

Towards a Determination of the Physiological Characteristics Distinguishing Successful Mixed Martial Arts Athletes: A Systematic Review of Combat Sport Literature

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Abstract

Background Mixed martial arts (MMA) is a combat sport underpinned by techniques from other combat disciplines, in addition to strategies unique to the sport itself. These sports can be divided into two distinct categories (grappling or striking) based on differing technical demands. Uniquely, MMA combines both methods of combat and therefore appears to be physiologically complex requiring a spectrum of mechanical and metabolic qualities to drive performance. However, little is known about the physiological characteristics that distinguish higher- from lower-level MMA athletes. Such information provides guidance for training interventions, performance testing and talent identification. Furthermore, while MMA incorporates techniques from both grappling and striking sports, it is unknown precisely how these disciplines differ physiologically. Understanding the relationship between higher-level competitors in grappling and striking combat sports can provide further insight into the development of the optimal performance profile of a higher-level MMA athlete.

Objective This article aims to analyse the scientific literature on MMA and the primary combat sports underpinning it to determine the physiological adaptations that

distinguish superior competitors, with a view to defining the optimal physiological profile for higher-level MMA performance. Furthermore, this article will explore the differences in these capabilities between grappling- and striking-based combat sports in the context of MMA.

Methods A literature search was undertaken via PubMed, Web of Science, SportDiscus and Google Scholar. The following sports were included for systematic review based on their relevance to MMA: mixed martial arts, boxing, Brazilian jiu-jitsu, judo, karate, kickboxing, Muay Thai and wrestling. The inclusion criteria allowed studies that compared athletes of differing competition levels in the same sport using a physiological performance measure. Only male, adult (aged 17–40 years), able-bodied competitors were included. The search history spanned from the earliest record until September 2015.

Results Of the eight combat sports searched for, five were represented across 23 studies. Sixteen investigations described maximal strength or neuromuscular power variables, while 19 articles reported anaerobic or aerobic measures. The results indicate that a number of strength, neuromuscular power and anaerobic variables distinguished higher- from lower-level combat sport athletes. However, these differences were less clear when groups were stratified within, rather than between competition grades. Greater aerobic power was generally not present amongst superior combat sport competitors.

Conclusion There appear to be differing physiological profiles between more successful grappling and striking combat sport athletes. This is represented by high-force demands of grappling sports causing an upwards shift of the entire force–velocity relationship driven by an increase in maximal strength. In comparison, smaller increases in maximal force production with more notable enhancements in lighter load, higher velocity actions may better identify

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superior performance in striking sports. Anaerobic capabilities largely distinguished higher- from lower-level combat sport athletes. In particular, longer-term anaerobic efforts seem to define successful grappling-based athletes, while superior competitors in striking sports tend to show dominance in shorter-term measures when compared with their lower-level counterparts. Given the demand for both forms of combat in MMA, a spectrum of physiological markers may characterize higher-level competitors. Furthermore, the performance profile of successful MMA athletes may differ based on combat sport history or competition strategy.

Key Points

Superior grappling and striking combat sport athletes appear to have differing, although interrelated, physiological profiles.

More successful mixed martial arts athletes likely possess a broad spectrum of adaptations, and these may differ based upon combat sport history.

These findings provide guidance for training interventions, physiological testing of performance, and talent identification for mixed martial arts and other combat sports.

1 Introduction

Formally regulated and often containing both professional and amateur pathways, mixed martial arts (MMA) is a full-contact sport that employs techniques from various combat disciplines in addition to manoeuvres that are specific to the sport itself [1]. In recent years, this sport has experienced unprecedented growth reflected by its rise in professionalism [2], making it a highly popular global sport [3]. Alongside this advancement has been an increased interest and demand for knowledge on evidence-based training practices to achieve success in the sport [4–12]. However, despite these factors MMA has not been rigorously researched by sports scientists. To the authors' knowledge, no primary investigations on the physiological components that define high performance in MMA have been described in the scientific literature. Specifically, it is unknown what physiological qualities separate higher- from lower-level competitors. Such evidence is a fundamental step towards gaining scientific insight into a sport and thus represents a considerable gap in the understanding

of MMA. An increase in this knowledge base can contribute to the development of a foundational training philosophy by ensuring that any exercise intervention is directed towards the physiological characteristics that directly impact the targeted sport [13]. Additionally, valid performance testing requires these data to develop protocols that effectively monitor the preparedness of the athlete for competition in addition to the physiological responses to the external training load, which is considered a crucial step in the development of the training process [10, 14]. A further understanding of the major factors underpinning successful performance can also be used to identify those who possess the ideal physiological profile for MMA success, therefore facilitating talent identification and athlete development [15]. Similarly, such data can assist in talent transfer [16–18], a process that is commonplace in MMA largely owing to its rapid growth in professionalism and similarities to pre-established combat sports where limited professional pathways are available.

Careful observation of the sport reveals that MMA is physiologically complex, whereby a spectrum of mechanical and metabolic qualities are used during competition. Specifically, this sport consists of intermittent activity with periods of engagement containing explosive high-force and high-velocity actions [19] over bout durations, which are generally scheduled for three 5-min rounds to five 5-min rounds at the professional level [20]. As such, capabilities including neuromuscular power [21] and force production [22], in addition to anaerobic and aerobic qualities [23] might all be plausible markers of higher-level athletes in this sport.

Strength is defined as the ability for the neuromuscular system to produce force against an external resistance [24] and is regarded as the principal training quality of many sports [25]. Similarly, when expressed maximally, it is an indicator of elite performance in intermittent collision sports with similar physiological demands to MMA [26, 27]. Maximal strength represents the greatest application of force during a single maximal effort action. This quality is often expressed during grappling combat when the mass of an opponent must be displaced to achieve a more desirable position. An increase in this capacity results in a positive impact on other qualities potentially relevant to MMA such as neuromuscular power [28], endurance performance [29, 30] and injury prevention [31]. Maximal strength can be further described in both absolute and relative terms. Specifically, while absolute strength may be defined as the peak force value produced during a maximal voluntary contraction superimposed with electrical stimulation [32, 33], this term also describes maximal voluntary strength when expressed independent of body mass [34]. In contrast, relative strength considers force production capabilities divided by body mass, lean body mass [35] or fat-free

mass [36] and is therefore an important consideration in weight class sports such as MMA. However, it has been suggested that allometric calculations are a more accurate method of scaling strength [35, 37], whereby the three-dimensional factor of body mass (BM) is scaled to the two-dimensional factor of force [37].

Maximal neuromuscular power holds similarities with strength, both in the interrelated mechanisms that underpin its development [38], and in its relationship to performance [21]. Specifically, it is a defining quality of superior competitors in high-intensity intermittent collision sports under a range of loading conditions [26, 27, 39]. In this context, maximal power is defined as the product of force and velocity generated by the neuromuscular system during a single, maximal effort muscle contraction [40, 41]. Mechanistically, the velocity of shortening of a sarcomere is inversely related to the amount of force it can produce [42]. This can be described in an applied form whereby the greater the external load applied to the athlete, the more force must be produced by the neuromuscular system to generate an explosive action, thus the lower the velocity of that action. As such, the application of this quality can occur along a spectrum ranging from high-force loaded actions to those with considerable velocity demands in relatively unloaded conditions [21]. Likewise, the power expressed in many MMA techniques span from high-velocity punches and kicks to the high-force collisions associated with many grappling manoeuvres. Further impacting power production is the ability to rapidly apply muscular force, known as the rate of force development (RFD) [43]. This quality is expressed when an action is applied with an intent to move explosively [44–46] and thus may also contribute to many decisive MMA techniques [19]. Maximal neuromuscular power can be reported and quantified using a number of methods, each with differing degrees of validity. The greatest instantaneous power value achieved during an action is considered peak power [47]. Additionally, the average of each sampled time point on the power-time curve may also be reported and is typically taken across either the entire concentric portion of the effort [48] or from the initiation of the concentric phase until the point at which peak power occurs [49]. However, peak power is considered the preferred method for reporting this quality [47] because of its considerably superior correlations to vertical jump performance when compared with average power [50, 51]. It is well understood that the highest power outputs typically occur during ballistic actions as a result of the minimization of the deceleration phase [52]. Thus, if the objective is to determine the maximal power capabilities of the neuromuscular system, then ballistic tasks provide the most valid approach. The components of this attribute can be directly quantified through the use of various testing devices. In

particular, a force plate provides vertical ground reaction force (GRF) information, which can be processed through forward dynamics, or displacement–time data acquired via a linear position transducer allows for power to be calculated via double differentiation. A combination of these kinetic and kinematic measures may also be employed and has been recommended as the most valid method [49]. However, alternate investigations suggest that the use of GRF data alone is the preferred approach [53]. Indirect methods such as vertical jump height can be used as an indicator of maximal power capabilities, while a valid prediction equation in conjunction with jump height may provide an estimate of power output (W).

The limited research available suggests that MMA combat consists of high-intensity engagements interspersed with periods of lower-intensity activity performed at work to rest ratio of between 1:2 and 1:4 [19]. This may occur over the aforementioned bout durations, however similar to many other combat sports, matches often last less than their allocated time [19]. The high-intensity intermittent activity (HIA) that occurs in MMA has the potential to impact a spectrum of physiological properties. Arguably, the primary responses to such a stimulus are those that are metabolic, although neuromuscular and musculoskeletal systems are also impacted [54]. An assessment of an athlete's metabolic qualities may estimate the ability to supply adenosine triphosphate (ATP) to the active muscles via three distinct processes: (1) the enzymatic division of stored phosphagens (ATP-phosphocreatine system); (2) the anaerobic breakdown of glucose or glycogen into lactic acid (anaerobic or fast glycolysis); and (3) the combustion of carbohydrates and fats in the presence of oxygen (aerobic or oxidative metabolism) [23]. Although distinct, these processes are not independent of one another and each may therefore impact MMA performance to varying degrees depending upon the style of competitive engagement. Anaerobic qualities are commonly assessed via measures derived from all-out cyclical tests using either the lower or upper body, over a range of long- (>30 s), intermediate- and short-term (<10 s) time frames.

