5, 6, 7, and10), external validity (items 11and 12) , internal validity-bias (items15, 16, 18, and 20) , internal validity-confounding(items 21and 25), and power (item 27). The score of item 27 was changed from 0-5 to 1 or 0 such that a study received 1 if the study had appropriate power; otherwise, it was scored 0. The quality assessment of the included studies was individually assessed by two reviewers and they resolved any disagreements about each item through deliberation. Kappa correlation coefficient was determined in order to identify inter-rater reliability for each checklist item between the two reviewers. Studies with scores of 11 or higher (65%) were deemed to be at a low risk of bias, and studies with scores below 11 were deemed to be at a high risk of bias [222].

6.2.5 Data extraction and synthesis

One of the authors extracted the following data from the included studies and the second author verified the information to decrease the risk of bias: author's names, the year of publication, study design, sample size, age, sex of participants, type of sleep manipulation, time of day that PC was measured, testing procedure, outcome measures, and main results. Since there was a methodological heterogeneity among the included studies, it was not advisable to do a meta-analysis. Hence, a qualitative synthesis was deemed appropriate for the present systematic review such that the collected data were classified into time of day, sleep loss (sleep loss * time of day), and forced desynchrony.

6.3 Results

6.3.1 Study identification

A total of 9507 studies were achieved through electronic databases. After removing 2958 duplicates, the titles and abstracts of the remaining 6549 studies were screened for qualification. The full text of 88 studies were evaluated in accordance with the inclusion and exclusion criteria wherein 46 articles [201-219, 223-248] were eligible for this systematic review. Finally, 3 studies [249-251] were added via hand-searching of the included studies' references for a total of 49 studies. (Figure 1)

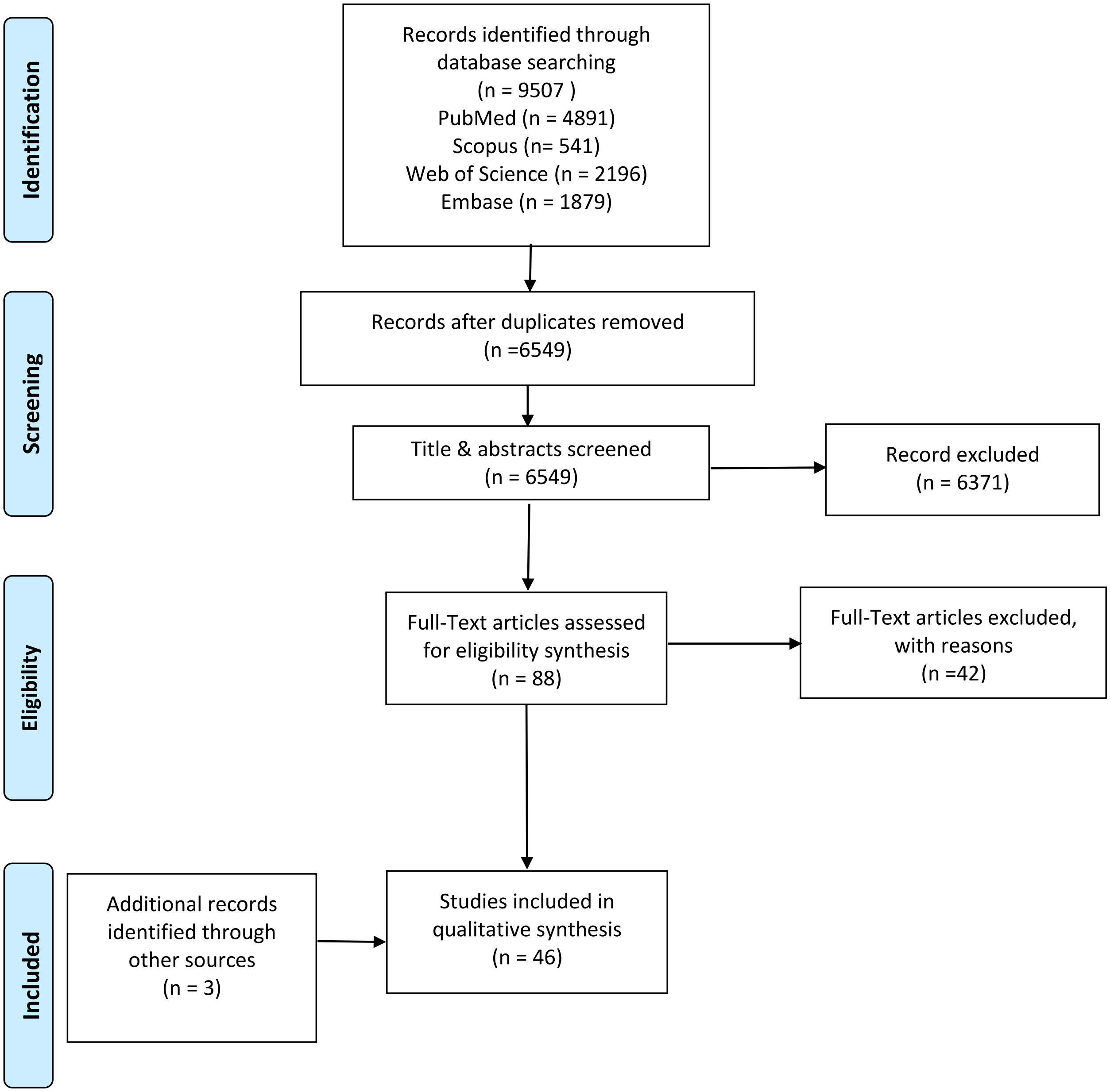

Figure 1. Flowchart of study selection process

6.3.2 Study characteristics

Detailed information regarding each study is provided in Table 1. A total of 1296 healthy subjects participated in all studies in which their age range was between 5.6 and 85.2 years. In twenty-five studies [201, 202, 205, 206, 211-214, 218, 219, 224, 225, 228, 234, 237-239, 242-247, 250, 251], both males and females were included, while 7 studies did not report the sex of subjects [208, 209, 229-231, 248, 249]. Sixteen studies [203, 204, 207, 210, 215, 217, 223, 226, 227, 232, 235, 236, 240, 241, 252] included only male participants and one study included only females [233].

Table 1. Study characteristics

Authors (yrs)	Study Design	Participants	Sleep Manipulation	Time of Day	Testing Procedure	Outcome Measures	Main Results
Aguiar et al (2014)	Cross-sectional	Healthy (N=60, sex=?) (SD: N=30, age: 24.93 ± 5.6 yrs) (NS: N=30, age: 27.16 ± 5.7 yrs)	One night without sleep (starting from 8 p.m.)	Between 8 - 11	60 s upright stance in a moving room, vision stimuli	Mean sway amplitude and velocity in AP direction during stable and a moving room; coherence, gain, phase, position, and velocity variability	Mean sway amplitude and velocity↑, coherence↓, gain and phase ↔, position and velocity variability ↑ in SD
Gribble et al (2007)	Cross-sectional	Healthy (N=30, f=17), age: 21.8 ± 3.74 yrs	No	Day 1 (10:00, 15:00, 20:00) Day 2 (10:00, 15:00, 20:00)	30 s SLS, EO and EC SEBT in the anterior direction	COPVX & COPVY Maximum reach distance in the anterior direction	COPVX↓, COPVY↓, and normalized reaching distance↑ at 10:00 than 15:00 and 20:00
Bougard et al (2011)	Cross-sectional	Healthy (N=20, m), age: 24.6 ± 4.6 yrs	One night without sleep from 10:30 p.m. until 5:00 a.m.	6:00 , 10:00 , 14:00 and 18:00	51.2 s DLS, EO and EC	COP surface area, LFS ratio, Romberg's index	6 a.m.↔; 10 a.m. and 2 p.m. (COP surface area↑); 6 p.m. (LFS ratio↑)

Kwon et al (2014)	Cross-sectional	Healthy (N=24, m= 10), age: 22.17 ± 1.61 yrs	No	9:00 , 13:00 , 17	30s static balance, EO move COP a long a track on a screen	COP (AP & ML), COP velocity; Performance time, total distance	COP (AP & ML)↓ at 9:00 a.m. than 1 p.m.; COP (ML)↓ at 1p.m. than 5 p.m.; total distance↑ at 1 p.m. than 9 a.m.
Baccouch et al (2015)	Cross-sectional	Healthy (N=12, m), age: 5.6 ± 0.4 yrs	No	7:00 , 10:00 , 14:00 , 18:00	25.6 s static balance, EO and EC	COP surface area, LFS ratio, Romberg's index, and mean COP velocity	PC↓ at 7 a.m. and 2 p.m. than 10 a.m. and 6 p.m.
Gribble et al (2004)	Cross-sectional	Healthy (N=24, f=11) (f, age: 20 ± 2.2 yrs) (m, age: 21 ± 1.9 yrs)	48 h SD from 19: 00 (Day 1) until 19: 00 (Day 3)	Day 2 (0:00, 6:00, 12:00, 18:00) Day 3 (0:00, 6:00, 12:00, 15:00)	15 s bipedal stance, EO	COP area, COP velocity	COP area ↔; COP velocity↑ from 0:00 to until the late afternoon sessions
Fabbri et al (2007)	Cross-sectional	Healthy (N=55, f=39) (f, age: 23.28 ± 3.59 yrs) (m, age: 23.87 ± 2.50 yrs)	12 h wakefulness from 21:00 to 9:00	22:00 and 8:00	60 s Romberg's test, EO and EC	MD-x, MD-y, SS, SL, LFS, and Romberg's index	SL↑; LFS↓; RI↓; PC↓ in EC than EO
Zouabi et al (2016)	Cross-sectional	Healthy (N=15, m), age: 22.43 ± 1.54 yrs	No	2 , 6 , 10 , 14, 18 , 22	51.2 s static condition and dynamic balance (standing on a dynamic balance plate), EO and EC	Total COP displacement, COP surface area, COP velocity, the average position of COP on the MD and AP	PC ↔; total COP displacement ↓ in EO than EC
Jorgensen et al (2012)	Cross-sectional	Healthy (N=34, f=24) (f, age: 73.4 ± 4.6 yrs) (m, age: 72.9 ± 5.4 yrs)	No	9 , 12:30, 16	30 s DLS, EO	Total sway length, velocity-moment, confidence ellipse area, and total sway area	PC↓ from 12:30 to 4 p.m.; sig differences in all parameters between 9 a.m. and 4 p.m.
Bougard et al (2014)	Cross-sectional	Healthy (N=19, m), age: 20.5 ± 1.3 yrs	No	6 , 18	51.2 s DLS, EO and EC	COP surface area, path length, PL (ML, AP), LFS, and Romberg's index	All parameters↑ in EC than EO; COP surface area↓ and LFS↑ at 6 p.m. than 6 a.m.

Liu et al (2001)	Cross-sectional	Healthy (N=7, m), age: 23.5 ± 0.8 yrs	awake from 22:00 to 4:00	22:00, 23:00, 00:00, 1:00, 2:00, 3:00, 4:00	30 s upright stance, EO and EC	Rectangle area, RMSL-x, RMSL-y, mean velocity (ML), mean velocity (AP), LF-x, LF-y, MF-x, MF-y, HF-x, and HF-y	RA↑, RMSL-y↑, MF-x↑, MF-y↑ from midnight and peak at 4 a.m.; RA↑ and MF-y↑ in EC than EO
Nakano et al (2001)	Cross-sectional	Healthy (N=10, m), age: 23.8 yrs	awake from 15:00 to 9:00	From 15:00 to 9:00, every hour	40 s upright stance, EO and EC	Postural sway in the AP and lateral direction	Postural sway↑ in the early morning in EC
Nèji et al (2019)	Cross-sectional	Healthy (N=105, m), age: 13.4 ± 1.3 yrs	No	Between 7-9 and between 17-19	Y balance test	Reach in AT, PM, and PL directions	PC↑ in the afternoon than the morning
Karagul et al (2017)	Cross-sectional	Healthy (N=42, sex=?) (trained group, age: 20.9 ± 2.4 yrs) (control group, age: 22.5 ± 1.46 yrs)	No	9:00, 13:00, and 17:00	SEBT test	Reaching distance of A, AM, M, PM, P, PL, L, and AL directions	PC sig different at TOD
Martin et al (2018)	Cross-sectional	Healthy (N=19, f=4), age: 21.9 ± 1.2 yrs	One night without sleep (starting from 22:00)	6:00, 10:00, 14:00, 18:00, and 22:00	30 s upright stance, EO and EC	COP surface, total displacement length of COP	PC↓ (COP surface↑, COP total length↑) in SD; no TOD effect
Aguiar et al (2015)	Cross-sectional	Healthy (N=30, sex=?) (SD: N=15, age: 23.60 ± 4.5 yrs) (NS: N=15, age: 27.35 ± 5.5 yrs)	One night without sleep (starting from 8 p.m.)	Between 8 - 11	60 s upright stance in a moving room, vision stimuli	Mean sway amplitude in AP direction, gain, phase, position, and velocity variability	Mean sway amplitude↑ after SD
Russo et al (2015)	Cross-sectional	Healthy (N=61, m), age: 22.3 ± 3.4 yrs	No	9 to 11 11 (10’) to 13 (10’) 15 to 17 17 (10’) to 19 (10’)	51.2 s upright stance, EO and EC	Length of COP sway path, Naiperian logarithm of the ellipse of confidence area, of the X mean, of the Y mean, and eccentricity of the ellipse area	No sig effect of TOD on PC
Smith et al (2012)	Cross-sectional	Healthy (N=9, f=6), age: 21.56 ± 2.51 yrs	awake from 5:30 a.m. to 7 a.m. (next day)	From 18 to 7 (next day), every hour	upright stance, EO and EC	ML sway, AP sway, trace length, C90 area, and velocity	AP sway↑ after 15 h; (ML sway, trace length, C90 area, and velocity)↑in EC than EO

Heinbaugh et al (2015)	Cross-sectional	Healthy (N=34, f=18), age: 23.4 ± 3.7 yrs	No	Between 7:00-10:00 (Day 1&2) Between 15:00-18:00 (Day 1&2)	20 s SLS, EO and EC Y balance test (A, PM, PL directions) Max 20 s single leg landing balance test	Stance time, COP sway area, COP sway speed (AP, ML directions), Maximum reaching directions (A, PM, and PL directions), DPSI during the first 3 s of landing	COP sway area↓, COP speed↓ in EO; stance time↑ and COP sway area↓ in EC in the afternoon than in the morning
Forsman et al (2013)	Cross-sectional	Healthy (N=12, f=2), age: 26.6 yrs	Awake for 26 h	8:00 to 8:00 (next day)- every 2 h	30 s DLS, EO	Sway variability (ML, AP), sway area, fractal dimension, sway velocity (ML, AP), and sway frequency (ML, AP)	Sig effect of TOD and TA for ML and AP sway variability, sway area, fractal dimension, ML sway velocity, and ML sway frequency
Korchi et al (2019)	Cross-sectional	Healthy (N=25, sex=?), age: 85.2 ± 8 yrs	No	8:00, 11:00, 14:00, and 17:00	25.6 s upright stance, EO and EC	COP surface area, mean resultant COP velocity, COPX, and COPY	PC↓ from the early morning to the evening
Bourelle et al (2014)	Cross-sectional	Healthy (N=8, f=3), age: 9.4 yrs	No	7-8 16-19	Weight bearing squat, 10 s mCTISB (EO, EC, solid ground, and foam rubber), 10 s unilateral stance (EO and EC), limits of stability, rhythmic weight shifts	The distribution of body weight in the lower limb between the right and left legs, speed of oscillations, response time, speed of movement, EPE, MXE, directional control	a better directional control at afternoon than the morning; sig in body weight distribution at afternoon
Rym et al (2019)	Cross-sectional	Healthy (N=24, sex=?) (athlete group, N=12, age: 5.5 ± 0.2 yrs) (control group, N=12, age: 5.6 ± 0.4 yrs)	No	7:00, 10:00, 14:00, 18:00	25.6 s upright stance	COP area, mean COP velocity, Romberg's index	PC at 7:00↓, 10:00 ↑, 14:00↓, 18:00↑
Souissi et al (2020)	Cross-sectional	Healthy (N=14,	4 h sleep restriction (either at	8:00	30 s unilateral stance (EO	Postural sway velocity, The distribution of	WBS↔; sway velocity↑ in sleep

		sex=?), age: 21.5 ± 2.3 yrs	22:30-3:00 or 2:30- 7:00)		and EC), 30s mCTSIB (EO, EC, firm surface, and foam surface), and weight bearing squat	body weight in the lower limb between the right and left legs	restriction at the beginning or at the end
Cheng et al (2018)	Cross-sectional	Healthy (N=66, m) (cohort 1, N=37, age: 23.3 ± 2.03 yrs) (cohort 2, N=29, age: 22.3 ± 1.11 yrs)	40 h (6:00 on day1 to 22:00 on day2)	*time awake (4, 16, 28, and 40 h)	Upright stance (solid platform (EO and EC) and foam padded-platform (EC))	Parameters of COP: whole path length, circumference area, mean and standard deviation of COPX, mean and standard deviation of COPY, and the ratio of weight distribution	PC ↓ started at 16 h for EO and at 28 h for EC
Avni et al (2006)	Cross-sectional	Healthy (N=10, f=3), age: 16-33 yrs	Awake for 25 h (starting from 9 a.m. to 10 a.m. the next day)	9:00, 13:00, 15:00, 18:00, 21:00, 23:00, 1:00, 3:00, 5:00, 7:00, 9:00, 10:00	48 s upright stance (head straight, eyes open, support solid; head straight, eyes closed, support solid; eyes open, head down, on soft support and platforms tilted 10° toes up)	Postural instability	A sig effect of TOD on PC
Bougard et al (2012)	Cross-sectional	Healthy (N=8, m), age: 21 ± 3 yrs	35 h of wakefulness	6:00, and 18:00	Stork stand test (dominant leg)	the time of standing on one leg	PC↑ at 18:00 than 6:00; PC↓ after SD
Cheng et al (2018)	Cross-sectional	(experiment 1, N=37, m, age: 21.3 ± 2 yrs) (experiment 2, m, N=60, age: 20.5 ± 1.9 yrs)	40 h of SD (starting from 6:00 (day1) to 22:00 (day2)	10:00 and 22:00 (of Day1), 10:00 and 22:00 (of Day2)	Static stance and dynamic test (drive COP to the target on screen)	Circumference area, MDx, MDy, SDx, SDy, Fourier frequency parameters on 8 different frequency bands	CA↑ and SDy↑ at 10:00; dynamic PC↔
Deschamps et al (2013)	Cross-sectional	Healthy (N=10, m),	No	8 , 12 and 17 ± 30 min	90 s stance (firm surface (EO	SD amplitude (AP), SD velocity (AP),	A sig effect of TOD, confidence