Within MMA combat repeated maximal efforts of force production may be expressed, often during grappling exchanges when there is an attempt to improve, or defend an advance, to a more dominant position. However, in some cases force application is driven not by the intent to apply maximal effort, but rather is internally paced. For example, such an expression occurs during lower-intensity engagements when both athletes are maintaining a given position with no attempts at advancement. This results in a conservation of effort strategy that distinguishes these two qualities. Accordingly for the purpose of this review, strength endurance and muscular endurance are defined as distinct and separate qualities. Strength is the ability to

apply force [25] and when expressed rapidly with maximal intent this quality is underpinned by the maximization of neural drive [45]. Strength endurance considers these factors and is characterized by the repetitive or sustained application of a maximal force effort for the duration of the assessment. As such, this can be classified as a higher-intensity endurance task. The length of a set of this quality is defined by a minimum of 10 to over 25 repetitions [55]. Conversely, muscular capacity measures that are paced either internally or by a constant external cue, such as a metronome, are classed as muscular rather than strength endurance.

The extended volume of HIA found in all competition levels of MMA stimulates a considerable cardiovascular and peripheral oxidative response [54]. As the scheduled bout duration increases with a higher competition level, the increased volume of HIA would put a greater proportional demand on aerobic metabolism at the expense of the glycolytic system [56, 57]. Thus, it is likely that as MMA competition level increases, so too does the relative aerobic requirement. However, the absolute demand on other metabolic, neuromuscular and musculoskeletal systems also increases [54]. As such, a training plan of higher-performing MMA athletes would require a greater volume of HIA, as opposed to aerobic specific training, to replicate this collective physiological response. The improved aerobic capacity brought about by HIA also has a positive impact on other metabolic processes that underpin MMA performance. Specifically, mitochondrial phosphocreatine may be shuttled to the myofibril contributing to the re-synthesis of ATP [58], while the lactate produced as a result of the high-intensity work periods in MMA is disposed of by oxidative metabolism linked by both cell-to-cell and intracellular processes [59]. Consequently, these metabolic interactions result in an improved recovery of both the ATP-phosphocreatine and glycolytic systems, allowing for work periods of greater intensity within an MMA bout.

Despite the paucity of data that exist on the physiological capabilities of MMA athletes, there is a body of research on the combat sports from which many of its techniques are derived. The sports that underpin the majority of MMA skills contain characteristics that allow them to be grouped into two distinct categories based upon differing technical demands. Grappling sports such as wrestling [36], judo [60] and Brazilian jiu-jitsu (BJJ) [61, 62] use throws, ground fighting and joint locks to achieve victory. In contrast, striking disciplines employ strategies that can include punches, kicks, elbows and knees, which are characteristic of combat sports that include boxing [63], karate [64], Muay Thai and kickboxing [65]. In conjunction with differing technical demands required by these two categories of combat sport is the potential for varying

metabolic and mechanical demands. Thus, while MMA is interrelated with already established grappling and striking disciplines, it is unknown precisely how these two groups differ physiologically. This further confounds any attempt to define the performance characteristics of successful MMA competitors. The purpose of this investigation is to establish the physiological profile of superior MMA athletes by systematically reviewing the literature on relevant combat sports to determine the physiological qualities that separate higher- from lower-level competitors. This review will also define and compare the capacities of grappling and striking sport athletes in the context of MMA to provide greater insight into the adaptations that distinguish high performance.

2 Methods

Consultation with coaches and athletes, combined with observation of MMA and discussion between authors was used to determine the combat disciplines that contribute the greatest to the sport. Based upon this, the following sports were included in this present systematic review: MMA, boxing, BJJ, judo, karate, kickboxing, Muay Thai and wrestling. Studies that compared competitors of differing performance or success levels in the same sport, and related a physiological effort to this as the primary outcome measure were included in the initial screening. The systematic search was conducted using PubMed, Web of Science, SportDiscus and Google Scholar with dates ranging from the earliest record to September 2015. All study designs were included. The search terms contained the aforementioned combat sports in addition to 'martial arts' OR 'combat sports' AND 'power' OR 'strength' OR 'anaerobic' OR 'aerobic' OR 'endurance' OR 'performance'. Studies were included if at least two of the subject groups were competitors of differing levels of competition or success in the same sport, adults (aged 17–40 years), male and injury free. Non-competing participants, or subjects whose participation in formal competition was not described, were excluded from this review. Only articles that were available from the publisher in the English language were consulted.

2.1 Selection of Studies and Data Extraction

Following the removal of duplicates, studies were screened for inclusion against the eligibility criteria, with any doubts on inclusion being resolved following joint review of the full text by all authors. The full text was retrieved from those references that were not removed based upon title or abstract, and were then reviewed to determine eligibility. Cited reference searches were performed on relevant

articles for additional studies that might have met the inclusion criteria. A visual representation for this process is presented in Fig. 1.

Because of the potential predominance of cross-sectional investigations, no methodological criteria were used to quantify quality. This is based on the lack of agreement on a valid and reliable system for assessing the methodological standard of such articles [66, 67]. Consistent with other discussions of the same review structure and which incorporate a prevalence of cross-sectional investigations, study characteristics impacting methodological quality were included in the discussion of the findings for each investigation [68]. Primarily, such factors included subject numbers, competition and success level in addition to validity of the performance measure. Data were extracted that described the participant number, competition level, measures taken, and the major findings of each study.

3 Results

The initial search yielded 2895 results that were identified and screened for potential eligibility. From this, 133 studies were retrieved for examination in greater detail. Four

potentially relevant studies were discovered from the reference list of the sourced articles. Following screening, 23 studies were determined to fit the inclusion criteria and were therefore included for review. Of these, 16 reported neuromuscular power or maximal strength measures. Articles that met the inclusion criteria containing anaerobic, aerobic, muscular and strength endurance measures totalled 19.

3.1 Characteristics of Studies

Of the eight combat sports included in the search, boxing, BJJ, wrestling, judo and karate were represented across the 23 eligible articles (Table 1). The higher-level group was defined in each study as the group representing the highest competition grade or who were considered more successful competitors within a competitive class. This ranged from provincial and state level competitors to world champions.

3.1.1 Maximal Strength and Neuromuscular Power Measures

Fifteen articles spanning five sports included maximal strength variables [36, 69–82] (Table 2), while four combat

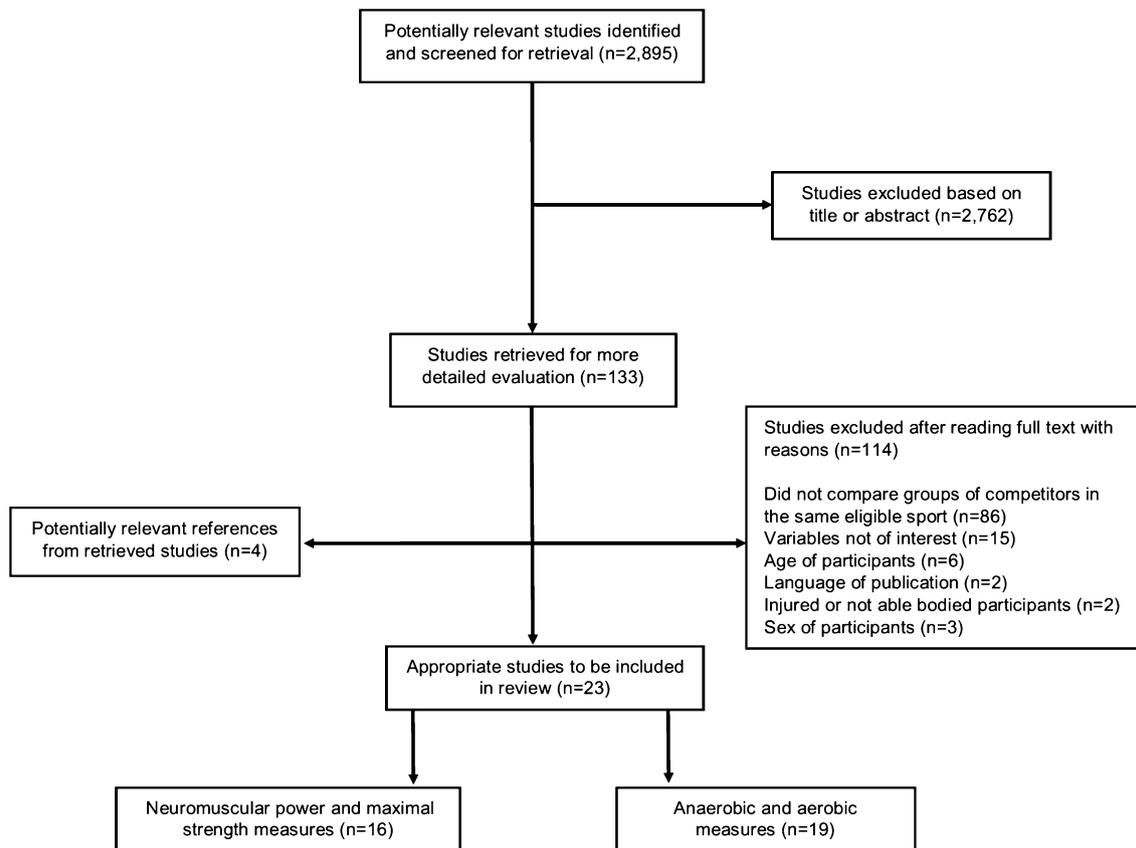


Fig. 1 Flow diagram describing publication selection for this review

Table 1 Combat sports meeting inclusion criteria

Sport	No. of articles meeting criteria
Brazilian jiu-jitsu	1
Boxing	2
Judo	8
Karate	4
Kickboxing	0
Muay Thai	0
Mixed martial arts	0
Wrestling	8

sports were described in six studies in which neuromuscular power measures were related to competition performance [36, 70, 74, 81–83] (Table 3). Articles containing fewer than 10 participants in the higher performance group totalled 8 of 16, considerably increasing the chance for a type II error. Seven investigations did not report a significant difference in any performance markers between groups [71–73, 76–79]. None of these studies clearly stratified groups by grade of competition. Of these seven studies, five compared athletes from groups stratified by performance at the same competitive level [76–79] or position within a single team, such as a reserve [71]. One distinguished competition rank by age (17–20 years vs. 21 years and over) [73]. The final investigation included a combined group of elite athletes, consisting of competitors who were of the same competitive grade or higher than the sub-elite group [72]. Thus, between and within competition level distinctions could not be made.

3.1.2 Anaerobic and Aerobic Measures

Anaerobic or aerobic markers were presented in investigations across four combat sports. Articles discussing grappling-based sports totalled 14, and included wrestling [36, 75–79, 84] and judo [71–73, 82, 85–87]. Boxing [69, 88] and karate [83, 89, 90] were described in the five studies that represented striking sports. Anaerobic and aerobic measures were reported in 11 (Table 4) and 13 (Table 5) studies, respectively. Four articles quantified muscular endurance capabilities, while one investigation [82] included outcome measures that met the description for strength endurance (Table 6). Three studies across two sports used reliable sports specific tests as a performance marker [71, 72, 90], while a similar measure with no accompanying reliability information was excluded from analysis [82]. A markedly increased risk of a type II error was present in six studies [69, 71, 76, 77, 79, 82] as a consequence of the higher-performance group containing fewer than 10 participants. Three of these low statistically powered articles were included in the six investigations

that found no statistically significant difference in any of these measures. The stratification of groups in these six studies was not by level of competition, but rather by success within a given competition level or event [76, 78, 79, 91], rank within a chosen team [71] or by age [73].

3.2 Maximal Strength

3.2.1 Maximal Dynamic Strength

Maximal dynamic strength capabilities were described in seven articles and included athletes from BJJ [81], judo [70, 71, 82], karate [74] and wrestling [36, 79]. Other than a single study using only isokinetic measures [79] all investigations incorporated multi-joint actions. Such assessments included the squat [70, 82], bench press [36, 70, 71], their Smith machine equivalents [36, 74], in addition to a hack machine squat [71], deadlift [82] and a 45° bench pull [71]. No studies compared this quality between competition grades in striking athletes. Significantly greater maximal dynamic strength measures were reported in four investigations, all of which stratified groups by competition level. Specifically, Fagerlund and Häkkinen [70] determined that the 1 repetition maximum (1RM) squat, both relative and absolute, was significantly greater amongst international judokas ($n = 7$; 185 ± 25 kg; 2.3 ± 0.56 kg·BM⁻¹) when compared with recreational competitors ($n = 7$; 140 ± 35.59 kg; 1.7 ± 0.3 kg·BM⁻¹, Cohen's $d = 1.27$, 95 % confidence interval [CI] 0.04–2.32). However, this difference did not remain when international-level competitors were compared with national-level players ($n = 6$; Cohen's $d = 0.5$, 95 % CI –0.64 to 1.57). Although squat 1RM did not reach differences of statistical significance in another study of international ($n = 5$, 179.0 ± 12.54 , BM: 100.7 ± 0.83 kg) vs. national level ($n = 5$, 170.0 ± 10.60 , BM: 100.3 ± 0.97 kg, Cohen's $d = 0.78$, 95 % CI –0.58 to 1.98) judo athletes of the same weight class, the 1RM deadlift did [82]. In general agreement with these increased dynamic strength values in superior competitors, significantly greater 1RM bench press and 1RM Smith machine squat have been reported in elite international wrestlers ($n = 46$) when compared with non-international athletes across all weight classes (8.4–24.6 %) [36]. Even when normalised to fat-free mass (FFM), these measures significantly distinguished the groups in this study. Likewise, higher-level BJJ competitors produced significantly superior values in the 1RM bench press than lower-ranked athletes. However, when comparing within competition level, Franchini et al. [71] and Rochel and colleagues [74] noted that both upper- and lower-body strength measures were not a discriminator of successful performance in judo ($n = 7$) and karate ($n = 7$), respectively. This is consistent

Table 2 Summary of studies examining the differences in maximal strength capabilities between higher- and lower-level combat sport competitors

Sport	Study, year	Higher-level competitors	Lower-level competitors	Relevant measures	Major findings
Boxing	Guidetti et al., 2002 [69]	Higher-ranked elite amateur boxers	Lower-ranked elite amateur boxers	Handgrip strength	Hand grip strength is significantly related to boxing competition ranking
Brazilian jiu-jitsu	da Silva et al., 2015 [81]	Total of both groups (<i>n</i> = 8) Black and brown belt competitors (<i>n</i> = 14)	Purple and blue belt competitors (<i>n</i> = 14)	IRM bench press: absolute	Higher-level competitors significantly > than lower-level athletes in this measure
Judo	Drid et al., 2015 [82]	Successful international 100-kg category competitors (<i>n</i> = 5)	Successful national 100-kg category competitors (<i>n</i> = 5)	Isokinetic strength; handgrip strength; IRM bench press; IRM squat; IRM deadlift Absolute measures were reported	Left isokinetic knee extension, IRM bench press and IRM deadlift significantly > in higher-level competitors
	Fagerlund and Hakkinen, 1991 [70]	Finnish international competitors (<i>n</i> = 7)	Finnish national competitors (<i>n</i> = 7); Finnish recreational competitors (<i>n</i> = 7)	IRM bench press: absolute and relative IRM squat (national level <i>n</i> = 6): absolute and relative	IRM squat, both relative and absolute, significantly > in INT compared with REC No significant differences between any of the groups in BP relative or absolute. No significant difference between INT and NAT in IRM squat relative and absolute
	Franchini et al., 2007 [71]	Brazilian team (<i>n</i> = 7)	Reserves (<i>n</i> = 15)	IRM bench press; IRM hack machine squat; IRM bench row Absolute and relative measures were reported	No significant difference in any maximal strength measures
	Franchini et al., 2005 [72]	Brazilian national and international medalists (<i>n</i> = 26)	Non-medallists in Brazilian national tournaments (<i>n</i> = 66)	Handgrip strength	No significant difference in isometric handgrip strength between groups
	Little, 1991 [73]	Provincial-level senior men (<i>n</i> = 17)	Provincial-level junior men (<i>n</i> = 9)	Isometric strength: handgrip, elbow flexors, back-leg, total	No significant differences in these measures between groups
Karate	Rochel et al., 2009 [74]	Brazilian black belt international competitors: winners (<i>n</i> = 7)	Brazilian black belt international competitors: losers (<i>n</i> = 7)	IRM SM bench press; IRM SM squat	No significant differences in these measures between groups

Table 2 continued

Sport	Study, year	Higher-level competitors	Lower-level competitors	Relevant measures	Major findings
Wrestling	Demirkan, et al., 2012 [75]	Selected elite junior Greco-Roman Turkish national team wrestlers ($n = 11$)	Unselected ($n = 37$)	Isometric strength: handgrip, back-leg	Significantly > back-leg strength in higher-level competitors
	Garcia-Pallares et al., 2011 [36]	Elite international Greco-Roman and freestyle competitors ($n = 46$)	Non-international amateur Greco-Roman and freestyle competitors ($n = 46$)	IRM SM squat; IRM bench press; handgrip strength, isometric back-leg strength Absolute and relative to FFM measures reported	IRM SM squat and bench press absolute and normalized to FFM significantly > in all elite weight classes; grip strength significantly > in elite LW and elite MW; absolute back-leg strength significantly > in all elite groups; however, when normalized to FFM this measure was not significantly different in the HW group
	Nagle et al., 1975 [76]	Successful Olympic freestyle wrestlers ($n = 8$)	Unsuccessful Olympic freestyle wrestlers ($n = 18$)	Handgrip strength	No significant difference in isometric handgrip strength between groups
	Silva, 1981 [77]	Qualifiers for US Junior World Team ($n = 8$)	Non-qualifiers ($n = 7$)	Handgrip strength	Lower handgrip strength contributed to the prediction of successful wrestling performance
	Silva, 1985 [78]	1980 US Olympic qualifiers ($n = 25$)	Non-qualifiers ($n = 39$)	Handgrip strength	No significant difference in isometric handgrip strength between groups
	Stine, 1979 [79]	All American ($n = 5$)	Moderately successful ($n = 6$); less successful ($n = 8$)	Isokinetic strength	No significant difference between any groups in isokinetic strength across various segments of the upper and lower body
	Ylinen et al., 2003 [80]	Finnish senior Greco-Roman wrestlers competing internationally ($n = 10$)	Junior Greco Roman wrestlers ($n = 10$)	A fixed neck isometric strength measurement system	Significantly greater isometric cervical extension, flexion and left and right rotation amongst higher-level competitors

INT international competitors, *NAT* national competitors, *REC* recreational competitors, *IRM* 1 repetition maximum, *SM* Smith machine, *BP* bench press, *FFM* fat-free mass, *LW* lightweight class; *MW* middleweight class, *HW* heavyweight class

Table 3 Summary of studies examining the differences in maximal power production between higher- and lower-level combat sport competitors