		age: 22.1 ± 1.7 yrs			and EC) and foam surface (EO and EC)	SD amplitude (ML), SD velocity (ML), Mean Velocity, and Area (95% ellipse)	ellipse↑ in the midday than the other times
Cagno et al (2014)	Cross-sectional	Healthy (N=40, f) (athlete group, N=20, age: 13.2 ± 0.5 yrs) (control group, N=20, age: 12.9 ± 0.6 yrs)	No	8:30- 9:30. 19:00-20:00	One leg Balance Beam Test (EC and EO), Star Excursion Balance Test	Time of movement during one leg balance test, maximum reaching distance during SEBT	No sig effect of TOD for athlete; PC↑ for non-athlete in the morning than the afternoon
Forsman et al (2007)	Cross-sectional	Healthy (N=30, f=15), age: 20-37 yrs	No	8:30 , 10:30 , and 13:30 Once a week at 8:30 for one month	22s upright stance	fractal dimension, most common amplitude of time, and time for open-loop control	All balance parameters ↓ from 8:30 to 13:30
Ghaeeni et al (2015)	Cross-sectional	Healthy (N=10, m), age: 69.45 ± 3.23 yrs	No	8:00, 12:00, 16:00, and 20:00	Standing stork test, and Star excursion balance test	Time of stance on one leg, and maximum reaching distance during SEBT	PC↑ at 16:00 than 8:00 in EO
Lovecchio et al (2017)	Cross-sectional	Healthy (N=10, f=5, age: 30 ± 8) (f, age: 21-45 yrs) (m, age: 23-33 yrs)	No	9:00 and 14 of two separate weekdays	35 s upright stance (EO and EC)	speed and the area of the 90% confidence ellipse of COP displacements	No sig effect of within days on PC; sig effect of between days on PC
Ma et al (2009)	Cross-sectional	Healthy (N=16, m), age: 20.75 ± 1.18 yrs	Awake for 24 h (from 8:00 to 8:00 of the following day)	8:00-8:50 , and 8:00-8:50 of the following day	30 s Romberg's test (EO and EC)	WPL, UAPL, CA, RA, SDx, SDy, Mx, and My	CA↑ and RA↑ in EC; SDy↑ in EO after wakefulness
Morad et al (2007)	Cross-sectional	Healthy (N=12, f=6), age: 20-60 yrs	Awake for 26 h (from 8:00 to 10:00 of the following day)	08:00, 09:00, 10:00, 23:00, 01:00, 03:00, 05:00, and 08:00, 09:00, and 10:00 of the following day.	48 s upright stance (EO and EC)	Stability (mean vertical pressure fluctuation), sway instability of pressure fluctuations, and diagonal weight shifting	A sig effect of TOD on PC in the morning of the second day of wakefulness
Patel et al (2008)	Cross-sectional	Healthy (N=18, f=8), age: 23.8 ± 4.8 yrs	24 h and 36 h SD	No	30 s quiet stance and four 50 s stimulation periods (EO and EC)	Variance of torque of AP and lateral movements	PC↓ after 24 h SD but less so after 36 h SD

Robillard et al (2011)	Cross-sectional	Healthy (N=13, f=6), age: 25 ± 2.7 yrs	26 h SD	No	20 s upright stance (EO and EC)	COP range (AP, ML), COP speed, RMS (AP, ML)	COP range$_{AP}$↑ after SD
Robillard et al (2011)	Cross-sectional	Healthy young (N=15, f=7), age: 24 ± 2.7 yrs; Healthy older adults (N=15, f=7), age: 64 ± 3.2 yrs	26 h SD	No	20 s upright stance (EO and EC)	COP range (AP, ML), COP speed (AP, ML)	COP range $_{AP}$↑ in both groups, but COP speed $_{AP, ML}$ ↑ only in older adults after SD
Sargent et al (2012)	Cross-sectional	Healthy (N=14, m), age: 21.8 ± 3.8 yrs	Forced desynchrony protocol for 13 consecutive days	Forced desynchrony protocol for 13 consecutive days	60 s upright stance (EO and EC)	COP area 95% for circadian phase and prior wake	A sig effect of TOD on PC in EC; no effect of wakefulness on PC
Sargent et al (2010)	Cross-sectional	Healthy (N=11, m), age: 22.7 ± 2.5 yrs	Forced desynchrony protocol for 13 consecutive days	Forced desynchrony protocol for 13 consecutive days	60 s upright stance (EO and EC)	COP area 95% for circadian phase and prior wake	No sig effect of TOD and prior wake on PC in both EC and EO
Schlesinger et al (1998)	Cross-sectional	Healthy (N=5, f=3), age: 20 yrs	24 h SD	Between 7:00 and 9:00	Upright stance (fixed floor-stable visual sense, sway floor-stable visual sense, sway floor-sway visual sense)	RMS sway of AP deviations	No sig effect of SD on PC
Vargas et al (2020)	Cross-sectional	SD (N=13, f=5), age: 24.8 ± 5.8 yrs; NS (N=13, f=5), age: 24.9 ± 5.9 yrs	12 SD	Between 8:00 and 10:00	62 s upright stance (fixation and saccade visual)	Mean sway amplitude and velocity of AP and ML	COP velocity↑ and mean sway↑ in both visual conditions after SD
Völker et al (2015)	Cross-sectional	Healthy (N=36, f=18), age: 34.8 ± 12.5 yrs	No	8:30-9:00 and 15:30-16:00	20 s upright stance (EO and EC)	Path length, confidence area, velocity, anterior-posterior variance, and mediolateral variance	A sig effect of TOD for velocity and path length
Son (2017)	Cross-sectional	Healthy (N=20, f=11),	No	9:00, 13:00, and 17:00	30 s upright stance and dynamic	AP and ML directions, COP velocity, performance	COP velocity↓, AP and ML distances↓,

		age: 22.2 ± 1.77 yrs			test (moving the COP toward the target on screen)	time, and total distance	and performance time↓ at 9:00 than 13:00
Forsman et al (2008)	Cross-sectional	Healthy (N=12, f=2), age: 21-38 yrs	Awake for 36 h (from 8:00 to 18:00 the next day)	*time awake (every 2 h)	30 s upright stance	Δt_c from the anterior-posterior COP	PC↓ between 2nd and 36th of time awake
Forsman et al (2007)	Cross-sectional	Healthy (N=20, f=4), age: 21-37 yrs	Awake for 30 h	*time awake (every 2 h)	30 s upright stance	TOC (calculated from COP traces)	PC↓ between 2nd and 30th of time awake
Forsman et al (2008)	Cross-sectional	Healthy (N=63, f=21), age: 20-38 yrs	Awake for 28 h (from 8:00 to 12:00 the next day (part 1) No SD (part 2)	*time awake (every 2 h) 8:30, 10:30, 13:30 (part 2)	30 s upright stance (part1) 22 s upright stance (part2)	TOC	PC↓ when time awake↑; PC↓ in the afternoon than in the morning
Gomez et al (2008)	Cross-sectional	Healthy (N=18, f=8), age: 17-38 yrs	24 and 36 h SD	NO	30 s upright stance (EO and EC)	Normalized variance of anteroposterior direction of head, shoulder, hip, and knee	SD affect the body movement variance in the AP direction
Kohen-Raz et al (1996)	Cross-sectional	Healthy (N=8, sex=?), age= 24-35 yrs	No	7:00 , 15:00 , 23:00	30 s upright stance (EO and EC)	Stability, power at .25 Hz, synchrony difference, and composite score, spectral power, and weight distribution difference	A sig effect of TOD on PC

Abbreviations: AP anterior-posterior, SD sleep deprivation, NS normal sleep, N number of subjects, f female, m male, SLS single-leg stance, DLS double-leg stance, EO eyes opened, EC eyes closed, SEBT star excursion balance test, COPVx center of pressure velocity in the mediolateral direction, COPVy center of pressure velocity in the anteroposterior direction, LFS length as a function of surface, PC postural control, MD-x mean deviation on lateral axis, MD-y mean deviation on anteroposterior axis, SS support surface, SL statokinesig length, RMSL-x root mean square of length in the lateral direction, RMSL-y root mean square of length in the anteroposterior direction, MV-x mean velocity in the lateral direction, MV-y mean velocity in the anteroposterior direction, LF-x low-frequency band power of postural sway in the lateral, LF-y low-frequency band power of postural sway in the anteroposterior direction, MF-x median-frequency band power of postural sway in the lateral direction, MF-y median-frequency band power of postural sway in the anteroposterior direction, HF-x high-frequency band power of postural sway in the lateral direction, HF-y high-frequency band power of postural sway in the anteroposterior direction, AT anterior, PM posteromedial, PL posterolateral, DPSI dynamic postural stability index, TOD time of day, TA time awake, mCTSIB oscillation speed, WBS weight

6.3.3 Methodological quality

The methodological quality of the included studies was evaluated in accordance with the modified Downs and Black checklist, which is represented in Table 2. Of the 49 studies, 21 articles [201, 202, 204, 206, 207, 209, 210, 212, 215, 216, 224, 225, 227-230, 233-235, 249, 251] were rated as high-quality and 28 as low quality [203, 205, 208, 211, 213, 214, 217-219, 223, 226, 231, 232, 236-250, 252]. Inter-rater reliability was 0.87 between the two reviewers who examined the quality of the included studies.

Table 2. Quality Assessment of the Included Studies

First Author (Year)	1	2	3	5	6	7	10	11	12	15	16	18	20	21	25	27	Tot.
Aguiar (2014)	1	1	1	0	1	1	0	0	0	U	1	1	1	U	0	1	9
Gribble (2007)	1	1	1	1	1	1	1	U	U	U	1	1	1	1	0	1	12
Bougard (2011)	1	1	1	2	1	1	1	U	U	0	1	1	1	U	0	1	12
Kwon (2014)	1	1	1	1	1	1	0	U	U	0	1	1	1	1	1	0	11
Baccouch (2015)	1	1	1	2	1	1	0	U	U	U	1	1	1	1	0	0	11
Gribble (2004)	1	1	1	1	1	1	1	U	U	U	1	1	1	U	0	1	11
Fabbri (2007)	1	1	0	0	1	1	0	U	U	U	1	1	1	U	U	1	8
Zouabi (2016)	1	1	1	1	1	1	1	U	U	U	1	1	1	U	0	0	10
Jorgensen (2012)	1	1	1	2	1	1	1	U	U	U	1	1	1	1	1	1	14
Bougard (2014)	1	1	1	2	1	1	0	U	U	U	1	1	1	U	0	0	10
Liu (2001)	1	1	1	1	1	1	0	U	U	U	1	1	1	U	U	0	9

Nakano (2001)	1	1	0	1	1	1	0	U	U	U	1	1	1	U	U	0	8
Neji (2019)	1	1	1	1	1	1	1	1	U	U	1	1	1	1	U	1	13
Karagul (2017)	1	1	1	2	1	1	1	U	U	U	1	1	1	U	1	1	13
Martin (2018)	1	1	1	2	1	1	1	U	U	U	1	1	1	U	0	1	12
Aguiar (2015)	1	1	1	1	1	1	0	U	U	U	1	1	1	U	1	1	11
Russo (2015)	1	1	1	1	1	1	1	U	U	U	1	1	1	1	0	1	12
Smith (2012)	1	1	1	1	1	1	1	U	U	U	1	1	1	1	0	0	11
Heinbaugh (2015)	1	1	1	1	1	1	1	U	U	U	1	1	1	U	0	1	11
Forsman (2013)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	0	0	9
Korchi (2019)	1	1	1	1	1	1	1	1	U	U	1	1	1	1	0	1	13
Bourelle (2014)	1	1	1	0	1	1	0	U	U	U	1	1	1	1	0	0	9
Rym (2019)	1	1	1	2	1	1	1	U	U	U	1	1	1	0	0	0	11
Souissi (2020)	1	1	1	1	1	1	0	U	U	U	1	1	1	1	0	0	10
Cheng (2018)	1	1	1	1	1	1	1	U	U	U	1	1	1	1	0	1	12
Avni (2006)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	0	0	9
Bougard (2012)	1	1	1	2	1	1	0	U	U	U	1	1	1	U	0	0	10
Cheng (2018)	1	1	1	1	1	1	1	U	U	U	1	1	1	1	0	0	11
Deschamps (2013)	1	1	1	1	1	1	0	U	U	U	1	1	1	1	0	0	10
Cagno (2014)	1	1	1	2	1	1	1	U	U	U	1	1	1	0	1	1	13
Forsman (2007)	1	1	1	1	1	1	1	U	U	U	1	1	1	1	0	1	12
Ghaeeni (2015)	1	1	1	1	1	1	1	1	U	U	1	1	1	1	0	0	12
Lovecchio (2017)	1	1	1	1	1	1	1	U	U	U	1	1	1	U	0	0	10
Ma (2009)	1	1	1	1	1	1	0	U	U	U	1	1	1	1	0	0	10
Morad (2007)	1	1	1	0	1	1	0	U	U	U	1	1	1	U	0	0	8
Patel (2008)	1	1	1	1	1	1	0	U	U	U	1	1	1	U	0	0	9
Robillard (2011)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	0	0	9
Robillard (2011)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	0	0	9
Sargent (2012)	1	1	1	0	1	1	0	U	U	U	1	1	1	U	0	1	9
Sargent (2010)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	0	0	9

Schlesinger (1998)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	0	0	9
Vargas (2020)	1	1	1	1	1	1	0	U	U	U	1	1	1	U	0	0	9
Volker (2015)	1	1	1	0	1	1	0	U	U	U	1	1	1	1	0	1	10
Son (2017)	1	1	1	1	1	1	1	U	U	U	1	1	1	1	0	1	12
Forsman (2008)	1	1	0	0	0	1	0	U	U	U	1	1	1	U	0	0	6
Forsman (2007)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	U	0	9
Forsman (2008)	1	1	1	0	1	1	1	U	U	U	1	1	1	U	U	1	10
Gomez (2008)	1	1	1	1	1	1	1	U	U	U	1	1	1	U	0	0	10
KohenRaz (1996)	1	1	1	0	1	1	0	U	U	U	1	1	1	1	0	0	9

Downs and Black Checklist items: **Reporting ((1)** Is the hypothesis/aim/objective of the study clearly described?; **(2)** Are the main outcomes to be measured clearly described in the Introduction or Methods section?; **(3)** Are the characteristics of the patients included in the study clearly described ?; **(5)** Are the distributions of principal confounders in each group of subjects to be compared clearly described**?**; **(6)** Are the main findings of the study clearly described?; **(7)** Does the study provide estimates of the random variability in the data for the main outcomes?; **(10)** Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?**); External validity ((11)** Were the subjects asked to participate in the study representative of the entire population from which they were recruited?; **(12)** Were those subjects who were prepared to participate representative of the entire population from which they were recruited?; **Internal validity – bias ((15)** Was an attempt made to blind those measuring the main outcomes of the intervention?; **(16)** If any of the results of the study were based on "data dredging", was this made clear?; **(18)** Were the statistical tests used to assess the main outcomes appropriate?; **(20)** Were the main outcome measures used accurate (valid and reliable)?**); Internal validity - confounding (selection bias) ((21)** Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?; of time?; **(**the randomized intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?; **(25)** Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?; **(27) Power:** Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?

6.3.4 Time of day

Twenty-one studies [201-205, 207, 223-225, 227, 229, 230, 232-235, 244, 248-251] exclusively examined the effect of circadian rhythm on PC, 11 studies [204, 205, 207, 223, 225, 229, 230, 232, 234, 235, 244, 248] investigated this influence in a static condition, four studies [227, 233, 235, 249] in a dynamic condition, and six studies [201-203, 224, 250, 251] in both conditions (static and dynamic). Of the 21 investigations [201-205, 207, 223-225, 227, 229, 230, 232-235, 244, 248-251] seventeen studies reported circadian rhythm significantly influenced PC, in which twelve studies [201, 202, 207, 224, 225, 227, 229, 230, 234, 235, 249, 251] were high-quality and five of them [223, 232, 244, 248, 250] were low-quality, and four studies [203-205, 233] reported no significant effect of time of day on PC such that three of them

[203, 205, 233] were low-quality and one study [204] was high-quality (the quality assessment of postural control variables regarding time of day is provided in supplementary material). Specifically, in the static condition, six studies [201, 224, 225, 229, 234, 251] demonstrated better PC in the morning compared to the other time of day, whereas four studies [202, 223, 235, 244] reported improved PC in the evening. In addition, two studies [207, 230] indicated an improvement in PC at 10 a.m. and 6 p.m. compared to 7 a.m. and 2 p.m.. While one study [248] determined a significant influence of circadian rhythm on PC, there was no specific pattern of postural control's improvement at a certain time of day. One study [232] also specified better PC at midday than the morning and the afternoon. Therefore, no specific pattern of how time of day influences PC was detected. During dynamic conditions, four studies [201, 224, 227, 251] reported improved PC in the morning, while one study [250] indicated better PC in the evening. One study [249] also revealed a significant impact of time of day on dynamic PC during the star excursion balance test; however, each variable of the examination demonstrated a different performance in PC in regard to time of day.

In terms of COP variables, twelve studies [201-203, 205, 207, 224, 225, 229, 230, 232, 244, 251] reported COP velocity as mean velocity [203, 205, 207, 224, 229, 230, 232, 244, 251], velocity-moment [225], velocity in the anteroposterior (AP) and mediolateral (ML) directions [201, 202], and standard deviation [232]. Eight studies [201, 202, 207, 225, 229, 230, 244, 251] demonstrated a significant change in COP velocity variables; however, different alterations were reported in regard to time of day. Nine studies [203, 204, 223-225, 229, 232, 244, 251] also extracted COP displacement variables of total distance [203, 225, 251], path length [204, 223, 244], COP sway in AP and ML directions [223, 224, 229, 250], Napierian logarithm of the X mean and Y mean [204], length of sway path [204], standard deviation amplitude [232], AP and ML variances [244], and the average position of COP at AP and ML [203]. Inconsistent results regarding to time of day were reported in which five studies [224, 225, 229, 244, 251] demonstrated significant differences for COP (AP and ML), total sway length, and path length. Moreover, ten studies [202-

205, 207, 225, 230, 232, 244] reported COP area, which included surface area [202, 203, 205, 207, 223, 225, 230, 232, 244], total sway area [225], Naiperian logarithm of the ellipse of confidence area [9], eccentricity of the ellipse area [9], and length of COP sway path [9].While six studies [7, 12, 28, 30, 36, 38] demonstrated significant differences for COP area, these studies did not demonstrate a conclusive effect of time of day on PC variables.

6.3.5 Sleep loss (sleep loss * time of day)

Twenty-five studies [206, 208-219, 226, 228, 231, 236-239, 242, 243, 252] manipulated sleep in order to investigate the effect of SD on PC. Eighteen of these studies [206, 210, 213-215, 217-219, 226, 228, 236-239, 242, 252] applied total SD (18-48 h), five studies [208, 209, 211, 212, 243] used one night of sleeplessness (8-12 h), and three studies [216, 231, 252] exerted sleep restriction (4-6.5 h). Of the 25 studies [206, 208-219, 226, 228, 231, 236-239, 242, 243, 252], twenty-three studies reported a negative influence of SD on PC, in which six studies [206, 209, 210, 212, 216, 228] were high-quality and seventeen of them [211, 213, 214, 217-219, 226, 228, 231, 236-239, 243, 252] were low-quality, and two studies [215, 242] did not demonstrate any significant effect of SD on PC so that one of the studies was high-quality [215] and the other one [242] was low-quality (quality assessment of postural control variables regarding sleep loss (sleep loss * time of day) is provided in supplementary material). One of those studies [215] did not demonstrate a significant effect of sleep loss on postural sway during the execution of a dynamic task (moving COP to the target on screen), but demonstrated a meaningful impact of SD on static PC. The other study [242] did not report postural sway after 24 h SD; however, it specified a significant effect of SD on PC during inhibitory a reaction task. Of the 26 investigations [206, 208-219, 226, 228, 231, 236-239, 242, 243, 252], ten studies [206, 211-214, 216, 217, 219, 226, 252] examined postural sway as a combination of both SD and time of day, 6 experiments [210, 218, 219, 228, 245, 246] concentrated on PC in several time of wakefulness, and 11 investigations [208, 209, 215, 231, 236-239, 242, 243, 247] considered no circadian rhythm's effect on PC after sleep loss. In particular, seven studies [211, 213, 214, 217, 219, 226, 252] demonstrated a reduction in PC in the early morning in response to SD; however, two studies [206, 216] reported different results in which one of them [216] indicated no change in postural sway at 6 a.m., an increase in COP surface area at 10 a.m. and 2 p.m., and an increment in LFS (length in function of surface) ratio at 6 p.m. The other research [206] revealed no alteration in COP area but gradual increases in COP velocity after midnight until the last measurement session (4 p.m.). One study [212] also reported no change in PC with respect to time of day. In terms of wakefulness, six studies [210, 218, 219, 228, 245, 246] indicated an increase in postural sway with increasing time awake. In the context of SD without circadian rhythm's effect, eleven studies [208, 209, 215, 231, 236-239, 242, 243, 247] specified negative influence of SD on PC; however, two of these studies [237, 247] revealed no deteriorating effect of SD on PC after 24 h until 36 h SD.

In regard to COP variables, eight studies [206, 219, 228, 231, 238, 239, 243, 252] reported COP velocity in which four studies demonstrated meaningful and higher value of mean sway velocity [206, 231] and COP speed in the AP [238] and ML [219, 238] directions in response to SD. Fourteen investigations [210-212, 215, 219, 226, 228, 236-239, 242, 243, 252] also extracted COP displacement, which included COP range (AP and ML) [238, 239], variance of torque of AP and lateral movements [237], RMS sway of AP [239, 242, 252] and ML [239] directions, standard deviation of mean displacement in the AP and ML [210, 215, 236], mean displacement (AP and ML) [210, 211, 215, 236, 243], whole path length [210, 236], unit area path length [236], and total displacement length of COP [212]. Many of the studies found a significant difference for COP displacement variables; in particular, COP range_{AP} [238, 239], $SD_{AP \text{ and } ML}$ [210, 215, 236], sway_{AP} [210, 219, 227], sway_{ML} [219], $RMSL_{AP}$ [252], and total displacement length of COP [210, 212] increased, after SD. Furthermore, the majority of the investigations reported an increase in COP area after sleep loss [210-212, 215, 236].

6.3.6 Forced desynchrony

Two studies [240, 241] applied forced desynchrony protocol, which manipulated circadian rhythm and time of wakefulness, to understand the effect of SD and time of day on PC such that the studies [240, 241] were low quality. The first [240] reported a significant effect of time of day on PC in eyes-closed condition while there was no change in COP area regarding wakefulness. However, the other research [241] did not reveal any meaningful influence of TOD and SD on PC in both eyes opened and eyes closed conditions.

6.4 Discussion

The aim of the current systematic review was to understand the effect of SD and circadian rhythm on PC. While there were inconsistent results surrounding a significant difference of a specific variable (e.g., COP displacement), all studies that considered sleep loss reported a negative and meaningful influence of SD on PC. The majority of investigations that measured PC in response to time of day found a significant change in PC; however, there was inconsistency between an improvement or deterioration in PC at a specific time of day.

It has been proposed that age can be a contributory factor that may affect PC [253]; hence, nine studies [207, 225, 227, 229, 230, 233, 235, 238, 250] considered this element to measure PC in response to circadian rhythm and SD in which five [207, 230, 232, 233, 250] and four [225, 229, 235, 238] investigations evaluated PC among children and older adults, respectively. Many of the studies revealed a significant influence of time of day and SD (one study [238]) on postural balance among these populations. However, the results of the investigations were inconsistent; in particular, two studies demonstrated an improvement in PC in the morning in older adults [225, 229], while Ghaeeni et al (2015) reported elderly individuals had a better performance in the standing stork test in the afternoon compared to the morning [235]. This difference in improved PC regarding time of day may be the result of the type of test and outcome variables. Robillard et al (2011) also indicated more deteriorating PC among older than younger adults, in which was observed an increase in COP range$_{AP}$ and COP velocity$_{(AP\ and\ ML)}$ after SD among older adults [238]. However, this study only demonstrated a significant effect of SD on COP range$_{AP}$ in young population [238]. Since it has been reported different mechanisms are responsible for PC in ML and AP directions [254], it is suggested PC that may be altered due to SD can differently be controlled in young and older adults [238]. Five studies [207, 230, 232, 233, 250] that measured PC regarding circadian rhythm in children reported contradictory findings [227, 250] that demonstrated improved PC in the afternoon. Two investigations [207, 230] indicated improved PC at 10 a.m. and 4 p.m., and one investigation [233] did not find any significant difference for PC variables among rhythmic gymnasts. However, the study of Cagno et al. (2014) specified an improvement in PC in the morning among children with normal physical activity. Hence, the level of physical activity may be a factor that could affect PC. This is because circadian rhythm of some physiological and psychological functions of athletes can be affected by their athletic performance and training [197]. In this context, nine studies [202, 204, 206, 227, 230-233, 249] evaluated PC in relation to time of day and SD among athletes resulting in an increase in COP velocity after partial [231] and total SD [206] in only two of these. In regard to circadian rhythm, the majority of the studies [202, 204, 227, 230, 232, 233, 249] found significant differences in PC in which three of them reported improvements in PC in the afternoon [202, 227, 232], whereas two investigations [204, 233] did not observe any meaningful change in PC among athletes.

While circadian rhythm and sleep loss can lead to changes in PC, the mechanism underlying this alteration has not been well understood. In this vein, several studies [208-210, 212, 223, 239, 243] investigated the possible mechanism triggering changes in PC that may be the result of time of day and SD. These investigations, however, reported no single pathway responsible for this change, in which visual information, sensory reweighting, cognitive function have been proposed as a possible mechanism causing alterations in PC. More precisely, three studies [210, 237, 247] indicated postural sway alterations after SD did not worsen progressively and sleep deprivation’s negative effect was reduced over time; hence, it was suggested that there is a compensatory mechanism by which people reweight sensory information (visual and proprioception) in order to be able to complete the PC task [210]. Robillard et al. (2011) also demonstrated a reduction in COP range$_{AP}$ during unchallenged sensory and attentional tasks after SD; however, these same authors observed a significant change in COP range$_{ML}$ and COP velocity with manipulations of sensory inputs and cognitive functions. Hence, it was concluded other physiological mechanisms may be responsible for changes in PC after sleep loss in addition to declines in cognitive performance. Altogether, it has been expected mechanisms triggering this alteration in PC that may stem from SD and circadian rhythm are complicated and controversial; thus, further study is needed to understand more about such mechanisms.

In regard to an objective assessment of sleepiness, it has been proposed that PC can assist in detecting those who are sleep deprived, which in turn can lead to preventing occupational and traffic accidents [213, 214]. Notably, several studies [213-215, 218, 245] demonstrated progressive increases in postural sway in response to sleep propensity, which can stem from wakefulness. In this context, some studies indicated worsened PC that may be the result of time of wakefulness associated with mental fatigue [213] and heart rate variability [215], which was reported as an important indicator of mental fatigue [215]. In terms of outcome measures of PC, some investigations were carried out to understand more sensitive variables to sleepiness; thus, stability index [213, 214], Fourier sway intensities [214], and the time interval of open-loop stance control [218] were reported as variables that are closely linked to time awake. Forsman et al. also reported COM-based balance is more responsive to wakefulness compared to COP-based balance [245]. While the aforementioned variables can help to specify those who experience sleepiness, circadian rhythm, as a confounder, can influence the progressive increase of postural sway in response to time awake [219, 245].

There are some methodological issues which need to be considered when interpreting the findings of this review. Masking effect (i.e. experimental and environmental factors) has been known as an element that can influence circadian rhythm [198]. Of the 49 studies, fifteen investigations [203, 204, 207, 216, 217, 223, 225-228, 230, 231, 240, 241, 252] considered the environmental and experimental factors (e.g., physical activity, stimulus drinks, consumption of a meal, and sleep time) that may result in affecting the findings of studies. Moreover, since the majority of studies applied the repeated measurement method to assess the effect of sleep loss and circadian rhythm on PC, the results of the investigation may be affected by learning effect. Thus, some of the studies [203, 205, 207, 212, 216, 217, 223, 224, 227, 229-234, 238, 239, 249] used counterbalance design to decrease the influence of learning on PC; however, the others did not employ counterbalancing. Chronotype (morningness-eveningness) has been also reported as a contributory factor that can affect performance; thus, eleven studies include this criterion when postural balance was evaluated [203, 205, 207, 212, 216, 217, 223, 224, 227, 230, 233, 243, 249]. Level of physical activity, sample size, sex of subjects are other elements that can impact the result of studies, whereas many of the studies did not concentrate on these factors. Clearer research designs and standardized procedures should be carried out in order to increase the repeatability of the studies and provide clearer results on the effects of time of the day and SD on PC measures during static and dynamic conditions.

The present systematic review also has a number of limitations: (1) we only included those studies that were published through peer review process, whereas other publications, including theses, were not included; (2) the heterogenous methodology among the included studies gave rise to not performing a meta-analysis; (3) Since quantifying PC is a complex process, numerous PC variables are used to assess PC. In this vein, the included studies applied various PC variables to evaluate PC in response to time of day and/or sleep deprivation, which in turn, it is not possible to define a definitive conclusion of the effect of time of day and sleep deprivation on postural control (i.e. whether confounding effect of time of day can be owing to different variables that were used) due to the fact that significant differences occurred among various variables.

6.5 Conclusion

The results of the present review underline that heterogeneous results are resent regarding both time of day and sleep deprivation. In particular, no specific time of day contributes to significant variations in postural control. A trending negative effect regarding sleep deprivation has been observed on postural control; however, further research is needed to confirm the retrieved result. Other variables, such as age, levels of physical activity, sensory contribution, and chronotype should be considered when planning to assess postural control in sleep studies.

Chapter7: Lower limb muscle activation pattern in male soccer players with lumbar hyperlordosis

7.1 Introduction

One important postural malalignment in the trunk, which is common among soccer players, is lumbar hyperlordosis [255]. In such a misalignment, the lumbar lordosis angle cumulatively increases over time because of the nature of soccer-related activities [255]. Prior studies [256, 257] have demonstrated lumbar hyperlordosis could be associated with several injuries in the knee joint and the lumbopelvic complex. Specifically, hamstring strain [258], spondylolysis [256], and anterior cruciate ligament and meniscus injuries [257] have been reported among soccer players with lumbar hyperlordosis.

Researchers mainly have concentrated on injuries in the lumbopelvic region and the knee joint among soccer athletes with lumbar hyperlordosis, while such a malalignment could affect the stability of the whole lower extremity. In this vein, lumbar hyperlordosis results in poor postural adaptation in the entire lower limb [259]. In this context, an increase in lumbar lordosis angle is associated with increased anterior pelvic tilt [260], which, in turn can result in increasing femoral internal rotation, knee hyperextension, and knee valgus [261, 262]. Excessive femoral internal rotation may lead to increased femoral adduction, while knee hyperextension may cause further femoral internal rotation compared to the tibia [263]. In such a case, the alteration may lead to foot pronation [264]. Collectively, these compensatory alignments can alter the neuromuscular function of lower limb muscles via changes in length, fiber orientation, and tension of muscles [265]. In fact, we have previously demonstrated that lumbar hyperlordosis and its associated compensatory malalignments contribute to increased gluteus maximus and quadriceps muscle activity [266]. However, there is no information regarding the influence of lumbar hyperlordosis on concentric and eccentric muscle activation. Since locomotor activity relies on the contribution of various muscle functions (concentric and eccentric) and there are neuromechanical differences in concentric and eccentric muscle actions [267-269], understanding whether lumbar hyperlordosis can alter concentric and eccentric muscle activation enhance our understanding of this malalignment on the lower limb muscle function.

Notably, during weight-bearing tasks, the alteration of the neuromuscular function of lower limb muscles can influence the functional stability of the lower limb; thus, soccer players could be more susceptible to injury. Namely, it was demonstrated that hamstring injury occurs during eccentric contractions, where hamstrings are stretched [270], and Sole et al. (2011) found changes in eccentric hamstring activation can lead to hamstring strain [271]. It was reported that soccer players with lumbar hyperlordosis experienced hamstring strain [258]; however, to the authors' knowledge, there is no information to demonstrate whether lumbar hyperlordosis can alter hamstring muscle function during eccentric contraction. Moreover, previous studies [272, 273] indicated that eccentric muscle ability plays a significant role to decelerate force rapidly and develop concentric force to execute a task successfully. Thus, the alteration of eccentric muscle function can contribute to changes in concentric muscle performance [272] and may cause injuries [271]. The altered neuromuscular function can also affect athletic performance [274, 275]. For instance, it has been suggested that a decrement in plantar flexor activation could diminish running speed performance among athletes in addition to altering the lower limb movement pattern [275]. In fact, such an alteration can affect the neutral biomechanics of lower limb joints whereby individuals who participate in high-demand sports activities, most notably soccer athletes, are more likely to experience non-contact injuries [274]. Hence, it is expected the alteration of the lower limb neuromuscular performance that may arise from lumbar hyperlordosis could be a factor in changing the functional stability of lower extremity. It is of great interest to reveal the influence of lumbar hyperlordosis on the eccentric and concentric muscle activation of the lower limb during weight-bearing tasks, including single leg squat, which is a common rehabilitation exercise as well as a clinical test to detect lower limb neuromuscular deficits in the eccentric and concentric phases of the task [276]. While it was demonstrated that athletes with lumbar hyperlordosis can experience alteration in gluteal and quadriceps muscles function, Izadi Farhadi and colleagues (2020) recruited athletes from different sports, which in turn can impact the result of the study since training may change muscle activation sequence. That is, any movement pattern, which can be distinct in different sports, is specified by sequence, timing, and amplitude of muscle activation; hence, it is expected athletes in various sports 80 demonstrate specific activation schema [277], which in turn can be a contributory factor when evaluating muscle activation. It is, therefore, necessary to measure muscle activation pattern to reveal whether lumbar hyperlordosis can alter muscle activation pattern in soccer athletes.