Sport	Study, year	Higher-level competitors	Lower-level competitors	Relevant measures	Major findings
Brazilian jiu-jitsu	da Silva et al., 2015 [81]	Black and brown belt competitors ($n = 14$)	Purple and blue belt competitors ($n = 14$)	Peak power in the bench press throw across incremental loads	No significant differences between groups in any loading conditions
Judo	Drid et al., 2015 [82]	Successful international 100-kg category competitors ($n = 5$)	Successful national 100-kg category competitors ($n = 5$)	CMJ height; long jump height; upper-body-only medicine ball throw	No significant difference between groups in any of these measures
	Fagerlund and Hakkinen, 1991 [70]	Finnish international competitors ($n = 7$)	Finnish national competitors ($n = 7$); recreational competitors ($n = 7$)	Bench press force-velocity profile at incremental absolute loads; SJ load-velocity profile at incremental absolute loads	Load-velocity curve shifts higher according to competition level in the incremental loaded SJ
Karate	Ravier et al., 2004 [83]	International French competitors ($n = 10$)	National French competitors ($n = 12$)	SJ; CMJ	Significantly > SJ height in higher-level competitors No difference in CMJ or CMJ – SJ
	Roschel et al., 2009 [74]	Brazilian black belt international competitors: winners ($n = 7$)	Brazilian black belt international competitors: losers ($n = 7$)	CMJ height; average power production at 30 % and 60 % 1RM of the SM squat and SM bench press	Significant > average power @ 30 % 1RM of both the SM squat and SM bench press amongst higher-level competitors No significant differences in CMJ, or peak power at 60 % 1RM SM squat or SM bench press
Wrestling	Garcia-Pallares et al., 2011 [36]	Elite international Greco-Roman and freestyle competitors ($n = 46$)	Non-international amateur Greco-Roman and freestyle competitors ($n = 46$)	CMJ height and estimated peak power; incremental load SM squat and incremental load bench press	Higher level competitors attained significantly > CMJ height and estimated peak power Peak power in the incremental SM squat and incremental bench press significantly > amongst higher-level competitors. All differences remained significant after adjustment for FFM

SJ squat jump, CMJ counter-movement jump, 1RM 1 repetition maximum, SM Smith machine, FFM fat-free mass

with an investigation containing sample groups of fewer than nine wrestlers that concluded that isokinetic strength of the upper- and lower-body segments did not differ amongst college wrestlers of diverse success levels [79].

3.2.2 Maximal Isometric Strength

Ten articles reported isometric strength measures [36, 69, 72, 73, 75–78, 80, 82]. All but three articles [36, 73, 75] only included tests that were across a single joint. Four studies determined that maximal isometric strength was significantly superior in higher-level competitors or positively related to competition performance. This included wrestlers in three separate studies [36, 75, 80] and a single investigation on boxers [69]. All measures incorporating multiple joints were taken using a portable analogue

[73, 75] or digital [36] back-leg dynamometer in a position similar to that of a mid-thigh clean pull, with two studies reporting significantly greater values in superior competitors [36, 75]. This included elite international wrestlers across all weight classes (123.6 ± 14.6 kg to 148.1 ± 11.2 kg vs. 98.3 ± 17.6 kg to 134.4 ± 10.4 kg) [36] and elite junior national wrestlers (163 ± 22 vs. 144 ± 22 kg) [75]. When normalised to FFM, Garcia Pallares et al. [36] reported that these significant differences held true for all but the heavyweight class (Cohen's $d = 0.53$, 95 % CI -0.34 to 1.37).

Five studies investigated the grip strength of wrestlers [36, 75–78], with three reporting no significant difference between groups [75, 76, 78]. One investigation concluded that lower values in this measure contributed to the prediction of superior competition performance [77]. In

Table 4 Summary of studies examining the differences in anaerobic capabilities between higher- and lower-level combat sport competitors

Sport	Study, year	Higher level competitors	Lower-level competitors	Measures	Major findings
Judo	Borkowski et al., 2001 [85]	Winners of Polish national championships ($n = 24$)	Second- and third-place getters at Polish national championships ($n = 48$)	30-s Wingate; relative PP, relative AC	No significant difference between groups in any markers
	Drid et al., 2015 [82]	Successful international 100-kg category competitors ($n = 5$)	Successful national 100-kg category competitors ($n = 5$)	8-s abbreviated Wingate-like test: MP	Significantly > MP amongst higher-level competitors
	Franchini et al., 2007 [71]	Brazilian national team	Reserves	ISST	No significant difference between groups in test performance
Franchini et al., 2005 [72]	Brazilian national and international medalists	Total of both groups ($n = 20$)	Non-medallists in Brazilian national tournaments	30-s upper body Wingate; relative PP, relative MP, FI, time to PP; ISST; post-combat La levels	Significantly > PP and MP amongst higher-level competitors; significantly > performance in the ISST
			Wingate ($n = 34$); ISST ($n = 23$); lactate concentration after combat ($n = 15$)		
Kim et al., 2011 [87]	Korean national team ($n = 10$)	University team ($n = 26$)	30-s Wingate; relative PP, relative MP	Relative MP significantly > in HLC when compared with LLC	Relative MP significantly > in HLC when compared with LLC
Little, 1991 [73]	Senior men ($n = 17$)	National French competitors ($n = 8$)	30-s upper body Wingate: absolute and relative PP, absolute and relative MP, absolute and relative AC	Exhaustive supramaximal exercise (2–3 min at 140 % of $\dot{V}O_{2max}$ velocity) on a treadmill ergometer, MAOD deficit. Time-course of concentration for anaerobic blood markers following activity	Higher-level competitors displayed significantly superior reduction in a spectrum of anaerobic blood markers
Ravie et al., 2006 [89]	International French competitors ($n = 10$)	French national-level competitors ($n = 12$)	Three 8-s sprints on a friction braked ergometer at 0.5, 0.7 and 0.9 N/kg BM; relative PP; maximal theoretical velocity; optimal velocity; relative maximal theoretical force	Significantly > relative PP, maximal theoretical velocity and optimal velocity amongst higher level competitors	No significant difference in relative maximal theoretical force
Ravie et al., 2004 [83]	French international-level competitors ($n = 10$)	French national-level competitors ($n = 12$)	Three 8-s sprints on a friction braked ergometer at 0.5, 0.7 and 0.9 N/kg BM; relative PP; maximal theoretical velocity; optimal velocity; relative maximal theoretical force	Significantly > relative PP, maximal theoretical velocity and optimal velocity amongst higher level competitors	No significant difference in relative maximal theoretical force

Table 4 continued

Sport	Study, year	Higher level competitors	Lower-level competitors	Measures	Major findings
Wrestling	Demirkan, et al., 2012 [75]	Selected elite junior Greco-Roman Turkish national team wrestlers (n = 11)	Unselected (n = 37)	Upper- and lower-body Wingate: absolute and relative PP, absolute and relative MP; Illinois agility test	Significantly > lower-body MP and upper-body relative MP amongst higher-level competitors Significantly superior performance in the Illinois agility test amongst higher-level competitors
	Garcia-Pallares et al., 2011 [36]	Elite (n = 46)	Amateur (n = 46)	30-s upper body Wingate: absolute PP, MP relative to FFM, FI, peak lactate; 10-m sprint	Significantly > absolute and relative MP amongst higher-level competitors across all weight classes Significantly > absolute and relative PP amongst higher-level competitors across all weight classes Significantly > peak lactate values amongst higher-level competitors across all weight classes No significant differences in FI between higher- and lower-level competitors
	Starzewska-Czapowska, 1999 [84]	Olympic Games, World and European Championship medalists (n = 20)	Athletes who placed second or third in the Polish national championships (n = 77)	Upper- and lower-body 30-s Wingate-type tests: relative PP, relative AC	Significantly superior performance in the 10-m sprint amongst higher-level heavy weight competitors only Significantly > relative PP for both upper- and lower-body in higher-level competitors No significant differences in upper- or lower-body AC between groups

PP anaerobic peak power, AC anaerobic capacity, FFM fat-free mass, FI fatigue index, HLC higher-level competitors, ISST intermittent sports-specific test, La lactate, LLC lower-level competitors, MP anaerobic mean power, MAOD maximal accumulated oxygen deficit, BM body mass

Table 5 Summary of studies examining the differences in aerobic qualities between higher- and lower-level combat sport competitors

Sport	Study, year	Higher-level competitors	Lower-level competitors	Ergometer	Major findings
Boxing	Guidetti, 2002 [69]	Higher-ranked elite amateur boxers Total between both groups ($n = 8$)	Lower-ranked elite amateur boxers	Treadmill	$\dot{V}O_{2max}$ was significantly related to boxing ranking
	Bruzas et al., 2014 [88]	Higher-ranked elite amateur boxers Total between both groups ($n = 12$)	Lower-ranked elite amateur boxers	Treadmill	$\dot{V}O_{2max}$ was significantly related to boxing performance
Judo	Borkowski et al., 2001 [85]	Winners of Polish national championships ($n = 24$)	Second- and third-place getters at Polish national championships ($n = 48$)	Cycle ergometer	No significant difference between groups
	Drid et al., 2015 [82]	Successful international 100-kg category competitors ($n = 5$)	Successful international 100-kg category competitors ($n = 5$)	Treadmill	$\dot{V}O_{2max}$ significantly > in higher-level competitors
	Franchini et al., 2007 [71]	Brazilian team ($n = 7$)	Reserves ($n = 15$)	Cooper test	No significant difference between groups
	Franchini et al., 2005 [72]	Brazilian national and international medalists ($n = 15$)	Non-medallists in Brazilian national tournaments ($n = 31$)	Treadmill	No significant difference between groups
	Little, 1991 [73]	Senior men ($n = 17$)	Junior men ($n = 9$)	Treadmill	$\dot{V}O_{2max}$ significantly > in lower-level competitors
Karate	Ravier et al., 2006 [89]	International French competitors ($n = 10$)	National French competitors ($n = 8$)	Treadmill	No significant difference between groups
	Chaabene et al., 2012 [90]	National-level competitors ($n = 20$)	Regional competitors ($n = 20$)	Sports-specific intermittent aerobic test	Significantly > time to exhaustion amongst higher-level competitors
Wrestling	Nagle et al., 1975 [76]	Olympic freestyle team members ($n = 8$)	Unsuccessful Olympic freestyle team candidates ($n = 18$)	Treadmill	No significant difference between groups
	Silva et al., 1985 [78]	US Olympic qualifiers ($n = 23$)	Non-qualifiers ($n = 37$)	Treadmill	No significant difference between groups
	Starczewska-Czapowska, 1999 [84]	Olympic Games, World and European Championships medalists ($n = 20$)	Competitors who placed second or third in the Polish national championships ($n = 77$)	Cycle ergometer (indirect)	$\dot{V}O_{2max}$ significantly > in higher-level competitors
	Stine, 1979 [79]	All American ($n = 5$)	Moderately successful ($n = 6$); less successful ($n = 8$)	Treadmill	No significant difference between groups

$\dot{V}O_{2max}$ maximal oxygen consumption

contrast to this, Garcia-Pallares et al. [36] reported significantly enhanced grip strength amongst lightweight and middleweight elite competitors when compared with their sub-elite counterparts. A further article [80] determined that significantly greater ($p = 0.001$) cervical spine isometric strength through extension, flexion, left and right rotation was attained by senior when compared with junior Greco-Roman wrestlers. In the single study to assess strength measures amongst boxers, it was established that grip strength was related to performance ($p < 0.01$), represented by a correlation coefficient of 0.87 [69]. No significant differences were found within judo players for any isometric strength measures

[72, 73, 82]. This included grip [72, 73, 82] and elbow flexor strength, in addition to back-leg strength as assessed via the aforementioned dynamometry [73].