As our knowledge about the effect of lumber hyperlordosis on lower limb muscle function is limited, we conducted a study to identify them among soccer players with lumbar hyperlordosis. Specifically, there is no information regarding concentric and eccentric activation of the lower limb muscle fnction among individuals with lumbar hyperlordosis during functional activities, including the single leg squat. Therefore, the objective of the current study was to compare the concentric and eccentric activation pattern in eleven muscles of the hip, thigh, and shank- gluteus maximus, gluteus medius, vastus medialis oblique, vastus lateralis, rectus femoris, semitendinosus, biceps femoris, lateral gastrocnemius, medial gastrocnemius, anterior tibialis, and soleus- among soccer players with and without lumbar hyperlordosis during single leg-squat (SLS). The SLS is a common rehabilitation exercise as well as a clinical test to detect lower limb neuromuscular deficits [276]. It was hypothesised that soccer players with lumbar hyperlordosis would have higher the lower limb muscle activation pattern compared to those with normal lumbar lordosis during the SLS performance.

7.2 Methods

7.2.1 Participants

Thirty male collegiate soccer players (15 with and 15 without lumbar hyperlordosis) were participated in the current study based on case-control design. Athletes were included in the present investigation if soccer players had age between 22-29 years and performed soccer for at least 6 years, normally three sessions per week, and at least 1.5 hours per each session. These athletes had no history of surgery or injury to the lower limbs or the lumbar area within the last six months prior to enrollment [265, 278]. Also, participants had no postural deformity in their knees (genu recurvatum, genu valgum, and genu varum) [279] or feet [280]. Upon enrollment, athletes were allocated to the normal and lumbar hyperlordosis groups based on the result of a pilot study [266] (see below). To decrease risk of bias, lumbar lordosis angle were assessed by a clinician and the EMG of the selected muscles were evaluated by another examiner. Participants were also informed regarding the type of test and how to perform the tasks, whereas they did not know about the measuring outcomes. All the athletes signed an informed consent before performing the test. Moreover, this study was verified by Institutional Review Board at the University of □.

7.2.2 Measurement of Lumbar Lordosis

To assess the lumbar lordosis angle, we used a 40cm flexible ruler. Several studeis [281, 282] reported high validity and reliability for this instrument. We measured the lumbar region of participants from the spinous process of T12 to the spinous process of S2 while the participants stood on their feet. The ruler was placed over the bony landmarks such that there was no space between the athletes' skin and the ruler, then the ruler followed the curvature of the spine. Then, the flexible ruler was carefully lifted from the body and placed on a white paper so that the spinal curvature could be traced. Next, we calculated the depth (H) and height (L) of the curve. Finally, we replaced the "H" and "L" variables in the Cobb's angle equation ($\theta=4 \text{ arc tan } 2H/L$) to calculate lumbar lordosis angle [281].

The normal lumbar lordosis angle reported in the literature using Cobb's angle is between 30-80 degrees [255]. Given this large range, we conducted a pilot study among male collegiate athletes to detect cut-off criteria by which to designate athletes as having normal lumbar lordosis or hyperlordosis. The results of the pilot study demonstrated that the normal lumbar lordosis angle's range was between 30.37±8.84 degrees; thus, the cut-off point to identify participants with lumbar hyperlordosis was considered greater than 39.2 degrees, or one standard deviation above the average of the population [266].

7.2.3 Electromyography Procedure

A surface electromyography (EMG) device (ME6000-T16, Megawin, Mega Electronics Ltd, Kuopio, Finland: interelectrode distance: 20 mm, input impedance >10 MW at 100Hz, preamplifier gain of 305, and110 dB common-mode rejection rate) sampling at 1000Hz was used to record the muscle activity of gluteus maximus (GMAX), gluteus medius (GMED), rectus femoris (RF), vastus lateralis (VL), vastus medialis oblique (VMO), semitendinosus (SEM), biceps femoris (BF), medial gastrocnemius (MG), lateral gastrocnemius (LG), anterior tibialis (AT), and soleus (SOL) during SLS task. Electrodes were placed based on SENIAM's (surface EMG for a non-invasive assessment of muscles) recommendation [283] and Cowan's study [284]. In order to prepare EMG recording, the skin was shaved, cleaned with alcohol, and then electrodes (adhesive, silver/silver chloride, and with 10 mm circular cross-section) were directly placed over the muscle belly in the muscles' fiber direction in a manner with bipolar configuration.

After electrode placement, the maximal voluntary isometric contraction (MVIC) of each muscle was determined in the same manner as Kendall's method [285]. Participants performed each MVIC twice for 6s each so that the mean of 2 seconds in the middle of each repetition was averaged to specify MVIC.

After the collection of the MVIC, participants were instructed on how to perform the SLS task and then permitted to completed sufficient familiarization trials. In this vein, soccer players crossed their arms over their chests, stood on the dominant leg (the leg that kicks a ball), squatted down to 60 degrees of knee flexion, and then returned to the start position. The nondominant limb was held fixed in 45 degrees of hip flexion and 90 degrees of knee flexion. In order to identify the knee flexion angle during the SLS task, an electrogoniometer (SG150, Biometrics Ltd, UK) synchronized with the EMG system was situated at the center of the knee joint on the lateral side. All athletes completed three correct SLS cycles. Correct trials necessitated that they maintained their crossed arms, the dominant knee reached 60 degrees of flexion, the heel of the dominant leg stayed on the ground, and the nondominant leg did not touch the ground during the SLS task.

7.2.4 Data Reduction and Statistical Analysis

All EMG data were filtered and exported with the Megawin software. Raw data were band-pass (10-450 Hz) and band-stop (59-61 Hz) filtered. Next, data were submitted to a root mean square (RMS) algorithm with a 50ms moving window to calculate the magnitude of muscle activity for each muscle during the SLS task [286]. To determine muscle activity during the descending and ascending phases of the SLS task, we reduced the EMG and knee flexion angle data to 100 points with MatLab software. The 100 points indicate 100% of the SLS cycle so that the 50% point corresponds to maximum knee flexion, and both 0% and 99% represent complete knee extension during the SLS cycle [286]. Alongside these points, 0-24%, and 25-49%, respectively, describe the initial and final descending phases of the SLS task. Further, 50-74% and 75-99%, respectively, denote the initial and final ascending phases of the SLS. After reducing the data to 100 points, we smoothed the data with a 3-point moving average window and then calculated 90% confidence intervals for the average of each percentage point in the Excel software. This was computed for each muscle during SLS. All regions that did not overlap in their confidence intervals for more than 3 successive points were recognized as having a statistically significant difference. Afterward, we calculate mean differences and related pooled standard deviations for each of the points where significant differences were observed. Finally, we used mean differences and associated pooled standard deviations to determine Cohen's d effect sizes, defined as weak (<0.2), small (0.21-0.39), moderate (0.4-0.7), large (0.71-0.99), and very large (>1.0).

To obtain a further thorough grasp of the muscle activity of the whole lower limb muscles during the SLS cycle, we summed normalised muscle activity of quadriceps femoris (VMO, VL, and RF), hamstring (BF, and SEM), and plantar flexors (MG, LG, and SOL).

To compare demographic characteristics, we used independent samples t-tests in SPSS 21 software such that the level of significance was set at $p < 0.05$.

7.3 Results

There were no differences in demographic data between groups with the exception of lumbar lordosis angle, which was significantly greater in the group with lumbar hyperlordosis (Table 1). The activation of gluteus maximus was significantly higher in soccer athletes with lumbar hyperlordosis compared to those with normal lumbar lordosis during initial descent (4-8%) of the SLS cycle (Figure 1). The effect sizes for this phase was very large at -3.92 (Figure 3).

Table1. Descriptive traits of participants (n=30)

	LHLG (n=15) Mean ± SD	NLLG (n=15) Mean ± SD	P-Value
Age (Years)	25.73 ± 2.31	25.80 ± 2.21	0.93
Height (cm)	178.87 ± 5.47	178.2 ± 4.98	0.73
Mass (kg)	74.97 ± 7.3	72.13 ± 6.04	0.25
Years of workout	10.07 ± 0.96	10.20 ± 0.86	0.69
Workout (hours/week)	8.13 ± 2.06	8.27 ± 2.12	0.86
Lumbar lordosis angle (°)	46.36 ± 4.62	33.07 ± 3.8	<0.001*

LHLG: lumbar hyperlordosis group, NLLG: normal lumbar lordosis group, *P-value < 0.05

The muscle activity of gluteus medius significantly differed between groups in the final descending and initial and final ascending phases (25-59%; d= 2.74, 62-78%; d= 3.29, 93-100%; d= 8.24; Figures 1 and 3) of the SLS cycle, during all of which muscle activity was greater in soccer players with normal lumbar lordosis than the lumbar hyperlordosis group.

Vastus medialis oblique activity was significantly greater in the normal compared to the hyperlordosis group during all descent and ascent phases of the SLS cycle (10-85%) (Figure 1). The effect size was very large (1.1) for all points with significant differences (Figure 3).

Vastus lateralis muscle activity did not significantly differ between the groups (Figure 1).

The activity of rectus femoris significantly differed in the final (75-86%, d= 1.14) ascending phase of the SLS cycle. During final ascent, RF muscle activity was higher in soccer players with normal lumbar lordosis than the lumbar hyperlordosis group (Figures 1 and 3).

The muscle activity of biceps femoris had significant differences in all phases of the SLS cycle (10-18%, d= -6.77; 42-49%, d=-6.26; 51-57%, d=-10.54; 80-98%, d=-5.24) between the groups. In this regard, the BF muscle activity was higher in soccer players with lumbar hyperlordosis than those with normal lumbar lordosis during these phases of the SLS cycle (Figures 1 and 3).

There was no significant difference in Semitendinosus muscle activity among soccer players with and without lumbar hyperlordosis (Figure 1).

Anterior tibialis muscle activity did not significantly differ betwixt the groups (Figure 1).

The muscle activity of soleus was significantly different during all phases of the SLS cycle other than the initial ascending phase (16-22%, d= 2.37; 24-29%, d= 9.23; 43-49%, d= 5.84; 78-83%, d=4.32; and 85-100%, d= 2.04) so that the activation of soleus was higher in athletes with normal lumbar lordosis than those with lumbar hyperlordosis (Figures 1 and 3).

Medial gastrocnemius activity was significantly different in the initial descending and the final ascending phases (4-18%, d=-1.31; 80-84%, d= -3.44; 97-100%, d=4.85) of the SLS, during all of which muscle activity was greater in soccer athletes with lumbar hyperlordosis than the normal lumbar lordosis group other than the 85-100% points, where the medial gastrocnemius activity in those with normal lumbar lordosis was higher than soccer players with lumbar hyperlordosis (Figures 1 and 3).

The activity of lateral gastrocnemius did not significantly differ between the groups(Figures 1).

Quadriceps femoris muscle activity was significantly different during all the phases (9-18%, d= 0.62; 24-31%, d= 1.61; 35-38%, d= 6.04; 42-62%, d= 1.99; 64-84%, d= 0.68) of the SLS so that the activation of quadriceps was lesser in soccer players with lumbar hyperlordosis compared to those with normal lumbar lordosis (Figure 2 and 3).

The hamstring muscle activation was greater in soccer athletes with lumbar hyperlordosis than those with normal lumbar lordosis during initial descent (14-21%, d= -11.98) and final ascent (82-98%, d= -5.37) phases of the SLS (Figure 2 and 3).

Plantar flexor muscles significantly differed during descent (24-28%, d= 8.65) and final ascent (85-100%, d= 4.59) phases of the SLS cycle such that soccer players with lumbar hyperlordosis had a lesser plantar flexor muscle activity compared to athletes with normal lumbar lordosis(Figure 2 and 3).

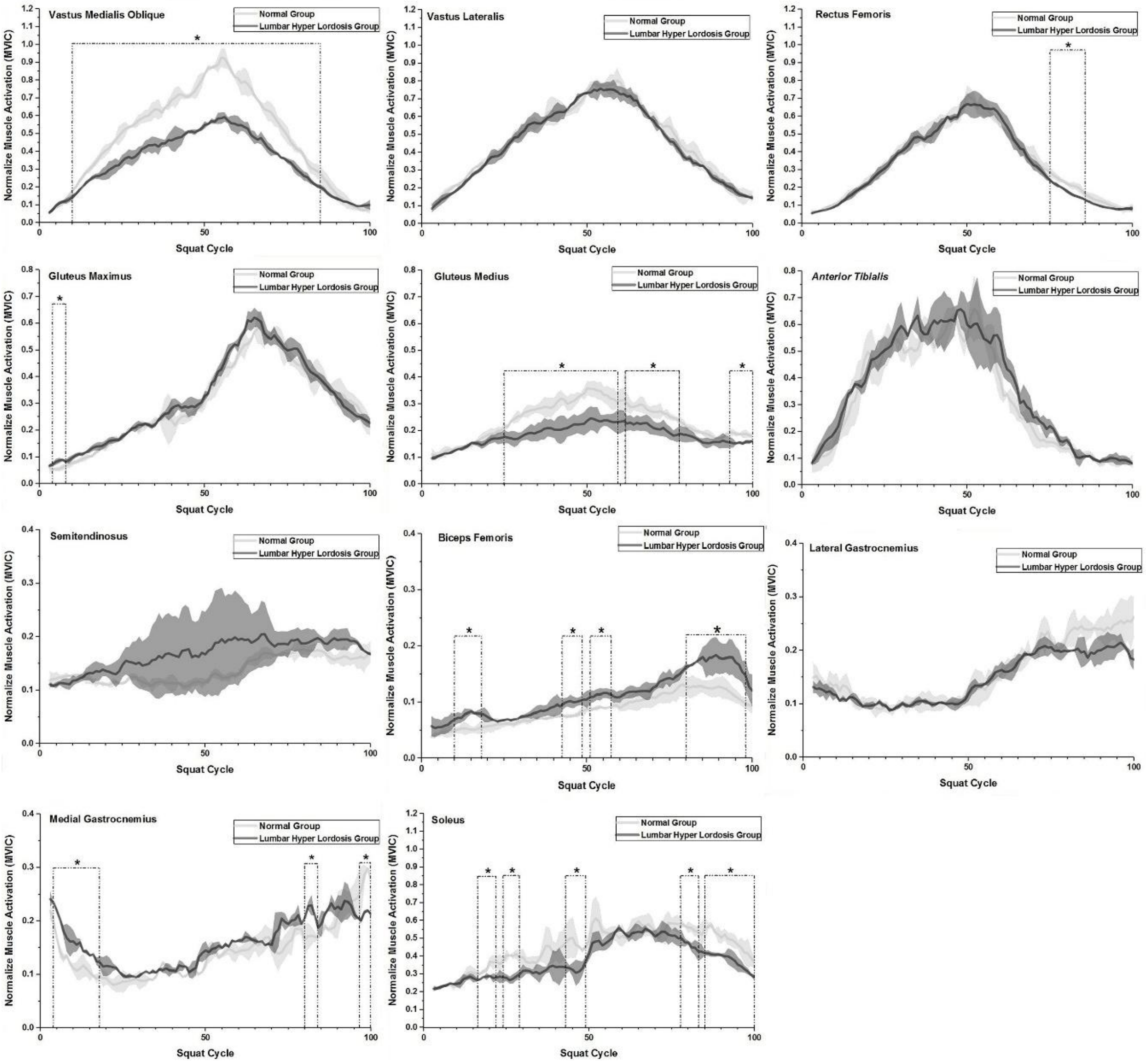

Figure 1. Between-group differences in muscle activation pattern during the single-leg squat task with 90% confidence interval. Ranges that did not overlap in their confidence intervals for more than 3 successive points were significantly different.

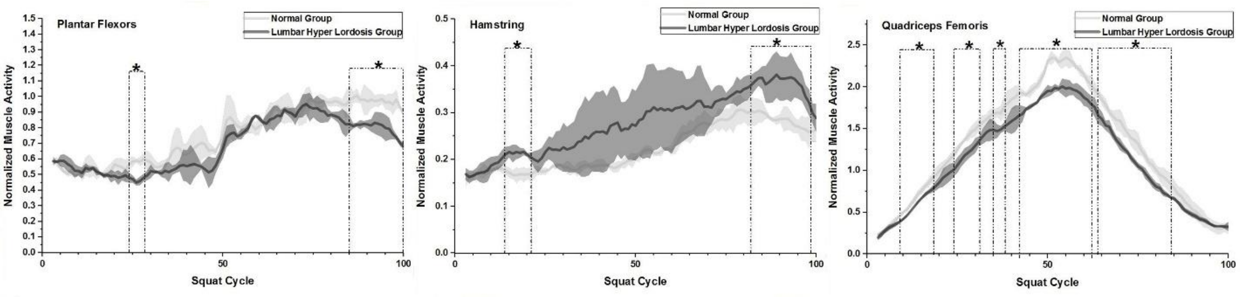

Figure 2. Between-group differences in muscle group activation pattern during the single-leg squat task with 90% confidence interval. Ranges that did not overlap in their confidence intervals for more than 3 successive points were significantly different.

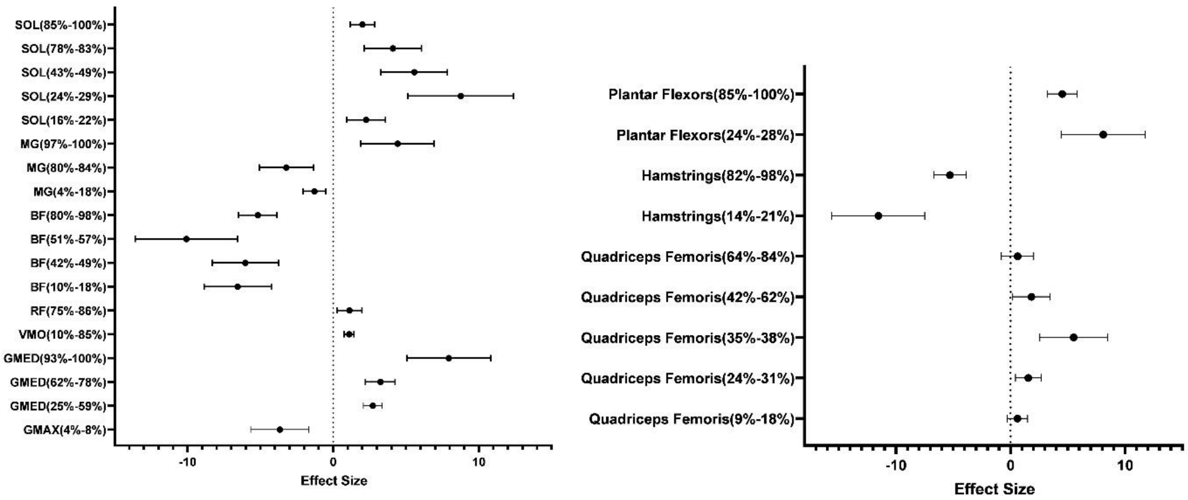

Figure 3. Effect sizes for significant differences betwixt lumbar hyperlordosis and normal lumbar lordosis groups during the single-leg squat task. The horizontal lines demonstrate 95% confidence interval for the effect size. GMAX= Gluteus Maximus, GMED= Gluteus Medius, VMO= Vastus Medialis Oblique, VL= Vastus Lateralis, RF= Rectus Femoris, SEM= Semitendinosus, BF= Biceps Femoris, MG= Medial Gastrocnemius, LG= Lateral Gastrocnemius, and SOL= Soleus.

7.4 Discussion

The purpose of the current study was to determine the comparison of eccentric and concentric lower limb muscle activation patterns in male soccer players with and without lumbar hyperlordosis during the single-leg squat (SLS)performance. Besides, the results of the present study provide interesting, worthwhile information for both sports performance and rehabilitation fields. Our findings demonstrated that activation of quadriceps, hamstrings, gluteal, and plantar flexor muscles were significantly different among soccer athletes with and without lumbar hyperlordosis during the SLS performance.

Behm (1995) stated that neuromuscular adaptation, which occurs in a squat performance, is associated with strength gains [287] . This is particularly true during the ascending phase of the squat when the quadriceps are firing concentrically [288]. In this context, the concentric activation of quadriceps femoris muscle was significantly different among soccer players with and without lumbar hyperlordosis. Specifically, athletes with lumbar hyperlordosis had less quadriceps activity than those with normal lumbar lordosis during the SLS performance. Furthermore, the eccentric activation of quadriceps muscle could impact on the concentric quadriceps performance via a stretch-shortening cycle (SSC) during sports activities, including running [289]. That is, the higher eccentric contraction produces more elastic strain energy, which in turn, could improve the concentric contraction if athletes immediately moves from a stretching phase (eccentric contraction) to a shortening phase (concentric contraction)- known as SSC [289]. During this SSC process, athletes recover the elastic recoil energy from eccentric to concentric muscle contraction. Significantly, soccer athletes with lumbar hyperlordosis had lower eccentric quadriceps activation compared to those with normal lumbar lordosis. Theoretically, it is expected the change in the eccentric quadriceps activation of soccer players with lumbar hyperlordosis could impact on concentric quadriceps contraction when they may have lower eccentric quadriceps activation during soccer-related activities (eg, running). Nevertheless, further study is required to clarify such a hypothesis.

In addition, in spite of statistical significance and moderate effect size, the confidence interval for quadriceps activity from 9-18% of the SLS cycle crosses zero. Hence, little clinical significance can be placed on our findings in that small range of SLS descent. Apart from that, change in lumbar lordosis angle may negatively affect quadriceps activation during the SLS task. Moreover, the role of quadriceps muscles is vital in order to provide knee joint stability. Specifically, Dionisio et al. (2008) reported that the motor unit firing of vastus medialis oblique (VMO) versus the other heads of quadriceps femoris muscles is increased among healthy individuals during the SLS performance [290], thereby it can provide stability for the knee joint. However, the findings of the present study showed that the VMO activity was lesser in soccer players with lumbar hyperlordosis than those with normal lumbar lordosis in both descending and ascending phases of the SLS performance. The alteration of VMO activity not only affects patellofemoral joint stability, but it also alters the biomechanics of patella, which can impact the moment arm of the quadriceps muscle [291].

The activation of hamstring muscle was higher in athletes with lumbar hyperlordosis than those with normal lumbar lordosis. As the hamstrings are biarticular, several studies [292] noted that excessive lumbar lordosis and subsequent increased anterior pelvic tilt is accompanied by increasing hamstring tension. This increased tension impedes further anterior pelvic tilt and shifts the hamstring as a dominant hip extensor instead of gluteus maximus. As such, one would expect more activation of hamstring in athletes with lumbar hyperlordosis. The higher activation of hamstrings in soccer players may result in muscle fatigue during soccer-related activities, potentially leading to hamstrings strain [293]. Higher hamstrings activity brings about overload/fatigue in such muscles during soccer match-play, impairing the ability of the hamstrings to decelerate the lower limb in sports activities, including sprinting [293]. In this regard, several studies [258, 293] have noted that lumbar hyperlordosis may trigger hamstring injuries, so the result of the higher activation of the hamstrings in soccer athletes with lumbar hyperlordosis aligns with such findings. Moreover, hamstring muscle activation could provide stability for the knee joint during the SLS performance because of its protecting function on the anterior tibial shear force, thereby decreasing anterior cruciate ligament (ACL) strain [294, 295]. However, it has been reported hamstring muscle fatigue that may arise from soccer match-play could diminish the control of the anterior tibial translation [296]. Theoretically, therefore, the overactivation of hamstrings in soccer players with lumbar hyperlordosis is expected to reduce the functional knee stability via a decrement in the control of anterior tibial shear force owing to hamstring fatigue. This possible mechanism, in turn, leads to anterior cruciate ligament rupture among soccer athletes as Lotfian et al. (2017) reported ACL rupture among male professional soccer players with lumbar hyperlordosis [257].

Although hamstrings are a dominant hip extensor, the hamstrings cannot control the position of the proximal end of the femur due to not having an attachment to the proximal femur. The result of gluteus maximus activity in the current study showed that soccer players with lumbar hyperlordosis compared to those with normal lumbar lordosis had higher gluteus maximus muscle activity in the initial descending phase of the SLS performance. Hence, it may be the gluteus maximus had a higher activation to counteract the movement of the femur in the acetabulum because lumbar hyperlordosis is expected to be accompanied by excessive femoral internal rotation [259]. Moreover, this result is in agreement with our previous study, where athletes with lumbar hyperlordosis had higher GMAX preactivity and reactivity than those with normal lumbar lordosis during a landing task [266]. Gluteus medius, in addition to gluteus maximus, has an essential function to provide hip stability during SLS performance [276]. In the present study, the activation of gluteus medius was lesser in soccer athletes with lumbar hyperlordosis compared to those with normal lumbar lordosis. In this regard, several studies stated that a decrease in gluteus medius activation is associated with hip adduction [276, 297]. In such a situation, it is expected to alter the demand for lower limb muscle performance during the SLS task.

In the current study, the plantar flexor muscles activation was lesser in soccer players with lumbar hyperlordosis than those with normal lumbar lordosis. In this context, plantar flexor muscle activity not only affects the ankle joint and adjacent segment, but it also impacts on upright posture in the trunk [298]. Quadriceps femoris muscle performance, in addition to plantar flexor, is required during the ascending phase of the SLS to return to the start position. An interesting finding in the present study is both quadriceps and plantar flexor muscles activity were lesser in soccer players with lumbar hyperlordosis than those with normal lumbar lordosis during the ascending phase of the SLS. However, despite statistical significance and a large effect size, the confidence interval for quadriceps activity from 64-84% of the SLS cycle crosses zero. Therefore, little clinical significance can be placed on our findings in that range of SLS ascent. Regardless, the hamstring activity was higher in soccer players with lumbar hyperlordosis compared to those with normal lumbar lordosis. It is expected that higher hamstring activity may compensate for lower activation of both quadriceps and plantar flexor muscles to help to extend the knee joint with hip extension during the ascending phase of the SLS [298].

7.5 Clinical Relevance

Clinicians and researchers should consider lumber hyperlordosis as a contributory factor to the alterations of the lower limb muscsle functions. Specifically, (1) Soccer players with lumbar hyperlordosis had lower eccentric and concentric quadriceps femoris activity than the normal group; (2) Soccer players with lumbar hyperlordosis had lesser GMED activity compared to those with normal lumbar lordosis, whereas they had higher GMAX activity compared to soccer players with normal lumbar lordosis; (3) Soccer players with lumbar hyperlordosis had higher Hamstring activity than the normal group; and (4) Plantar flexor muscle activity was higher in soccer players with normal lumbar lordosis than the hyperlordosis group.

7.6 Limitations

We affirm the current study has some limitations. First, the speed of the SLS exercise during both descending and ascending phases of SLS was not controlled. Also, while proper instruction was given to the athletes to descend in the desired knee flexion angle, the knee flexion angle was not standardized. However, the descending and ascending phases of the SLS were reduced to 50 points to standardize each SLS task according to kinematic data. Finally, the sample size of the present study was low.

7.7 Conclusion

This study highlights that lumbar hyperlordosis alters the lower extremity muscle activation pattern among male soccer players during the SLS. In this vein, quadriceps femoris, plantar flexor, and gluteus medius muscles had a lesser activation in soccer players with lumbar hyperlordosis than those with normal lumbar lordosis. Conversely, both gluteus maximus and hamstring muscles activity were higher in athletes with lumbar hyperlordosis compared to the control group. This alteration may negatively affect muscle performance during the SLS performance. In this vein, further study is demanded to find out whether such an alteration stemming from lumbar hyperlordosis in the lower limb muscles contribute to injury in soccer players and change in athletic performance.

Chapter8: Motor Learning in Response to Different Experimental Pain Models Among Healthy Individuals

8.1 Introduction

Pain is an unpleasant but important perception, in order to attract attention and avoid further damage to the body. However, patients and athletes are often required to learn new movement patterns as part of a rehabilitation program in the presence of pain conditions. While it may be necessary to perform rehabilitation exercise immediately after an injury in order to return to optimal performance, there is concern surrounding the effect of pain on the learning process. It has been reported that pain, as a sensory input, might affect the sensorimotor system leading to changes in motor performance, including redistribution of muscle activation patterns, and a reduction in muscle endurance that is essential for performing dynamic motor skills [299-301]. In this vein, several studies [302-304] demonstrated that pain can give rise to neuroplastic changes in the cortex. However, these neuroplastic changes have been associated with both decreases in motor performance [304] and improvements in motor learning outcomes in response to pain [305].

In order to investigate the influence of pain on the learning process, experimental pain models, including muscle and cutaneous pain, have been used to test its effect on motor learning [299, 303, 305, 306]. Other studies have examined the impact of chronic pain on motor learning [307, 308]. However, chronic pain cannot detect the pure influence of pain on this process, as chronic pain can also be associated with pain-related fear or tissue damage both of which could affect motor learning [300]. Therefore, using only experimental pain models can assist in studying the pure effect of pain on the learning process.

To date, although many studies [299, 302, 303, 305, 306, 309-311] have examined the effect of experimental pain models on motor learning; they have provided contradictory findings. For example, some studies have suggested that acute cutaneous pain models improve motor learning acquisition [302, 303] and retention [302], whereas Bilodeau and colleagues (2016) applied a similar experimental pain model and demonstrated no alteration in the learning process [310]. Bouffard and colleagues (2016) also reported no alteration in motor performance in response to a similar experimental pain induction while those who experienced pain indicated distinct motor strategies compared to participants without pain performing a similar task [312].

Despite the growing literature on the knowledge of the learning process in the presence of experimental pain models, there has been no systematic study reviewing this literature. Considering the contradictory results related to motor learning during pain, it is important to synthesize and critically assess the studies on motor learning to assess experimental pain models. This information will help to a better understanding of the effect of pain on skill learning acquisition and retention, which is important for developing sport training and rehabilitation programs. Hence, the aim of the current study is to systematically review the research outputs that have examined the effect of experimental pain models (including muscle pain and cutaneous pain) on motor learning (including motor adaptation, motor performance and motor strategy, but not neuroplasticity) among healthy human participants.

8.2 Methods

This systematic review was reported based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [313] and the protocol of the current review was registered in The International Prospective Register of Systematic Reviews (PROSPERO), registration number is CRD42020211489 [314]. A preprint of the present review is available on Medrxiv [315].

8.2.1 Search Strategy

Electronic databases (PubMed, Web of Science, and Embase) were used to search the literature up to April 2021. A combination of free-text terms and MeSH terms regarding motor learning (including retention) and experimental pain was applied (see supplementary material section). Search strategies of relevant systematic reviews [300, 316] were also checked in order to carry out an elaborate strategy. In addition, references of included studies were hand-searched to detect all pertinent studies, as well as the citations of the included studies were checked via Google Scholar.

8.2.2 Eligibility Criteria

All studies that have the following criteria were included in this systematic review: (1) results of research from healthy human subjects; (2) experimental pain was induced in order to detect the effect of pain on the learning process; (3) original research with full text written in the English language; and (4) all study designs other than all types of reviews, meta-analysis, letter to editors, and theses. Studies that induced pain that can result in structural tissue damage, including pain with eccentric exercise and ischemia, were excluded from this study.

8.2.3 Study Selection

Extraction of studies was performed by one reviewer, after which two authors independently reviewed retrieved titles and abstracts after removing duplicates. In the title and abstract screen phase, the two reviewers discussed any dispute regarding mismatch between their selections, and the full-text of any studies that were not agreed to be removed were considered for assessment in the second phase. Full-text was also reviewed by the two reviewers to ensure that studies were selected in accordance with the inclusion and exclusion criteria. In the case of disagreement between the two authors surrounding the inclusion or exclusion of a study in the full-text screen phase, the issue was resolved through consultations with a third reviewer. The two reviewers agreed on 3058 studies at the title and abstract screening stage, in which the full-text of 16 studies were directly agreed upon for full text screening. Discussion on a further 17 studies was done, out of which an additional 10 studies were selected to screen full-text. This resulted in 26 studies total for the full-text screening. Out of this number, twenty-one studies were agreed between the two reviewers at the full-text screening stage. The third reviewer consulted on the 5 other studies.

8.2.4 Data Collection and Synthesis

In order to collect data, a standard form was used so that the following information was included in a table: (1) pain characteristics (location (i.e. the segment of pain induction), type, and intensity (i.e. mean pain)); (2) outcome variables (i.e. parameters that were used to assess learning); (3) test protocol; (4) general information about characteristics of subjects; and (5) main results. One author gathered the mentioned data from all included studies and another author checked the collected data to decrease error and bias in data collection. A narrative synthesis was also applied to describe the collected data, which were categorized into cutaneous pain, muscle pain, and tongue pain. Furthermore, it was determined that it was not feasible to conduct a meta-analysis because of a methodological heterogeneity among the included studies. A qualitative synthesis, therefore, was considered for the current review.

8.2.5 Quality Assessment

Two authors independently assessed the quality and bias of all included studies based on a modified version of the checklist for measuring the quality of RCTs (randomised controlled trials) and non-RCTs written by Downs and Black [221, 317]. In the modified version of the checklist, item 27 (power) was changed from 0-5 to 0 or 1 so that a study was scored 1 if the study reported a statistical power ≥ 80%; otherwise, it received 0 [317], so that the overall score of the checklist changed from 32 to 28. The quality of included studies was divided into the following four levels: excellent (26-28), good (20-25), fair (15-19), and poor (≤14) [318]. Inter-rater reliability for the qualitative items was also measured by using the Kappa correlation coefficient between the two reviewers.

8.3 Results

8.3.1 Study identification

A total of 3500 articles were generated via electronic databases. The titles and abstracts of 3075 studies were screened after removing 425 duplicates. The full text of 26 studies [299, 302-306, 310-312, 319-335] were assessed in agreement with the inclusion and exclusion criteria in which only 16 studies [299, 302-306, 310-312, 319-325] were included in this review. Finally, one study [336] was added through a hand-searching of the citations of the relevant studies through Google Scholar; thus, 17 studies were included in this review (Figure 1).