3.3 Maximal Neuromuscular Power

3.3.1 High-Velocity Neuromuscular Power

In the context of this review, ‘high velocity neuromuscular power’ refers to expressions of power in which no additional load is added to the system for lower body tasks, while a medicine ball throw was considered a high-velocity

Table 6 Summary of studies examining the differences in muscular and strength endurance capabilities between higher- and lower-level combat sport competitors

Sport	Study, year	Higher-level competitors	Lower-level competitors	Measures	Major findings
Judo	Drid et al., 2015 [82]	Successful international 100-kg category competitors ($n = 5$)	Successful national 100-kg category competitors ($n = 5$)	Bench press with BM to failure; squat with BM to failure; pull-ups to failure	All of these measures significantly > in higher-level competitors
	Franchini et al., 2011 [86]	Brazilian national team athletes ($n = 16$)	State-level judo athletes ($n = 12$)	Duration in sports-specific maximal isometric hold; number of repetitions in a sports specific pull-up during an isometric hold	Significantly > number of dynamic repetitions of the sports specific pull-up amongst higher-level competitors No significant difference in isometric hold duration between groups
Wrestling	Nagle et al., 1975 [76]	Olympic freestyle team members ($n = 8$)	Unsuccessful Olympic freestyle team candidates ($n = 18$)	Bench press 50 lbs 30 bpm to a metronome: number of repetitions to failure	Significantly > number of repetitions amongst higher-level competitors
	Silva et al., 1981 [77]	Qualifiers for US Junior world team ($n = 8$)	Non-qualifiers ($n = 7$)	Bench press 50 lbs 60 bpm to a metronome: number of repetitions to failure, both relative and absolute	Lower absolute and relative muscular endurance contributed to the prediction of successful wrestling performance
	Silva et al., 1985 [78]	1980 US Olympic wrestling qualifiers ($n = 25$)	Non-qualifiers ($n = 38$)	Bench press 50 lbs 60 bpm to a metronome: number of repetitions to failure, both relative and absolute Grip muscular endurance	No significant differences between groups in any of these measures

BM body mass, bpm beats per minute

expression of power by the upper body. These qualities were described in four articles, including two investigating karate [74, 83] and single articles on wrestling [36] and judo [82]. One further judo study [70] presented the position of the load–velocity curve in graphical form, which included an unloaded condition for the lower body. However, the authors only reported strength values in relation to this figure. Ravier et al. [83] noted significantly greater ($p \leq 0.05$; Cohen's d : 1.27, 95 % CI 0.31–2.13) squat jump height (SJ) as calculated by flight time amongst elite international-level karate competitors ($n = 10$; 42.3 ± 4.8 cm) when compared with national-level competitors ($n = 12$; 37 ± 3.6 cm); however, no statistically significant differences were reported for counter-movement jump (CMJ) ($p > 0.05$; Cohen's d : 1.01, 95 % CI 0.45–1.86) or CMJ minus SJ ($p > 0.05$; Cohen's d : -0.2 , 95 % CI -1.03 to 0.65). Similarly, no significant differences ($p > 0.05$; Cohen's d : -0.66 , 95 % CI -1.69 to 0.46) were identified in CMJ height between international level winners ($n = 7$) and losers ($n = 7$) in simulated competition [74]. This is in agreement with reports of non-significant distinctions

between international- and national-level judokas in both CMJ height (Cohen's $d = 0.77$, 95 % CI -0.58 to 1.97) and long jump distance (Cohen's $d = 0.32$, 95 % CI -0.96 to 1.54) while also holding true to an upper-body-only medicine ball throw (Cohen's $d = 1.20$, 95 % CI -0.24 to 2.41). In contrast to these findings, the only study on wrestling describing such measures reported that elite international-level competitors produced a significantly greater CMJ performance than lower-level competitors. This was represented by differences between 8.9 and 16.6 % across all weight classes in jump height and 7.6 and 10.3 % in estimated peak power [36]. Furthermore, these differences remained significant after adjustment for FFM.

3.3.2 High-Force Neuromuscular Power

Studies discussing loaded neuromuscular power capabilities totalled four, representing judo [70], karate [74], BJJ [81] and wrestling [36]. These investigations included measures of the weighted SJ [70], bench press [36, 70] and bench press throw [81] in addition to Smith machine

versions of both the squat [36] and bench press [74]. All studies incorporating lower-body assessments of this quality reported a measure that was superior in the more competitive group, while more mixed findings were present across the upper body. Peak power produced by international wrestlers in the squat and bench press was significantly greater than the values expressed by non-international wrestlers, with differences ranging from 14.0 to 29.8 % across all weight classes for both measures [36]. This distinction remained significant after normalizing for FFM. Average power in the squat and bench press at 30 % 1RM was a significant differentiator of performance for winning international karate fighters ($n = 7$: squat: 298.7 ± 6.4 W, bench press: 252.6 ± 9.1 W) when compared with teammates who lost to the winning athletes in simulated competition ($n = 7$: squat: 269.5 ± 23.1 W, bench press 205.7 ± 5.9 W) [74]. However, the successful competitors did not attain greater values when these tasks were performed at 60 % 1RM. When assessed across multiple loads to establish a load-velocity profile of the lower body, it was concluded that the curve shifts to higher values in accordance with competition level amongst judokas [70]. However, the upper-body force-velocity relationship of these competitors [70], in addition to the bench throw load-power profile of higher- and lower-level BJJ athletes [81], did not differ significantly between competitive groups.

3.4 Anaerobic Profile and Strength Endurance

3.4.1 Lower-Body and Sports-Specific Anaerobic Profile

Of the ten studies investigating lower body and sports specific anaerobic capabilities, a total of eight reported measures that were superior amongst higher-level competitors [36, 72, 75, 82–84, 87, 89], while the remaining two articles described no significant difference between groups [71, 85]. Three studies assessed these capabilities in wrestlers [36, 75, 84]. In the two investigations that applied 30-s Wingate assessments, it was noted that absolute average power (611 ± 144 W vs. 518 ± 135 W) [75] and relative average power (11.52 ± 0.82 vs. 10.98 ± 1.01 W·kg⁻¹) [84] was significantly greater amongst elite competitors. It was also reported that change of direction ability as measured by the Illinois agility test was a defining characteristic ($p \leq 0.02$) of elite junior Greco-Roman national team wrestlers, when compared with wrestlers who were not selected for that team [75]. However, in the 10-m sprint, only heavyweight wrestlers reported a significantly superior performance (-6.8 %), while non-significant differences were achieved by

lightweight (-2.2 %) and middleweight (-2.8 %) higher-level competitors [36]. Both investigations into karate athletes concluded that enhanced anaerobic performance was a characteristic of international-level competitors when compared with national-level fighters. Specifically, during 8-s maximal efforts on a friction braked ergometer at incremental resistances, Ravier et al. [83] noted significantly greater ($p \leq 0.05$) maximal power output (12.5 ± 1.3 vs. 10.9 ± 1.5 W·kg⁻¹), in addition to significantly higher ($p \leq 0.001$) maximal theoretical velocity (263.1 ± 15.9 vs. 232.8 ± 13.7 rpm) and optimal peddling velocity (135.4 ± 5.6 vs. 119.2 ± 10.4 rpm) amongst the international competitors. During a supramaximal treadmill run to exhaustion at 140 % of $\dot{V}O_{2\max}$, Ravier and colleagues [89] reported a greater accumulation of various anaerobic blood markers in lower-level (national) competitors. This included peak values of blood H⁺ (75.9 ± 8.8 vs. 89.2 ± 6.7 nmol·L⁻¹), NH₄⁺ (118.7 ± 22.7 vs. 180 ± 67.9 μmol·L⁻¹) and La (17.9 ± 1.1 vs. 20.7 ± 2.7 mmol L⁻¹), which were significantly higher ($p < 0.01$, $p < 0.05$, $p < 0.05$, respectively) in the national-level group. Additionally, the magnitude of increase in La (4.3 ± 1.6 vs. 7.5 ± 3.8 mmol⁻¹) and NH₄⁺ (28.1 ± 19.8 vs. 78.5 ± 51.9 μmol·L⁻¹) was significantly higher ($p < 0.05$ and $p < 0.01$ respectively) in the national-level athletes, while the magnitude of decrease from the peak recorded La levels was significantly greater ($p < 0.05$) in the international group (4.2 ± 1 vs. 3.2 ± 1.8 mmol·L⁻¹). No statistically significant difference was found in the maximal accumulated oxygen deficit (MAOD) between groups (67.76 ± 8.00 vs. 64.50 ± 6.40 mL·kg⁻¹, Cohen's $d = 0.44$, 95 % CI -0.52 to 1.36).