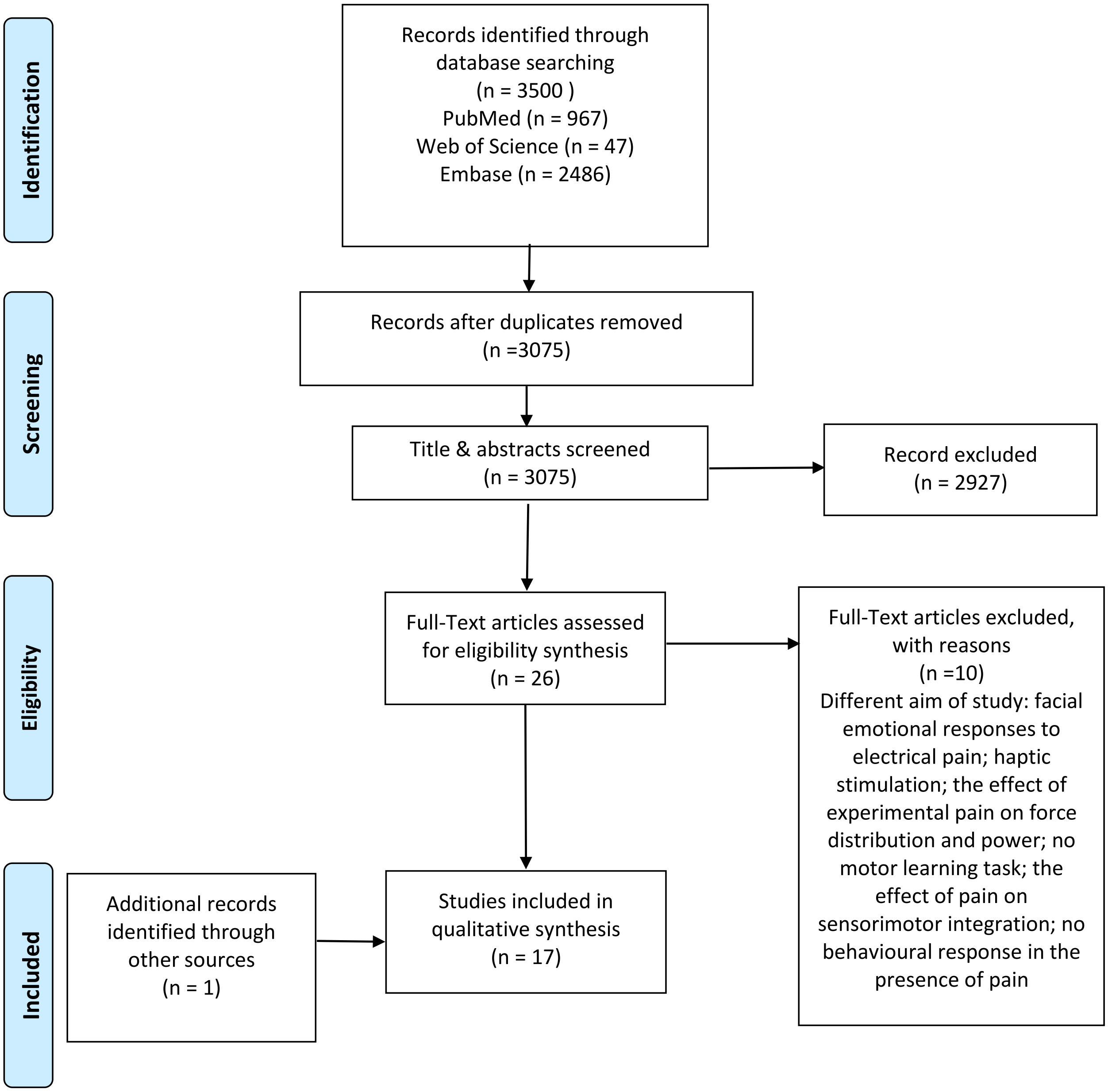

Figure 1. Flowchart of study selection process

8.3.2 Study characteristics

A total of 484 healthy participants were included across all studies with the ages ranging between 18 and 47 years. Out of the seventeen studies, Arieh and colleagues [319] included only male participants, but both male and female participants were included in the other sixteen studies [299, 302-306, 310-312, 320-325, 336]. Extensive information concerning each study is represented in Table 1.

Table 1. study characteristics

Authors (yrs)	Participants	Pain Characteristics	Testing Procedure	Outcome Measures	Main Results
Arieh et al (2021)	Healthy (N=30, f=0) (remote pain, local pain, and control group, N=10), age: 18-25 yrs	Capsaicin gel to the outer side of the elbow 5 cm (local pain); capsaicin gel to the upper part of the knee joint (remote pain); severity of pain was 7- measuring by VAS	Dart-throwing skill during acquisition (with pain) and retention (without pain) (1 h, 24 h, and 1 w) phases	Coordination variability pattern during throwing in both acquisition and retention phases (maximum wrist flexion range, maximum elbow extension range, shoulder angular displacement range, angular throw velocity, and throw duration)	No sig effect of pain on dart-throwing learning
Bilodeau et al (2016)	Healthy (N=45) (remote pain N=15, f=10, age: 28.5 ± 9.5 yrs); (local pain N=15, f=10, age: 27.4 ± 7.1 yrs); and (control group N=15, f=10, age: 28.8 ± 8.8 yrs)	Thermode 3×3 cm (heat pain) before acquisition phase to the dorsal part of the left wrist (local pain) and the external part of the left leg below the knee joint (remote pain); severity of pain was measured- measuring by NPRS	Finger-tapping task (reproducing the sequence 4-1-3-2-4) during 30s	Error rate and speed of tapping sequences during baseline, post-immediate, post-60 min, and post-24 h (retention)	No sig effect of tonic pain on the acquisition and retention of finger-tapping task
Bouffard et al (2014)	Healthy (N=30) (pain group N=15, f=8, age: 26.0 ± 1.4 yrs); (control group N=15, f=7, age: 26.1 ± 2.1 yrs)	Capsaicin gel around the ankle prior to acquisition phase; severity of pain was moderate- measuring by NPRS	Walking task in the presence of a force field adaptation paradigm in two days (acquisition (baseline 1, baseline2, adaptation, and wash-out) and retention (baseline, adaptation, and wash-out))	A movement error signal that was made based on the ankle angular displacement	Sig effect of tonic pain on the retention phase of a locomotor task, while no sig change in the acquisition phase of gait
Bouffard et al (2016)	Healthy (N=37) (pain group N=13, f=8, age: 26.1 ± 1.15 yrs);	Capsaicin gel around the ankle between Baseline 1 and Baseline 2 in the	Walking task in the presence of a force field	A mean absolute error, which was created based on	No sig effect of cutaneous pain on total

	(control group N=24, f=10, age: 25.8 ± 0.85 yrs)	first day and prior to baseline in the second day; severity of pain was 5.6 ± 0.7 in Day 1 and 5.5 ± 0.7 in Day 2- measuring by NPRS	adaptation paradigm in two days (acquisition (baseline 1, baseline2, adaptation, and wash-out) and retention (baseline, adaptation, and wash-out))	the ankle kinematics, and tibialis anterior ratios that showed TA muscle activation in the adaptation phase relative to baseline	motor performance during both acquisition and retention phases
Bouffard et al (2018)	Healthy (N=47) (pain group N=17, f=7, age: 25 ± 1 yrs); (control group N=30, f=14, age: 25 ± 1 yrs)	Hypertonic saline to the tibialis anterior muscle prior to baseline 1 in the first day; the intensity of pain was 5.3 ± 1.2 out of 10- measuring by NPRS	Walking task in the presence of a force field adaptation paradigm in two days (acquisition (baseline 1, baseline2, adaptation, and wash-out) and retention (baseline, adaptation, and wash-out))	A mean absolute error, which was created based on the ankle kinematics; relative timing of ankle error; tibialis anterior ratios that showed TA muscle activation in the adaptation phase relative to baseline	No sig effect of muscle pain on total motor performance during both acquisition and retention phases
Dancey et al (2016)	Healthy (N=24) (pain group N=12, f=8, age: 20.8 ± 3.3 yrs); (control group N=12, f=6, age: 22.8 ± 2 yrs)	Capsaicin gel for pain group and topical cream for the control group in the lateral part of the right elbow; pain intensity average was above 4- measuring by NPRS	Tracing sequences of sinusoidal pattern waves with various amplitudes and frequencies using the thumb in four phases (pre-acquisition, acquisition, post-acquisition, and retention (24-48 h later))	Motor error which showed the average distance of subjects' effort trace from the displayed sinusoidal wave	An improvement in motor learning in response to cutaneous pain
Dancey et al (2016)	Healthy (N=48) (experiment 1 (N=24; pain group N=12, f=7, age: 20.8 ± 3.3 yrs; control group N=12, f=6, age: 22.8 ± 2 yrs) (experiment 2 (N=24; remote pain group N=12, f=7, age: 21.8 ± 3.3 yrs; local pain group N=12, f=7, age: 22.9 ± 4.3 yrs)	Capsaicin gel for pain group and topical cream for control group, remote pain and control pain in the lateral part of the dominant elbow and local pain in the Abductor Pollicis Brevis muscle area; pain intensity average was approximately 6 during post-motor learning- measuring by NRPS	A repetitive typing task	Response time and accuracy during a typing task at the begging and end of the motor acquisition and 48 h later (motor learning retention)	An improvement in motor learning retention in the presence of local pain; improved motor performance in the baseline in the presence of acute pain
Dancey et al (2018)	Healthy (N=36) (local pain group N=12, f=8, age: 21.2 ± 2.2 yrs); (remote pain group N=12, f=8, age: 20.3 ± 2.5 yrs); (contralateral pain	Capsaicin gel for pain group in which remote and contralateral pain in the lateral part of the dominant and non-dominant elbow, respectively; local pain in the Abductor Pollicis	Tracing sequences of sinusoidal pattern waves with various amplitudes and frequencies using thumb in	Motor error which showed the average distance of subjects' effort trace from the displayed sinusoidal wave	No sig effect of pain location on motor learning acquisition and retention

	group N=12, f=8, age: 21.4 ± 2.4 yrs)	Brevis muscle area; pain intensity average was evaluated- measuring by NPRS	four phases (pre-acquisition, acquisition, post-acquisition, and retention (24-48 h later))		
Dancey et al (2019)	Healthy (N=24) (pain group N=12, f=9, age: 19.9 ± 0.9 yrs); (control group N=12, f=9, age: 20.7 ± 1.4 yrs)	Capsaicin gel for pain group and topical cream for control group in the lateral part of the dominant elbow; pain intensity average was above 4- measuring by NPRS	Tracing sequences of sinusoidal pattern waves with various amplitudes and frequencies using the thumb in four phases (pre-acquisition, acquisition, post-acquisition, and retention (24-48 h later))	Mean motor error which showed the average distance of subjects' effort trace from the displayed sinusoidal wave	An improvement in motor performance in the presence of tonic pain
Lamothe et al (2014)	Healthy (N=29) (pain group N=15, f=7, age: 25.8 ± 4.1 yrs); (control group N=14, f=8, age: 26.6 ± 4.8 yrs)	Capsaicin gel for pain group above the elbow between two baseline in the first day; pain intensity average was 7.8 ± 0.9 at the initiation of baseline 2- measuring by NPRS	A reaching task in the presence of force field adaptation in four phases (baseline1, baseline2, acquisition, and retention (24h))	Final error and the initial range of deviation	No sig effect of tonic pain on baseline reaching performance; a larger final error in the pain group than the control group during both acquisition and retention
Mavromatis et al (2017)	Healthy (N=30) (pain group N=15, f=6, age: 26 ± 6 yrs); (control group N=15, f=6, age: 27 ± 6 yrs)	Capsaicin gel for pain group around the lateral part of the first metacarpal after the first TMS baseline measurement; pain intensity average was above four at the training blocks- measuring by NPRS	A modified version of the sequential visual isometric pinch task in three phases (baseline 1, baseline 2, and acquisition)	Movement time, accuracy, and a skill measure	No sig effect of cutaneous pain on motor skill acquisition
Dancey et al (2014)	Healthy (N=24) (pain group N=12, f=7, age: 24.5 ± 6.6 yrs); (control group N=12, f=6, age: 23.4 ± 2 yrs)	Capsaicin gel for pain group and topical cream for control group in the lateral part of the right elbow; pain intensity average was 5 in the post-application phase-measuring by NPRS	A repetitive typing task applying the middle three fingers	Motor training accuracy; reaction time	An improvement in motor performance in the presence of tonic pain
Ingham et al (2011)	Healthy (N=9, f=2, age: 24 ± 1.1)	Hypertonic saline for pain group; remote pain in the infrapatellar fat pad of the knee and local pain in the FDI; pain intensity average was 0.2 ± 0.4 (vehicle control), 1.7 ± 1 (FDI pain) and 2.1 ± 1.6	A quick movements of finger (the right index finger) adduction	Training performance based on peak acceleration of index finger movement	No sig effect of pain on motor performance

		(remote pain)- measuring by NRS			
Salomoni et al (2019)	Healthy (N=22) (pain group N=11, f=7, age: 24.5 ± 6.6 yrs); (control group N=11, f=5, age: 23.4 ± 2 yrs)	Hypertonic saline to the anterior deltoid muscle prior to baseline 2 and before the force field 1 in the first day; the intensity of pain was 4.2 ± 0.3 (out of 10) in the first injection and 3 ± 0.4 in the second injection- measuring by NPRS	A reaching task in the presence of force field adaptation in six phases (baseline1, baseline2, force field 1, force field 2, washout 1, force field 2 and washout 2)	Movement accuracy based on the peak perpendicular error and the peak hand velocity; muscle activity of anterior and posterior deltoid, biceps brachii, triceps brachii, and pectoralis major	No sig effect of pain on the final performance; experimental pain group used different strategies to perform the same task compared to the control group
Boudreau et al (2007)	Healthy (N=9, f=2, age: 24 ± 1.1)	Capsaicin gel for pain group and vehicle cream for the control group to the tongue; pain intensity average was between 4 and 6 during the task- measuring by VAS	A tongue-protrusion task	A performance score based on the time that participants kept the cursor within the target box	A sig and negative effect of pain on the overall performance score
Boudreau et al (2010)	Healthy (N=26) (lidocaine group N=9, f=6, age: 24.6 ± 1.1 yrs); (control group N=9, f=3, age: 24 ± 3.5 yrs); (capsaicin group N=8 f=2, age: 23 ± 2.5 yrs)	Capsaicin and lidocaine gels for pain groups and vehicle cream for the control group to the dorsum of the tongue before the first task; pain intensity was maintained above 4- measuring by NRS	A tongue-protrusion task	(Overall, a tongue-task trial, initial, within-session gains) motor performance	A sig decrease in motor performance in the pain groups than the control group
Gallina et al (2018)	Healthy (N=14, f=7, age: 18-47)	Hypertonic saline to the infrapatellar fat pad, distal vastus medialis, proximal vastus medialis, and vastus lateralis; the intensity of pain was approximately 3 in four different pain locations- measuring by NRS	Isometric knee extension contraction	Muscle activation of VMO, VL, and RF; isometric knee extension force	A sig alteration in both muscle activation and knee extension force in response to different locations of pain

Abbreviations: f female, yrs years, VMO vastus medialis oblique, VL vastus lateralis, RF rectus femoris, sig significant, VAS visual analogue scale, NRS numerical rating scale, TMS transcranial magnetic stimulation, FDI first dorsal interosseus

8.3.3 Methodological quality

The methodological quality of the included studies was assessed based on the modified version of Downs and Black checklist, which is provided in Table 2. Out of 17 studies, eleven studies [302, 303, 305, 306, 310-312, 321, 323, 325, 336] were evaluated as fair quality and 6 articles as poor quality [299, 304, 319, 320, 322, 324]. Inter-rater reliability was 0.72 between the assessors who evaluated the methodological quality of the included articles. Some of the items in the Downs and Black checklist may either be difficult for experimental studies on pain in motor learning to be assessed positively (e.g. item 13) or are often not reported in these experimental studies (e.g. items 11, 12, 19).

Table 2. Quality Assessment of the Included Studies

First Author (Year)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**Tot.**
Arieh (2021)	1	1	1	1	1	1	1	0	0	1	U	U	0	U	U	1	1	1	U	1	U	1	1	U	0	U	0	14
Bilodeau (2016)	1	1	1	1	2	1	1	0	0	1	U	U	0	U	U	1	1	1	U	1	U	1	1	U	0	U	0	15
Bouffard (2014)	1	1	1	1	1	1	1	0	1	1	U	U	0	U	U	1	1	1	U	1	U	1	1	U	0	U	0	15
Bouffard (2016)	1	1	1	1	1	1	1	0	1	1	U	U	0	U	U	1	1	1	U	1	1	1	1	U	0	U	0	16
Bouffard (2018)	1	1	1	1	1	1	1	0	0	1	U	U	0	U	U	1	0	1	U	1	0	0	U	U	0	U	0	11
Dancey (2016)	1	1	1	1	1	1	1	0	0	1	U	U	0	1	U	1	1	1	U	1	1	1	U	U	0	U	0	15
Dancey (2016)	1	1	1	1	1	1	1	0	0	1	U	U	0	1	U	1	1	1	U	1	1	1	U	U	0	U	0	15
Dancey (2018)	1	1	1	1	1	1	1	0	0	1	U	U	0	U	U	1	1	1	U	1	1	1	1	U	0	U	1	16
Dancey (2019)	1	1	1	1	1	1	1	0	0	0	U	U	0	1	U	1	1	1	U	1	1	1	1	U	0	U	0	15
Lamothe (2014)	1	1	1	1	1	1	1	0	1	1	U	U	0	U	U	1	1	1	U	1	U	1	U	U	0	U	0	14

Mavromatis (2017)	1	1	1	1	1	1	1	0	0	1	U	U	0	U	U	1	1	1	U	1	U	1	1	U	0	U	0	14
Dancey (2014)	1	1	1	1	1	1	1	0	0	1	U	U	0	1	U	1	1	1	U	1	1	1	1	U	0	U	0	16
Ingham (2011)	1	1	1	1	1	1	1	0	1	1	U	U	0	U	U	1	1	1	U	1	U	1	1	U	0	U	0	15
Salomoni (2019)	1	1	1	1	1	1	1	0	0	1	U	U	0	1	U	1	1	1	U	1	0	1	1	U	0	1	0	16
Boudreau (2007)	1	1	1	1	0	1	1	0	0	1	U	U	0	1	U	1	U	1	U	1	U	U	1	U	0	U	0	12
Boudreau (2010)	1	1	1	1	2	1	1	0	0	1	U	U	0	1	U	1	1	1	U	1	0	0	1	U	0	U	0	15
Gallina (2018)	1	1	1	1	1	1	1	0	0	1	U	U	0	1	U	1	U	1	U	1	0	U	1	U	0	U	0	13

Abbreviations U, unable to determine; 1, yes; 0, no. (For item 5)- 0, no; 1, partially; 2, yes.