Five studies described anaerobic capabilities of judo athletes in either the lower body or through sports-specific tests [71, 72, 82, 85, 87]. Three of these investigations reported measures that differentiated competition level [72, 82, 87]. Significantly greater mean power measures in the 30-s Wingate [87] and 8-s cycle ergometer test [82] have been reported by the higher-level competitors in this sport. In a sports-specific judo test, Brazilian national and international medallists had a significantly superior ($p \leq 0.001$) performance than lower-ranked national competitors [72]. Conversely, Franchini et al. [71] reported no difference in this test between Brazilian national team competitors and the reserves for that team. Similarly, Borkowski and colleagues [85] determined that maximal anaerobic power (Cohen's $d = 0.17$, 95 % CI -0.32 to 0.66) and total work performed (Cohen's $d = 0.02$, 95 % CI -0.48 to 0.5) during the 30-s Wingate assessment did not differentiate between Polish national championship winners, and those who placed second or third to those winners.

3.4.2 Muscular Endurance, Strength Endurance and Upper Body Anaerobic Power

Five studies investigated upper body anaerobic capabilities, including two from judo [72, 73] and three from wrestling [36, 75, 84]. All but one study [73] (relative peak power Cohen's $d = 0.08$, 95 % CI -0.73 to 0.89 ; relative mean power Cohen's $d = -0.23$, 95 % CI -1.03 to 0.59) reported a measure of this quality that represented a significant indicator of performance level. Garcia Palares et al. [36] determined that elite wrestlers in all weight categories attained significantly greater mean and peak power output during an upper body Wingate test compared with amateur competitors by a magnitude of between 16.0 and 22.0 %. Similarly, Demirkan and colleagues [75] stated a greater relative average anaerobic power was present in selected elite (4.9 ± 0.6 W·kg⁻¹) vs. unselected (4.4 ± 0.7 W·kg⁻¹) junior national team wrestlers. This trend is continued with findings of increased relative upper body anaerobic power in a 30-s Wingate-type test [84] amongst Olympic Games, World or European Championships medalists (9.78 ± 0.42 W·kg⁻¹) compared with athletes who placed second or third (9.37 ± 0.77 W·kg⁻¹) in the Polish national championships.

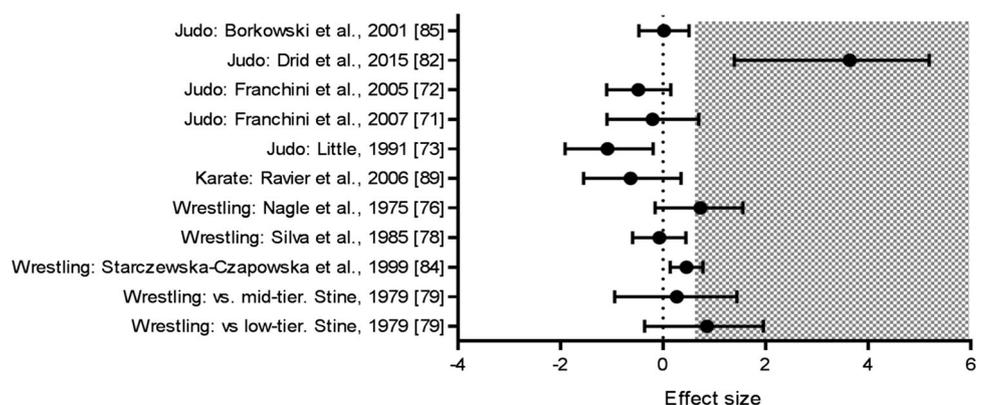
Two articles reported measures involving grip endurance, and included athletes from judo [86] and wrestling [78]. One study [86] took measures using the gi (the uniform worn by judo, BJJ and karate competitors) in a pull-up and isometric hang action. In this investigation Franchini et al. [86] reported Brazilian national team judo athletes performed a significantly greater number of repetitions in the pull-up task than state-level athletes; however, there was no difference in isometric hold duration. In a more conventional assessment employing a dynamometer, Silva et al. [78] found no difference in grip strength endurance between groups. Upper-body dynamic muscular endurance was assessed in three studies across wrestling only [76–78]. Each of these quantified this quality via the total number of repetitions during an absolute resistance

bench press paced by a metronome. Muscular endurance was not found to be superior amongst higher-level competitors in two of these studies, resulting in Cohen's d and respective 95 % CI of -0.03 , -1.04 to 0.99 [77]; and -0.01 , -0.52 to 0.49 [78]. Three strength endurance measures were described in a single article that reported the number of repetitions to failure in the squat and bench press with BM, in addition to the pull-up was significantly greater in international vs. national judokas [82].

3.5 Aerobic Profile

A total of 12 studies investigated aerobic power as a marker of superior performance (described in Fig. 2 for articles containing all required variables). In addition to this, one study incorporated a sports-specific aerobic test that attempted to replicate the mechanical and physiological demands of karate competition. Four sports were represented, consisting of boxing [69, 88], judo [71–73, 82, 85], karate [89, 90] and wrestling [76, 78, 79, 84]. Aerobic power was determined to be indicative of performance level in four studies across three sports. Guidetti et al. [69] and Bruzas et al. [88] reported superior maximal oxygen uptake ($\dot{V}O_{2\max}$) ($r = 0.81$, $p \leq 0.05$ and Spearman's $\rho = 0.7$ and $p < 0.01$, respectively) in higher-level amateur boxers. Of the three studies on wrestlers, one noted significantly greater $\dot{V}O_{2\max}$ in elite wrestlers compared with sub-elite. This increase ($p \leq 0.01$) was documented in a combined pool of freestyle and Greco-Roman wrestlers who were medallists at the Olympic Games, World Championships or European Championships (57.06 ± 5.64 mL·kg⁻¹·min⁻¹) compared with athletes who placed second or third in national championships (54.12 ± 6.98 mL·kg⁻¹·min⁻¹) [84]. However, no difference in this quality was noted between successful and unsuccessful Olympic freestyle competitors (Cohen's $d = 0.73$, 95 % CI -0.15 to 1.56) [76], collegiate wrestlers (vs. moderately successful Cohen's $d = 0.27$, 95 % CI -0.94 to 1.44 ; vs.

Fig. 2 Cohen's d values (± 95 % CI) for maximal oxygen uptake amongst higher vs. lower-level combat sports competitors. A positive effect represents a superior performance by the more competitive group. The shaded area indicates \geq a moderate positive effect (0.6). CI confidence interval



less successful Cohen's $d = 0.86$, 95 % CI -0.36 to 1.96 [79], or US Olympic trial qualifiers vs. non-qualifiers (Cohen's $d = -0.07$, 95 % CI -0.59 to 0.45) [78]. Three of five investigations into this quality in judo athletes failed to report a significant difference between competitive groups (Cohen's $d = 0.02$, 95 % CI -0.05 to 0.51 [85]; Cohen's $d = -0.2$, 95 % CI -1.09 to 0.7 [71]; Cohen's $d = -0.48$, 95 % CI -1.1 to 0.15 [72]), while one investigation showed significantly greater $\dot{V}O_{2\max}$ in junior- ($59.26 \pm 3.95 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) vs. senior-level ($53.75 \pm 5.57 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) competitors [73]. This is in contrast to reports of international competitors ($n = 5$, $55.99 \pm 5.01 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) attaining significantly superior values in this measure when compared with their national-level counterparts ($n = 5$, $48.72 \pm 3.85 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) [82]. Finally, while no difference was determined between elite international and national level French karatekas (Cohen's $d = -0.63$, 95 % CI -1.55 to 0.35) [89], a significantly higher performance in an intermittent sports specific test was reported amongst national vs. regional competitors in this sport [90].

4 Discussion

4.1 Maximal Strength

4.1.1 Maximal Dynamic Strength

A number of mechanisms underpin maximal dynamic strength including increases in cross-sectional area (CSA) [92], neural drive [93, 94], in addition to improved inter-muscular coordination [95]. There is strong evidence of dynamic strength as a discriminator of combat sport performance in this present review. The two studies where this quality was not related to performance were each from a grappling [71] and a striking [74] discipline. Both accessed only small samples with the higher level groups containing seven participants only in each study, which reduces the potential to detect a significant difference. While effect size (ES) calculations may be employed, such small samples limit the conclusions that can be drawn from these data regardless. Additionally, although other studies [70, 82] determined the presence of this quality with a similar or smaller sample, it was likely owing to the difference in grade of competition between the higher- and lower-level groups. Specifically, the latter investigations noted significant differences between international and national [82] and recreational competitors [70]. Conversely, in the two studies where no difference was reported, both the higher- and lower-level groups were of the same competition grade. Thus, only a narrow distinction in competitive ability was present. This was represented by a stratification

between national team members and reserves of that team [71], and winners and losers during simulated competition from a pool of international competitors [74]. These findings are supported by the understanding that as the distinction in competition level between athletes decreases, so too does any physiological differences between them, particularly at the elite level [96]. As such, small changes in physiological capabilities can have a more meaningful impact on performance than at lower and more divergent performance levels [96]. In an investigation with a much larger sample ($n = 46$), maximal dynamic lower- and upper-body strength clearly distinguished elite international wrestlers from sub-elite competitors [36]. The sub-elite group in this investigation were classed as amateur with no further description supplied, although it would be intuitive to suggest that the terms 'elite' and 'amateur' denote differing competition ranks in this case. Such methodology increases the likelihood that significant differences would be detected. Taken together, it appears that maximal dynamic strength is crucial to higher-level performance in grappling sports, while larger samples with group stratification between, rather than within, competition level is needed to better understand the contribution of this attribute to superior performance in striking-based combat sports. Despite an absence of evidence for maximal dynamic strength distinguishing higher-level performers in striking sports, this quality appears to be of considerable importance to these athletes. In particular, increases in lower-body strength have resulted in enhanced punching impact force in boxers [97] and have been associated with punching acceleration in elite karate competitors [98]. Considering this and the greater window of adaptation potentially present in striking athletes, the development of maximal dynamic strength would certainly be advantageous.