Downs and Black Checklist items: Reporting ((1) Is the hypothesis/aim/objective of the study clearly described?; **(2)** Are the main outcomes to be measured clearly described in the Introduction or Methods section?; **(3)** Are the characteristics of the patients included in the study clearly described ?; **(4)** Are the interventions of interest clearly described?; **(5)** Are the distributions of principal confounders in each group of subjects to be compared clearly described**?**; **(6)** Are the main findings of the study clearly described?; **(7)** Does the study provide estimates of the random variability in the data for the main outcomes?; **(8)** Have all important adverse events that may be a consequence of the intervention been reported?; **(9)** Have the characteristics of patients lost to follow-up been described?; **(10)** Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?**); External validity ((11)** Were the subjects asked to participate in the study representative of the entire population from which they were recruited?; **(12)** Were those subjects who were prepared to participate representative of the entire population from which they were recruited?; **(13)** Were the staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive?**); Internal validity – bias ((14)** Was an attempt made to blind study subjects to the intervention they have received?; **(15)** Was an attempt made to blind those measuring the main outcomes of the intervention?; **(16)** If any of the results of the study were based on “data dredging”, was this made clear?; **(17)** In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls ?; **(18)** Were the statistical tests used to assess the main outcomes appropriate?; **(19)** Was compliance with the intervention/s reliable?; **(20)** Were the main outcome measures used accurate (valid and reliable)?**); Internal validity - confounding (selection bias) ((21)** Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?; **(22)** Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time?; **(23)** Were study subjects randomised to intervention groups?; **(24)** Was the randomised intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?; **(25)** Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?; **(26)** Were losses of patients to follow-up taken into account?); **(27) Power:** Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?

8.3.4 Cutaneous pain

Eleven studies [299, 302-306, 310-312, 319, 323] applied capsaicin gel, resulting in cutaneous pain, to understand the effect of acute pain on motor learning. There was no consensus surrounding the effect of cutaneous pain on motor learning among these studies. Specifically, five studies [304, 310, 312, 319, 323] reported no significant change in motor performance in response to acute pain; however, some of them indicated alterations in the constructs of learning [312, 319]. In contrast, six studies [299, 302, 303, 305, 306, 311] demonstrated a statistically significant influence of cutaneous pain on motor learning. Each of the studies measured different motor learning variables applied during different motor tasks to study the effect of pain. In this context, Dancey and colleagues carried out a series of studies [302, 303, 305, 306, 323] to reveal the role of cutaneous pain on motor learning during typing and tracing series of sinusoidal patterns. The results of their studies show a statistically significant and positive influence of the experimental pain on skill acquisition learning [302, 303, 305, 306] and retention [302, 306]. While one study demonstrated that local pain improved retention of learning compared to remote pain [302], another study did not observe any significant effect on motor learning variables in response to different pain locations (remote, local, or contralateral) [323]. Two studies that used finger-tapping [310] and sequential visual isometric pinch [304] tasks to show the effect of cutaneous pain on motor learning found no significant differences in the pain group compared to the control group for both motor learning acquisition [304, 310] and retention [310]. In addition, while Lamothe et al. (2014) indicated a significant improvement in motor performance in both control and pain groups during a new reaching adaptation task, the pain group demonstrated a larger final error to perform the same task compared to the control group in both acquisition and retention phases [299]. Bouffard et al. (2014) revealed a significant decrease in the performance during the retention test of motor in the experimental cutaneous pain group during a novel locomotor adaptation task, with no difference between the groups during the initial learning [311]. In a related study [312], they did not observe any considerable difference in either the learning or the retention of the new locomotor task, but in this study the capsaicin gel was applied in both the learning and retention tests. However, Bouffard and colleagues (2016) found that participants had a different pattern of kinematic errors in the presence of pain during walking (Table 3). Finally, Arieh et al. (2021) demonstrated no significant difference in movement accuracy in both acquisition and retention phases of motor learning in response to the experimental pain during dart-throwing skill [319]. Nevertheless, participants in the pain group showed different coordination patterns in the shoulder-elbow and elbow-wrist joints to perform the task even one week later (Table 3).

Table 3. synthesized results of the included studies

Authors	Type of pain	Motor performance	Motor strategies
Arieh et al (2021)	Cutaneous pain	No change in acquisition and retention phases	Change in coordination patterns
Bilodeau et al (2016)	Cutaneous pain	No change in acquisition and retention phases	No report
Bouffard et al (2014)	Cutaneous pain	No change in acquisition but a decrease in retention phase	No report
Bouffard et al (2016)	Cutaneous pain	No change in acquisition and retention phases	Change in a pattern of kinematic errors
Bouffard et al (2018)	Muscle pain	No change in acquisition and retention phases	Change in feedforward strategies
Dancey et al (2016)	Cutaneous pain	An increase in acquisition and no change in retention phases	No report
Dancey et al (2016)	Cutaneous pain	An increase in acquisition and retention phases	No report
Dancey et al (2018)	Cutaneous pain	No change in acquisition and retention phases regarding pain location (local pain Vs remote pain)	No report
Dancey et al (2019)	Cutaneous pain	An increase in acquisition and retention phases	No report
Lamothe et al (2014)	Cutaneous pain	A decrease in acquisition and retention phases	larger final error to perform a reaching task
Mavromatis et al (2017)	Cutaneous pain	No change in the acquisition phase	No report
Dancey et al (2014)	Cutaneous pain	An increase in the acquisition phase	No report

Ingham et al (2011)	Muscle pain	No change	No report
Salomoni et al (2019)	Muscle pain	No change	Change even after the resolution of pain
Boudreau et al (2007)	Tongue pain	A decrease in total performance	No report
Boudreau et al (2010)	Tongue pain	A decrease in total performance	No report
Gallina et al (2018)	Muscle pain	Change in total performance	Change in muscle activation pattern

8.3.5 Tongue pain

Boudreau and colleagues [320, 321] applied capsaicin gel to the tongue. The result of their studies revealed a significant negative influence of experimental cutaneous pain on overall motor performance during a tongue-protrusion task in a single day of training.

8.3.6 Muscle pain

Four studies [322, 324, 325, 336] evaluated motor learning by injecting hypertonic saline, resulting in muscle pain, during different tasks. All studies revealed no significant effect of experimental muscle pain on motor performance. Specifically, Bouffard and colleagues (2018) did not observe any statistically significant change in acquisition and retention of a novel locomotor adaptation task in response to the experimental pain [322]. However, motor strategies were different in those who experienced pain compared to the control group such that subjects with pain less depended on feedforward strategies than subjects without pain (Table 3). Ingham et al. (2011) also demonstrated no significant effect on motor learning in a finger adduction task in which muscle pain was applied in different locations. While Salomoni and colleagues (2019) did not observe any statistically significant alteration in final motor performance in the pain group compared to the control group during a reaching adaptation task, those who experienced the experimental muscle pain applied a distinct strategy to perform the task in comparison with the control group [336]. The experimental group also produced the same strategy in the next day in the absence of pain. A similar result was found by Gallina and colleagues in which the muscle pain location produced lasting changes in the muscle activation pattern during an isometric knee extension contraction task [324].

8.4 Discussion

The aim of the current study was to understand the effect of acute pain on motor learning among healthy individuals. Inconsistent results have been reported surrounding this topic in the literature; however, most of these studies are in agreement with the negative consequences of acute pain in the learning process. Moreover, while some studies did not demonstrate any significant effect of experimental pain on skill learning acquisition and retention, they indicated those who experienced pain produced a distinct strategy to perform the novel task compared to control groups such that the participants displayed the same strategy in pain resolution even after one week.

Learning new movement patterns is an integral part of sport and rehabilitation [337], while pain can give rise to alterations in the learning process. Results of the studies that have examined the effect of experimental pain on motor learning corroborate the role of acute pain on changes in the learning process; however, the studies demonstrated contradictory findings. Specifically, a series of investigations by Dancey and colleagues [302, 303, 305, 306] revealed a positive and statistically significant effect of cutaneous pain on the learning process. It has been suggested that pain can lead to an increase in attention while performing a dynamic task thereby those who experience pain can execute a function with lesser errors than no pain condition [302, 338]. In this context, Dancey and colleagues reported an improvement in skill learning acquisition and retention in the presence of experimental pain because of attention mechanism, in which local pain brought about a better overall motor performance compared to remote pain [302, 303, 305, 323]. It was argued that local pain may result in more attention to the part of the body (i.e. internal attention) underlying learning [302], which in turn can lead to more changes in cortical neuroplasticity

[339], and subsequently improve in the learning of motor tasks. However, a recent study [340] indicated that external attention can engender more accuracy and better performance in comparison to internal attention, including performing a task in the presence of pain. Whereas Mavromatis and colleagues [304] applied a similar experimental pain model compared to the work of Dancey [302, 303, 305, 323], they did not observe any significant effect of acute pain on the skill learning acquisition. However, the training-related alterations in corticospinal excitability were showed a similar result to Dancey's study in the presence of cutaneous pain [304]. In contrast to the previous studies, Boudreau and colleagues [320, 321] reported a significant negative influence of cutaneous pain on overall performance scores. While all of these studies applied a similar experimental tonic pain, the studies used a range of tasks to understand the effect of pain on motor learning which might explain some of the differences in the findings. In particular, different motor tasks and different types of learning depend on different brain mechanisms and brain areas [341, 342]. These differences may actually be one of the major reasons why we find inconsistent results of the effect of pain on motor learning [310]. For example, force field adaptation and sequence learning tasks can rely on cortico-cerebellar and cortico-striatal plasticity, respectively [343]. Similarly, Seidler and colleagues found large differences in brain activation even within a similar task; where performance with smaller errors during movements to large easy to reach targets were associated with greater activation in the contralateral primary motor cortex, premotor cortex and the basal ganglia, and larger errors during movements to small targets associated with greater activation in the ipsilateral motor cortex, insular cortex, cingulate motor area, and multiple cerebellar regions [344]. That is, variations in the task difficulty (e.g. target size) can influence the degree of feedforward relative to feedback control that contributes to the task performance, and therefore the specific brain areas involved. It is very likely that the different circuitry and adaptation mechanisms involved in different motor tasks have different reactions to painful stimuli.

While the studies that applied cutaneous pain to evaluate motor learning revealed contradictory results, most research examining experimental muscle pain on motor learning outcomes found no significant effect on motor performance while revealing alterations in motor strategies [322, 325, 336]. Indeed, it has been reported that these two experimental pain models interact distinctly with neural processes that are responsible for motor adaptation [345], which in turn can lead to observe different results in skill learning acquisition and retention in response to cutaneous or muscle pain models. This distinction between cutaneous and muscle pain models was particularly clear in a series of studies by Bouffard and colleagues [311, 312, 322] demonstrating motor learning outcomes in response to experimental muscle and cutaneous pain models during a locomotor adaptation task. Specifically, there was no alteration in skill learning acquisition or retention in the presence of experimental muscle pain [322]. However, they did find a statistically significant reduction in retention (but not acquisition) of the same test in the presence of the cutaneous pain model [311]. However, a follow-up study showed that cutaneous pain had no effect on either the acquisition or the retention as long as this pain was also applied during the test for retention [312]. That is, it appeared that the cutaneous pain acted as a contextual signal for the selection of the newly learned locomotion model [312], similar to the manner that visual, proprioceptive and vestibular signals can be used to learn and recall different motor memories [346-348]. Although no considerable influence of cutaneous pain on motor performance or motor learning was shown, Bouffard and colleagues reported that participants in the pain group produced a distinct strategy compared to the control group to perform a locomotion task. Specifically, they found that participants had a different pattern of kinematic errors in the presence of pain during walking suggesting the pain group used less predictive compensation (anticipatory strategies) for the changes in the task [312]. This finding was supported by several other studies [319, 322, 336] which found participants exposed to experimental pain expressed a different strategy for motor adaptation compared to control participants despite no significant change in overall motor performance in the skill learning acquisition and retention. Notably, Salomoni et al. (2019) found that participants who experienced experimental muscle pain produced less co-contraction and muscle activation of the elbow and shoulder muscles compared to the pain-free control group during a reaching task, and this distinct motor strategy was continued on the next day (retention) despite the pain no longer being present. This smaller muscle co-contraction could potentially reduce joint stability in the coordination of musculoskeletal system [349, 350] and subsequently increase the potential for musculoskeletal injuries during sport training and rehabilitation [351]. Arieh and colleagues (Arieh et al., 2021) also showed a similar motor performance in response to experimental pain compared to the control group during dart-throwing skill; however, participants in the pain group showed different coordination patterns in the shoulder-elbow and elbow-wrist joints to perform the task even one week later. These different movement patterns may be a strategy to decrease pain while still performing the motor adaptation task, as suggested by Hodges and Tucker [301], in which pain affects the redistribution of activity within and between muscles [352, 353] to perform a motor task with a pain-free movement pattern. While this mechanism might be used to reduce pain during the learning process, such an alteration could potentially be associated with repercussions for the health condition of joints over longer time periods. That is, redistribution of muscle function can bring about changes in natural biomechanics of the joints by increasing joint load [301]. These changed patterns of muscle activation or joint coordination can then persist over long periods of time either due to use-dependency [342, 354, 355] or because the adaptation process resulted in local minimum of the solution space [355].

8.5 Limitations and Recommendations

The results of the present systematic review need to be interpreted with the consideration of the following methodological issues. In terms of experimental pain models, the International Association for the Study of Pain has suggested considering sex and gender differences in pain investigations [356] since women exhibit higher pain sensitivity in response to numerous pain conditions compared to men (for review, see

[357, 358]). Despite this, none of the included studies [299, 302-306, 310-312, 319-325, 336] reported sex differences in motor learning outcomes in response to experimental pain models. Hence, it can be difficult to exclusively generalize the findings of the current systematic review to each sex and gender. As a result, it is recommended that further studies specify the influence of experimental pain modalities on motor adaptation and performance in regard to sex and gender differences. Aside from the former issue, it has been proposed that the experimental pain sensitivity can be altered across the menstrual cycle [359]; therefore, future investigations need to consider this element as a confounder, which in turn can lead to affect the result of studies and to hardly interpret the alterations of motor learning variables in response to experimental pain models.

Studies that were included in the current review applied different experimental pain models. Two investigations [345, 360] demonstrated that cutaneous pain evokes distinct emotional and perceptual responses compared to deep pain. In particular, it has been reported that superficial pain can only be perceived surrounding the site of injection, whereas deep pain can diffuse to the other adjacent segments. Moreover, different cardiovascular and behavioral responses were observed in regard to the origin of pain (superficial or deep) [345, 360]. These differences may lead to affect the result of pain studies. For example, several studies [322, 324, 325, 336] that applied hypertonic saline injection to induce muscle pain did not report the depth of the injections, which potentially makes it difficult to generalize the effects of experimental muscle pain on motor learning variables. A very superficial injection might be more similar to cutaneous pain, whereas deeper injections may produce pain over wider areas. Thus, it is suggested that further studies report the depth of the hypertonic saline injection. Moreover, the aforementioned experimental pain models are continuously affected by any movement or posture of the subjects. That is, while hypertonic saline injection and capsaicin pain models- as tonic pain- can help to understand neurophysiological processes responsible for pain adaptation, perceived pain can be exacerbated or alleviated by specific movements or postures among those who experience musculoskeletal pain. This could lead to an alteration of motor adaptation when pain is increased or decreased [331, 361, 362]. In this vein, a recent study by Gallina and colleagues proposed a new experimental pain model whereby pain can be modulated in regard to changes in movement and posture. Specifically, a low-frequency sinusoidal electrical stimulation has been suggested as a task-relevant pain in order to unravel the previously mentioned limitation [331].

While the included studies applied visual analogue scale (VAS) or numeric rating system (NRS) to measure pain intensity, each study varied the evaluation methods, which can affect the interpretations of research findings [363]. In addition, none of the included studies assessed the pain intensity at specific times throughout the experiment, or reported information such as assessment frequency, endpoint or anchors that are important to reproduce such studies, (for review, see [363]). Moreover, stress arising from injection could lead to increase pain sensitivity in particular subjects [364], such that studies in which nonpainful injections were applied for control group could still result in stress and affect baseline pain sensitivity. This could make it difficult to interpret the pure influence of experimental pain models on motor learning variables, without controlling this potential confound. This is, the studies that applied nonpainful injection, including isotonic saline, in the control group, did not report stress measurements in this group, and future investigations need to also consider the stress from injection and to precisely manage pain intensity evaluation across all conditions. Pain intensity is also of great interest for further studies in which to understand the effect of decreased or increased pain intensity on motor adaptation. More specifically, any simple correlation between anticipated sensory input and behavioral output is challenged by taking into consideration the nature of relief [365]. For instance, mild pain will be rewarding if it immediately comes after severe pain. In this manner, Seymour and colleagues (2005) demonstrated the possible neural process for pain relief in the upper motor level in which pain and relief related-expectancies were reported that can result in a strong impact on the following experience of actual pain. Moreover, there have been reported that several psychological factors, including depression [366, 367], social support (for review, see [368]), and sleep deprivation [369] can affect pain perception and intensity. None of the included studies reported these elements, which could have influenced the results of the research.

Since there are reports that ethnicity, race, and culture may bring about different pain perceptions (for review, see [316, 370]), it is impossible to generalize the results of the current systematic review to different racial and ethnic groups. The individual differences in pain perception [371, 372] also pose a question whether personal differences can trigger different responses in motor learning variables concerning experimental pain models. Nonetheless, none of the included studies demonstrated inter-subject responses to motor skill acquisition and retention in the presence of experimental pain models. Future studies are needed to examine whether there are significant differences between individuals regarding motor learning variables in response to experimental pain models. Wide individual variability could limit our ability to detect a major group effect of pain on motor adaptation.

In terms of motor learning, sleep between the acquisition and retention phases can be a factor that also influences motor learning, and only one study [310] considered this issue before evaluating motor learning in response to experimental pain. Moreover, as physical and mental performances can fluctuate due to circadian rhythm; it has been suggested that physical and mental tests should be measured at the same time of day, especially for studies that apply repeated measurement protocols [373]. None of the studies reported this possible factor when assessing motor learning in response to experimental pain models. Furthermore the difficulty of a new motor adaptation task can result in a challenge to the success of performing a task [374]; hence, the optimal challenge point should be determined when designing a motor learning task, to ensure that sufficient outcome measurement sensitivity is obtained. Otherwise, if the tasks are too difficult, too simple, or the performance measurement is too imprecise, a study may find no difference between control and pain groups even when a difference actually exists, producing a type 2 error (false negative). None of the included studies mentioned this important issue. In addition, only one study [323] reported an adequate sample size for carrying out its research. Finally, the studies included in this review particularly focused on the effect of pain on motor learning in young healthy individuals, so further studies are needed to verify if similar effects are found in children and older adults, as well as expanding to patients and chronic pain conditions.

The current systematic review also has several limitations. First, only studies that were published in English language were considered to be reviewed while researches with other languages were not included in the present systematic review. Second, we did not include any theses or dissertations in our review. While including dissertations can help to decrease the potential publication bias (a bias that may arise from the fact that those results that are statistically significant are more likely to be published), theses have not been peer reviewed. Here we focused only on including peer reviewed and published literature. Third, pain can trigger alterations in the construct of learning, which in turn can lead to neuroplastic changes in the cortex; however, we only reported data regarding behavioral response in the presence of experimental pain models, and excluded studies that focused only on neural plasticity. While a recent systematic [375] examined the effects of pain on corticospinal excitability, there is still an open question regarding the general effects of pain on neural plasticity induced during motor learning. Finally, the heterogenous nature of the included studies did not allow us to perform a meta-analysis, and therefore a narrative synthesis of the included studies was done instead.

8.6 Conclusion

Overall, this systematic review found heterogeneous results regarding experimental pain models' influence on motor learning. In particular, although experimental pain models have been reported to lead to changes in the skill learning acquisition and retention, many studies have also shown unaltered adaptation in motor learning outcomes. Finally, several studies have shown that distinct strategies have been observed in the pain group even after pain resolution. These variable results highlight the need for further studies to clarify the effect of pain on motor learning.

Chapter 9: General Discussion

This thesis was carried out to improve our knowledge regarding: (1) strength and conditioning training strategies during bench press exercises; (2) postural control assessment and postural malalignment; (3) pain and motor adaptation. All specific aims of the current thesis were highlighted in the following to address the findings of the studies.

Objective 1: Determine the specific relative load (i.e., 1RM) at which female athletes can sustain propulsive concentric action during the bench press throw

Key Findings (Chapter 3):

- Our results revealed that, at approximately 80% of their 1RM, women transitioned into a completely propulsive concentric phase. In contrast, men exhibited this purely propulsive phase at around 85% of their 1RM.
- Women exhibited an 87% propulsive phase even at just 20% of their 1RM, and from 35% to 75% of their 1RM, the propulsive phase ranged from 90% to 99%. This suggests that propelling the barbell into the air during this phase becomes particularly challenging.

Objective 2: Compare the load-velocity characteristics between male and female athletes during the bench press throws

Key Findings (Chapter 3):

- We observed a significant difference in the load-velocity relationship between men and women. Specifically, women displayed lower velocities when handling lighter relative loads compared to men. Conversely, women exhibited higher velocities when dealing with loads exceeding 85% of their 1RM, in comparison to their male counterparts.

Objective 3: Compare the effects of different types of CAs on the volume of bench press exercise

Key Findings (Chapter 4):

- Concentric-only contraction significantly enhances both the number of repetitions and the time under tension during bench press performance compared to the control condition.
- The number of repetitions and total work are greater in the concentric-only contraction than in the eccentric-concentric contraction.
- Time under tension is also higher in the concentric-only contraction compared to the isometric contraction.

Objective 4: Assess the impact of a CA utilizing the ballistic bench press exercise on subsequent bench press throw performance with different loads

Key Findings (Chapter 5):

- The conditioning activity protocol enhanced mean velocity for all the loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM). Additionally, PV and PP showed increases with the CA at the higher loads (70% and 90% of 1RM).
- Peak velocity and peak power showed increases with the conditioning protocol at the higher loads (70% and 90% of 1RM).

Objective 5: To systematically review the research that examined the effect of time-of-day and sleep deprivation on postural control variables among healthy individuals.

Key Findings (Chapter 6):

- While there were inconsistent results surrounding a significant difference of a specific variable (e.g., COP displacement), all studies that considered sleep loss reported a negative and meaningful influence of sleep deprivation on postural control.
- The majority of investigations that measured postural control in response to time of day found a significant change in postural control; however, there was inconsistency between an improvement or deterioration in postural control at a specific time of day.

Objective 6: To compare the concentric and eccentric activation pattern in eleven muscles of the hip, thigh, and shank- gluteus maximus, gluteus medius, vastus medialis oblique, vastus lateralis, rectus femoris, semitendinosus, biceps femoris, lateral gastrocnemius, medial gastrocnemius, anterior tibialis, and soleus- among soccer players with and without lumbar hyperlordosis during single leg-squat.

Key Findings (Chapter 7):

- Quadriceps femoris, plantar flexor, and gluteus medius muscles had a lesser activation in soccer players with lumbar hyperlordosis than those with normal lumbar lordosis.
- Both gluteus maximus and hamstring muscles activity were higher in athletes with lumbar hyperlordosis compared to the control group. This alteration may negatively affect muscle performance during the SLS performance.

Objective 7: To systematically review the research outputs that have examined the effect of experimental pain models (including muscle pain and cutaneous pain) on motor learning (including motor adaptation, motor performance and motor strategy, but not neuroplasticity) among healthy human participants.

Key Findings (Chapter 8):

- Experimental pain models have been reported to lead to changes in the skill learning acquisition and retention, many studies have also shown unaltered adaptation in motor learning outcomes.

- Several studies have shown that distinct strategies have been observed in the pain group even after pain resolution. These variable results highlight the need for further studies to clarify the effect of pain on motor learning compared to the control group.

During the execution of a bench press with light and medium loads, an additional phase is observed where deceleration exceeds the influence of gravity alone. This occurs as athletes exert force in the opposite direction to the motion of the load. Consequently, the concentric portion of the lift can be further divided into a "propulsive" phase (characterized by positive force) and a "braking" phase (characterized by negative force) [10]. Previous studies demonstrated that men with comparable training backgrounds exhibit a steeper slope in the load-velocity relationship compared to women [7, 172, 173]. Thus, general equations that were formerly published to detect the propulsive phase of the concentric contraction might not be well-suited for women [174]. The study that was summarized in chapter 3 indicated the appropriate load to maintain velocity in female athletes during a bench press throw. Chapter 3 is the first investigation to reveal differences in propulsive phase during bench press throw between men and women. The results revealed that, at approximately 80% of their 1RM, women transitioned into a completely propulsive concentric phase. In contrast, men exhibited this purely propulsive phase at around 85% of their 1RM. Interestingly, women exhibited an 87% propulsive phase even at just 20% of their 1RM, and from 35% to 75% of their 1RM, the propulsive phase ranged from 90% to 99%. This suggests that propelling the barbell into the air during this phase becomes particularly challenging. Furthermore, we observed a significant difference in the load-velocity relationship between men and women. Specifically, women displayed lower velocities when handling lighter relative loads compared to men. Conversely, women exhibited higher velocities when dealing with loads exceeding 85% of their 1RM, in comparison to their male counterparts (chapter 3).

Chapters 4 and 5 investigated the influence of the conditioning activity protocols on the subsequent bench press performance. Participating in a high-intensity conditioning exercise prior to engaging in athletic endeavors can trigger a temporary elevation in muscle contractility, resulting in enhanced performance for the subsequent task [12]. The lower threshold for motor unit recruitment in ballistic movements compared to slower contractions suggests that low-load ballistic activity could induce potentiation without excessive fatigue [17]. It has been demonstrated that incorporating a bout of ballistic exercise can improve subsequent explosive activities such as the bench press throw [17]. However, the effectiveness of a conditioning activity in potentiating ballistic movements with different loads remains unclear. This is due to the influence of training load on the mechanistic aspects of ballistic movement. Chapter 5 investigated to determine whether bench press throw performance with different loads can be modified in response to a conditioning activity using ballistic exercises. In this vein, the conditioning activity enhanced mean velocity for all the loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM). Moreover, peak velocity and peak power showed increases with the conditioning activity protocol at the higher loads (70% and 90% of 1RM). These results are consistent with similar protocols that used velocity-based training with low (40% 1RM), moderate (60% of 1RM), and heavy (80% of 1RM) loads (Tsoukos et al. 2021; Tsoukos et al. 2019). While other studies (Tsoukos et al. 2021; Tsoukos et al. 2019) have applied bench press throws with 30% of 1RM as a baseline, we considered 30%, 50%, 70%, and 90% of 1RM (chapter 5).

It has been shown that incorporating heavy-load resistance training (>85% of 1RM) effectively increases the overall volume of subsequent exercises, such as squats and bench presses [19, 20]. The type of contraction employed as a CA can also influence the extent of PAP, resulting in varied outcomes. Different contraction types may elicit distinct mechanisms due to varying levels of neuromuscular fatigue, leading to a diverse range of findings. Chapter 4 was the first study indicated the potential influence of contraction types on subsequent activity volume. The study demonstrated the significant effects of contraction types on the volume of subsequent bench press exercise. Specifically, concentric-only contraction significantly enhances both the number of repetitions and the time under tension during bench press performance compared to the control condition. Furthermore, it was observed that the number of repetitions and total work are greater in the concentric-only contraction than in the eccentric-concentric contraction. Additionally, time under tension is also higher in the concentric-only contraction compared to the isometric contraction. These observations are consistent with the research conducted by Alves et al. (2020), which showed an increase in the number of repetitions performed in bench press exercises as a result of the PAPE effect. However, it is important to note that their protocol employed eccentric-concentric muscle contractions. The findings of the current study also align with those from the investigation by Krzysztofik et al. (2020), which indicated a significant increase in time under tension in response to PAPE effects during bench press exercises carried out until volitional failure. However, while they employed eccentric-concentric conditioning contractions to induce PAPE, our study did not observe a significant increase in time under tension following eccentric-concentric conditioning contractions (chapter 4).

Chapter 6 and 7 summarized investigations related to postural control. More specifically, postural control (PC) measurement is used among various researchers and clinicians as a way to detect deficits in the neuromuscular system that impair balance. It has been suggested that PC can be varied at different times of the day [201, 202]. However, several studies have not demonstrated any significant differences between PC and time of day [203-205]. Moreover, changes in a normal sleep and wake cycle may impair visual, vestibular, and somatosensory integration resulting in poor muscle function and postural orientation [208-210]. Since both sleep homeostatic (i.e., tendency to sleep that is affected by time of wakefulness) and circadian rhythm processes that may result in deficiency in performance are closely linked [5], it has been suggested that both factors can concurrently lead to deteriorating PC [212, 216]. In chapter 7, we systematically reviewed studies that measured postural control variables inn response to different time of day and/or sleep deprivation. The results of the review underline that heterogeneous results are resent regarding both time of day and sleep deprivation. In particular, no specific time of day contributes to significant variations in postural control. A trending negative effect regarding sleep deprivation has been observed on postural control; however, further research is needed to confirm the retrieved result. Other variables, such as age, levels of physical activity, sensory contribution, and chronotype should be considered when planning to assess postural control in sleep studies.

In chapter 8, the muscle activation of the selected lower limb muscles was examined during the single leg squat among soccer athletes with lumbar hyper lordosis. The results of the present study provide interesting, worthwhile information for both sports performance and rehabilitation fields. Our findings demonstrated that activation of quadriceps, hamstrings, gluteal, and plantar flexor muscles were significantly different among soccer athletes with and without lumbar hyperlordosis during the SLS performance.

Pain is an unpleasant but important perception, in order to attract attention and avoid further damage to the body. However, patients and athletes are often required to learn new movement patterns as part of a rehabilitation program in the presence of pain conditions. While it may be necessary to perform rehabilitation exercise immediately after an injury in order to return to optimal performance, there is concern surrounding the effect of pain on the learning process. Hence, several studies examined the effects of experimental pain models on the learning process. We systematically reviewed the studies to gain a better understanding of the effects of pain on the learning process (chapter 8). Inconsistent results have been reported surrounding this topic in the literature; however, most of these studies are in agreement with the negative consequences of acute pain in the learning process. Moreover, while some studies did not demonstrate any significant effect of experimental pain on skill learning acquisition and retention, they indicated those who experienced pain produced a distinct strategy to perform the novel task compared to control groups such that the participants displayed the same strategy in pain resolution even after one week.

9.1 Thesis Conclusion

The first part of the thesis examined the concepts of strength and power in a practical framework, concentrating on two areas: the prescription of optimal loads and the development of short-term strategies. The findings offer practical insights for strength and conditioning coaches to enhance athletes' training programs and improve their bench press performance. The initial study revealed that women transitioned into a fully propulsive concentric phase at roughly 80% of their 1RM, while men achieved this entirely propulsive phase at approximately 85% of their 1RM. Additionally, a significant disparity emerged in the load-velocity relationship between men and women. To elaborate, women exhibited reduced velocities when handling lighter relative loads in contrast to men. Conversely, women demonstrated higher velocities when dealing with loads exceeding 85% of their 1RM, as compared to their male counterparts. These findings hold notable implications for prescribing bench press throw loads for women, which should differ from those recommended for men. Further studies are necessary to validate the efficacy of the proposed load recommendations. The studies related to the short-term strategies demonstrated that, in comparison to a control condition, concentric-only conditioning contractions in bench press exercises performed to volitional failure result in a significant increase in the number of repetitions and time under tension. Other muscle contraction types did not trigger a PAPE effect. Furthermore, concentric-only conditioning activities notably increased the number of repetitions and total work when compared to eccentric-concentric conditioning contractions. Additionally, time under tension was also greater in concentric-only contractions than in isometric conditioning contractions. The last study indicated that a conditioning activity protocol using ballistic exercise can lead to a PAPE effect and improve bench press throw performance with different loads. Specifically, the CA protocol enhanced mean velocity for all the loads (30% 1RM, 50% 1RM, 70% 1RM, and 90% 1RM). Additionally, peak velocity and peak power showed increases with the CA at the higher loads (70% and 90% of 1RM). Moreover, the second part of the thesis revealed time of day and sleep deprivation can affect postural control; hence, these factors should be considered when evaluating postural control. Furthermore, the results demonstrated that an increase in lumbar lordosis angle among male soccer players can result in the alteration in muscle activation pattern in the lower limb muscles. Finally, the last part of the thesis, which systematically evaluated the studies that examined the learning process in response to pain, revealed although experimental pain models have been reported to lead to changes in the skill learning acquisition and retention, many studies have also shown unaltered adaptation in motor learning outcomes.

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Appendix 1: List of discussed abstracts and publications

- Ficarra, S., Di Raimondo, D., Navarra, G. A., **Izadi, M.**, Amato, A., Macaluso, F. P., . . . Barile, A. M. (2022). Effects of Mediterranean Diet Combined with CrossFit Training on Trained Adults' Performance and Body Composition. *Journal of Personalized Medicine*, *12*(8), 1238.

- **Izadi, M.**, Franklin, S., Bellafiore, M., & Franklin, D. W. (2022). Motor Learning in Response to Different Experimental Pain Models Among Healthy Individuals: A Systematic Review. *Frontiers in human neuroscience*, *16*, 863741.
- **Izadi, M**., Thomas, E., Thomas, A. C., & Bellafiore, M. (2022). The effect of time-of-day and sleep deprivation on postural control: A systematic review. *Gait & Posture*.
- Navarra, G. A., Thomas, E., Scardina, A., **Izadi, M**., Zangla, D., De Dominicis, S., . . . Bellafiore, M. (2021). Effective strategies for promoting physical activity through the use of digital media among school-age children: A systematic review. *Sustainability*, *13*(20), 11270.
- Seidi, F., **Izadi, M.**, Thomas, A. C., & Bellafiore, M. (2023). Lower limb muscle activation pattern in male soccer players with lumbar hyperlordosis. *Journal of Bodywork and Movement Therapies*, *36*, 263-269.

- **Izadi, M.,** Pillitteri, G., Thomas, E., Battaglia, G., Bianco, A., Bellafiore, M. (2024) Sex differences in the determination of prescribed load in ballistic bench press. *Frontiers in exercise physiology, accepted*
- **Izadi, M.,** Pillitteri, G., Thomas, E., Battaglia, G., Bianco, A., Bellafiore, M. (2024) Influence of Various Types of Muscle Contractions on Subsequent Bench Press Volume. Journal of sports science and medicine. Submitted
- **Izadi, M.,** Pillitteri, G., Thomas, E., Battaglia, G., Bianco, A., Bellafiore, M. (2024) Bench press throw performance with different loads in response to the execution of a conditioning activity. *Sports medicine and health science*. Submitted
- Izadi, M., Thomas, E., Thomas, A., Pillitteri, G., Ficarra, S., Amato, A., Zangla, D., Palma, A., Bianco, A., Bellafiore, M. (2021) Sleep loss, Circadian rhythm, and Postural control: A Systematic Review. *SISMES*