Data have been reported on the lower and upper body maximal dynamic force capabilities of regional level MMA athletes. Schick et al. [99] determined that these athletes possess relative bench press and squat strength of 1.1 and $1.3 \text{ kg}\cdot\text{BM}^{-1}$ respectively. This is generally lower than all levels of Finnish judokas whose values reach 1.1 and $1.7 \text{ kg}\cdot\text{BM}^{-1}$ in the bench press and squat respectively amongst recreational competitors, while 1.2 and $2.3 \text{ kg}\cdot\text{BM}^{-1}$ has been reported for international competitors in these two measures [70]. However no data exist employing these assessments on higher-level MMA athletes. Additionally, differing protocols for dynamic strength tests can confound comparison of results across separate studies. The study holding the greatest statistical power of all those reviewed provides strong evidence that both upper- and lower-body maximal dynamic strength contributes to grappling performance [36]. This capacity might also influence MMA performance, and may be

present to a greater extent in MMA athletes with a grappling-dominant background.

4.1.2 Maximal Isometric Strength

It is recognized that grappling exchanges, like those found in MMA, require expressions of isometric strength [100]. Of the seven studies that investigated these qualities, six were conducted on grappling sports. Despite the apparent advantage of increased isometric strength for grappling performance, the relationship between this characteristic and performance level was mixed. This is likely in part a consequence of the predominant use of single-joint tests. Such measures often have little relationship to dynamic actions [101–104] and do not accurately assess training-induced changes in dynamic performance [105]. For these reasons, such data provide limited evidence on the impact of improved isometric strength of the neuromuscular system on combat sport performance. Conversely, standing multi-joint isometric measures in which the athlete replicates a relevant athletic position have reported strong correlations with dynamic actions [44, 106–109] and are sensitive enough to detect training-induced changes in performance [107]. Thus, it is suggested that the mechanisms that underpin dynamic force production more closely overlay maximal isometric force when such measures are taken in a sports-specific position [44, 110]. When performed using instrumentation such as a force plate or load cell, standing multi-joint isometric assessments yield valuable force–time data that allow for various measures of RFD, force at predetermined time points and maximal force [44, 111, 112]. However, none of the reviewed studies used this equipment, thus there are no force–time measures to be examined. It would be of great interest to investigate these capabilities as discriminators of performance in MMA and other combat sport athletes.

Only three studies included multi-joint measures, each using a portable back-leg dynamometer [36, 73, 75]. This instrument can be configured to allow the athlete to apply force via combined isometric hip and knee extension when standing, although the protocols were not clearly defined in any of the reviewed papers. This is a critical action in the proximal to distal sequencing of athletic movements similar to those found in MMA [113] and therefore are likely to be more indicative of sports performance than single-joint isometric actions. All three studies investigated grappling athletes, with two significantly distinguishing between higher- and lower-level competitors in wrestling [36, 75]. However, this measure did not reach a significantly greater magnitude when comparing senior vs. junior provincial judo representatives [73]. This study failed to reveal significantly higher values in any performance

markers amongst senior-level competitors. The groups in this study were stratified by age (17–20 years vs. 21 years and older), rather than competitive level. The reported age for high-calibre judokas includes 24.3 ± 3.35 years [87] and 22.4 ± 2.9 years [85]. Thus, it is possible that some subjects in the 17- to 20-year age range might be superior competitors than those in the older class. Regardless, it appears that at an international level of competition, greater functional isometric strength is a key attribute distinguishing elite competitors in a grappling-based sport. More research is needed to determine the multi-joint isometric strength levels of superior striking athletes. As the isometric strength capabilities of MMA athletes are unknown, these findings suggest that it would be worthwhile to investigate the presence of this quality in these athletes, and examine its relationship to performance level and combat sport history.

4.2 Maximal Neuromuscular Power

4.2.1 High-Velocity Maximal Neuromuscular Power Capabilities

The highest power outputs produced by the neuromuscular system generally occur in the unloaded jump squat (CMJ) [114]. Thus, the limited investigation into the expression of unloaded power as a differentiator of performance in combat sport competitors represents a notable gap in the literature considering the reliance on this function for many sporting actions [21], including strikes, which require force to be produced in as little as 50–250 ms [43]. Accordingly, two out of the three studies [74, 83] investigating this quality did so on karate fighters, where striking actions predominate. However, these articles report conflicting results on the contribution of this ability towards elite performance. Specifically, SJ [83] but not CMJ [74, 83] or CMJ minus SJ [83] height significantly differentiates higher-level competitors in this sport. This may suggest that RFD rather than the ability to use the stretch shortening cycle is a key quality of karatekas. This contention is supported by the presence of a negative ES (Cohen's $d = -0.2$) associated with the more competitive athletes in the CMJ minus SJ measure [83]. However, as no force–time data exist, such a conclusion is only speculative. Additionally, small sample sizes were present in both these studies (≤ 12), which reduces the potential to detect a statistical significance. Cohen's d calculations describe a moderate magnitude of effect (1.01) towards CMJ performance of international compared with national competitors [83]; however, a moderate negative effect (-0.85) was found in winners vs. losers within elite-simulated competition [74]. This suggests that greater unloaded lower body power may define more successful karate competitors between, but not within

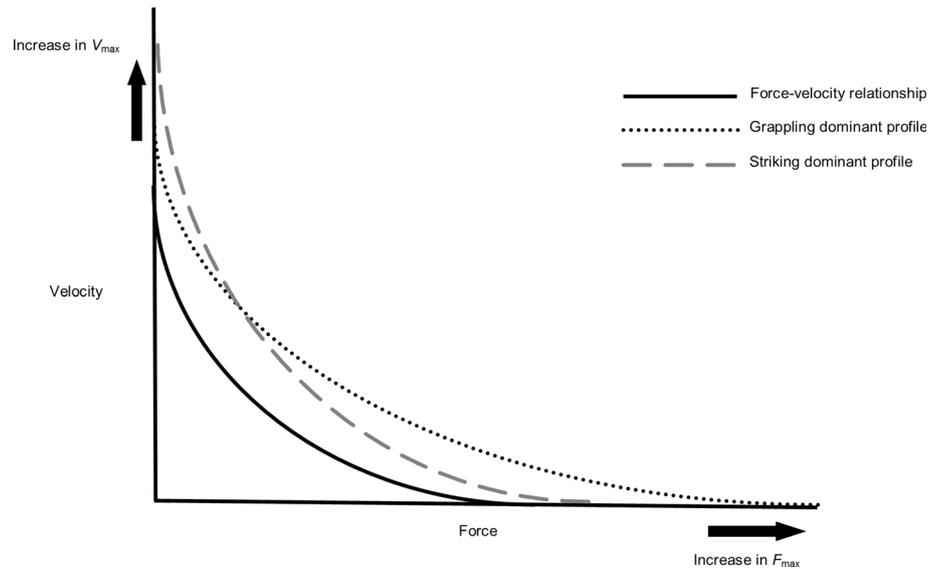
elite competition levels. A possible explanation for more dominant RFD yet less definitive stretch shortening cycle capabilities can be found when examining the style of kicks predominantly used in this sport. Observation suggests that these athletes often deliver such techniques with minimal counter-movement to prevent the early detection of the invariant features of the action by the opponent. This is in contrast to the kicks commonly performed in Muay Thai and kickboxing, whereby a swift stretch-shorten cycle action is often used to deliver a more powerful strike [115]. This increased power as a result of the counter-movement is underpinned by the effective use of stored elastic energy [116, 117], and is considered a key mechanism in power production [38]. Although no data exist, close examination of the sport indicates that the latter technique plays a more critical role in MMA.

The reviewed data suggest that elite grappling-based athletes possess superior CMJ performance compared with lower-level competitors represented by statistically significant [36] and moderate ES differences [82] between groups. This is likely explained by the high force demands of the sport. Specifically, although much of the activity within these sports is against the mass of an opponent and therefore requires considerable maximal force application, these efforts develop many of the mechanisms underpinning unloaded power expressions. This includes the impact on the inherent mechanics of the force–velocity relationship, whereby an increase in the ability to apply maximal force allows for a greater amount of force to be applied at a given velocity of shortening, thereby increasing maximal power capabilities [118]. This is particularly apparent in less trained subjects, where the window of adaptation is greater [119]; however, as strength levels increase, such a stimulus has a decreased impact on increases in maximal power [120, 121]. Favourable alterations to the nervous system also occur, including an increased motor unit recruitment [122], firing frequency [123] and possibly synchronization [124]. Behm [125] suggested that training improves the ability to activate synergists [125], and therefore this enhanced quality might also be present in these athletes. Synergistic activation enhances force production and improves coordination [95], thereby resulting in heightened unloaded power expressions. Additionally, increases in velocity-dominant power production are influenced by fibre type. Type IIa and IIx fibres contain greater amounts of ATPase than type I fibres, which results in an increased cross-bridge cycling rate and, in turn, increased maximal velocity (V_{\max}) [126, 127]. These neural and morphological factors may also underpin the improved SJ performance in the karate athletes. However, differing adaptations driving improved velocity-dominant power performance may exist between grappling- and striking-based athletes. While grappling-based athletes display an

increase in maximal force (F_{\max}), it is possible that the high-velocity techniques, like those found in striking-based sports, instead shift V_{\max} positively [119], allowing greater velocity to be applied at a given force. Additionally, a more rapid shortening can be attributed to a longer fascicle length whereby a greater number of sarcomeres in series allows the fibre to shorten at a higher velocity [128]. This feature has been reported in velocity-dominant power athletes when compared with both endurance athletes and untrained controls [129]. While an enhanced ability to control antagonists is likely present in athletes with superior power production [22, 38], it may exist to a greater extent in striking than grappling athletes. The actions performed by striking-based combat athletes require considerable acceleration of the limb into free space before contact with an opponent. Minimizing the magnitude of activation of antagonists would allow a greater acceleration of the limb [130], while increasing the degree of activation in the instant prior to contact would then stiffen the joint allowing effective transfer of forces onto the opponent [131, 132]. Such activation patterns have been reported in the trunk musculature of elite MMA athletes performing striking techniques [132].

There are a number of methodological limitations present in the reviewed studies. Specifically, although CMJ jump height was measured, no investigations directly quantified the components of maximal power in an unloaded CMJ. As this action is where the highest power outputs of the neuromuscular system generally occur [133], this represents a fundamental gap in the literature for the reviewed combat sports. One study did attempt to quantify this quality by applying a prediction equation to jump height [36]. However, the formula resulted in considerably lower peak power values than are often reported in the literature. Regardless, even with a valid prediction equation, the product provides only an estimate of power output. Taken together, this indicates mixed findings in investigations of striking sports that hold a small statistical power, and more conclusive findings in a grappling-based sport. If these results are taken in the context of MMA activity possibly consisting of greater grappling than striking exchanges [9], then it is conceivable that these athletes may possess high levels of power and RFD capabilities when expressed in unloaded conditions. Research using GRF or displacement–time data in unloaded ballistic actions is needed to confirm and compare the presence of these adaptations between competition levels within both MMA and other combat sports. It would also be of interest to examine the velocity-dominant power capabilities of MMA athletes with differing combat sports backgrounds. Specifically, would an MMA athlete with a predominantly striking background possess differing qualities to one with a grappling background (Fig. 3)?

Fig. 3 Proposed lower body power profile of a mixed martial artist based upon combat sport history and dominant strategy. Increased power production occurs at differing magnitudes throughout the spectrum dependent upon profile type (adapted from Haff and Nimphius [158], with permission). V_{\max} maximal velocity, F_{\max} maximal force



4.2.2 High-Force Maximal Neuromuscular Power Capabilities

Somewhat more consistent findings than those of high-velocity power are noted when examining force-dominant power expressions, with each of the investigations into this quality mostly reporting a measure that differentiated competition performance. The aforementioned neural mechanisms and fibre-type preferences that support velocity-based power production also contribute to high-force power capabilities. However, greater CSA is a central factor to force production [92] and thus plays a more dominant role in loaded power efforts. Such an enhancement in CSA can occur through an increase in volume of myofibrils within the muscle fibre [134]. Additionally, a greater pennation angle can contribute to an increased CSA as a result of a more parallel arrangement of the sarcomeres [135]. However, this adaptation is in contrast to the increased fascicle length, which aids in V_{\max} , and thus may slow the velocity of shortening of the sarcomere [136].

4.2.2.1 Lower Body Higher-level competitors displayed superior lower-body power-generating capacities in all reviewed studies across both striking and grappling sports. The distinct presence of this quality in the lower body can be explained by the fundamental nature of athletic movements, whereby such actions are driven by forces generated by the powerful lower body and expressed distally [113]. This is particular pivotal in MMA and grappling-centred combat sports whereby the mass of an opponent must be overcome, requiring rapid forces to be initially applied by the lower body then expressed against an external load represented by the opponent.

An examination of the force–velocity relationship formed from ballistic expressions across a spectrum of resistances provides valuable insight on the power capabilities of an athlete. This information is critical as it can highlight deficiencies and strengths that might not appear when assessing with a single load [137]. However, only one study has compared this relationship between higher- and lower-level combat sport competitors [70]. Fagerlund and Häkkinen [70] reported a higher shift of the lower-body load–velocity curve as judo competition level increased over three different competitive groups. This appeared to be primarily underpinned by a shift in F_{\max} , translating into greater velocity throughout the loading spectrum, particularly under increasing resistances, when compared to lower-tier competitors. Elite wrestlers also produced greater maximal power during the squat with this value occurring between 61.8 and 63.7 % of 1RM [36]. This percentage was similar to that found in the sub-elite group, which suggests a more even shift of the force–velocity relationship. The increased CMJ performance by the elite group in this study supports this notion.

Amongst karate athletes peak power was significantly greater in more successful international competitors at 30 % 1RM of the Smith machine squat, but not at 60 % 1RM [74]. This enhanced ability under lighter loads may in part be explained by the demand for effective high-velocity strikes by these athletes. Specifically, as these were not full-contact competitors the nature of combat is such that it is not necessary to cause increased damage to an opponent in this form of competition. Consequently, there may be a heightened demand for velocity, rather than force based expressions. This is supported by findings of stronger relationships between various punches thrown by karate athletes and peak velocity in the jump squat at 40 % BM,

when compared with the 1RM machine squat [98]. This represents a potential distinction from MMA, whereby it is advantageous to cause greater damage with a strike and leads to the potential for a more force dominant profile. Although no statistically significant difference was reported for CMJ height in the reviewed study [74], there are distinctions between this measure and the lighter loaded jump squat that may explain the divergent findings. Specifically, the CMJ is an unrestrained ballistic task, demanding a greater degree of inter-muscular coordination than the Smith machine squat. This leads to an increased likelihood of more variability in the data, which when combined with low subject numbers, would considerably reduce the potential to detect a statistically significant difference. Additionally, both groups in this study were of the same international competitive level, differentiated only by success in a simulated bout. As discussed previously, the narrower the distinction between groups, the greater the physiological similarities. Consistent with the findings for unloaded power, methodological limitations were also uncovered for force-emphasised conditions. Specifically, the only studies that reported values for maximal force-emphasised power did so in non-ballistic tasks and therefore eliminated the potential to accurately assess the maximal power capabilities of the system [36, 74]. Furthermore, one of the two studies reported only average power [74]. While the reporting of average power itself is not incorrect [47], this measure is confounded when calculated across the entire duration of a non-ballistic action. As acceleration becomes negative in the final stages of these movements, the corresponding power output declines and may also result in a negative value, particularly under lighter loads [138]. As such, the maximal power capabilities of the athletes in this study were considerably underestimated. The only other investigation reporting data on this quality [36] appears to contain limitations in its calculation method, as it describes peak power values that are well below that commonly reported in the literature for the same instrumentation. Although the authors did cite an investigation to explain their methodology [138], this reference only described upper-body maximal power, while calculations for lower body and the inclusion of BM are unknown. However, it is possible that the methodology only considered power applied to the barbell and disregarded power applied to the entire system (barbell + body) and therefore did not sufficiently explain the power production capabilities of the athlete [139]. These findings highlight the need for valid assessments of peak power output in loaded ballistic actions amongst higher- and lower-level competitors throughout all combat sports in this review. Although not a combat sport, it has been suggested that rugby league has similar mechanical and physiological demands to MMA [9]. In this sport, force-

dominant power capabilities have been reported to differentiate competition level [26, 27, 140] and this might therefore hold true in MMA [9]. Despite the methodological limitations of the reviewed studies, collectively this provides evidence that lower-body force dominant power capabilities are a differentiator of performance for grappling-based athletes across the spectrum of loads and striking-based athletes at lower external loads. Because of the combined striking and grappling components of the sport, this suggests that MMA athletes may have superior lower-body power production capabilities across the entire force-velocity spectrum. It is also conceivable that two distinct lower-body power profiles are present in MMA athletes. Specifically, grappling dominant fighters may excel under increasing loads underpinned by greater F_{max} , when compared with this, lower increases in force and marked velocity-based power could be indicative of MMA competitors who emphasise striking techniques (Fig. 3). Further research is needed to fully explore this contention.

4.2.2.2 Upper Body Greater upper body power was attained by elite karatekas at 30 % 1RM, but not 60 % 1RM during the Smith machine bench press [74]. In accordance with lower-body loaded power, this is likely explained by the velocity-centred demands of the sport, whereby rapid attacks are executed in primarily unloaded conditions and increased damage to an opponent is not necessary to achieve victory. Force-dominant upper-body power was found to be indicative of performance in wrestlers [36] but not in judokas [70] or BJJ competitors [81]. It is possible that differences in the upper-body clinching actions of judo and BJJ athletes, facilitated by the use of the gi (the uniform used for training and competition), may shift the demands away from those that are neuromuscular to a more metabolic adaptation. As grasping of an opponent's clothing is disallowed in MMA as it is in wrestling, it is reasonable to contend that the upper-body loaded-power capabilities of these athletes may more closely resemble wrestlers than judokas or BJJ competitors.

4.3 Anaerobic Capabilities

The contemporary body of scientific evidence suggests that MMA activity occurs at a work-to-rest ratio of approximately 1:2–1:4, with periods of high intensity activity typically lasting 6–14 s, and separated by lower intensity efforts of 15–36 s [19]. Such intermittent activity requires contribution from all major metabolic systems, particularly anaerobic glycolysis [54, 141]. In general agreement with this, for MMA bouts that extend the full duration, lactate accumulations reaching $20 \text{ mmol}\cdot\text{L}^{-1}$ have been reported [142], suggesting that high-intensity glycolysis is indeed a major energy supplier. Such increased levels match those

found in wrestling [143] and are greater than those found in striking sports such as kickboxing [144], boxing [145] and karate [146]. In further support of the importance of anaerobic contributions to MMA performance, it has been reported that, approximately 77 % of fights end as a consequence of high-intensity exertions lasting 8–12 s [19]. Such engagements may take the form of multiple high-powered strikes, or rapid changes in position which allow fight-ending techniques to be applied. Anaerobic supply of ATP represents approximately 90 % of all energy system contributions for maximal efforts lasting 10 s [23], thereby highlighting the critical role of this energy system in MMA combat.

4.3.1 Lower Body and Sports-Specific Anaerobic Capabilities

Anaerobic performance measures of the lower body were predominantly reported as superior in higher-level competitors. This enhanced ability was present in both grappling- and striking-based sports. Short- and longer-term lower body anaerobic capabilities appear to be an effective differentiator of competition level amongst these athletes. Longer-term efforts such as those expressed in a 30-s Wingate performance [75, 84, 87] and measures from a sports specific judo test [72] mostly differentiated superior competitors in grappling sports. In the only two studies that did not report a significant difference (and only a trivial to small ES), groups were stratified within competition level. Specifically, one study described national team representatives vs. reserves of that team [71], while the other described winners of a national championship compared with second- and third-place getters in that event [85]. Such a narrow distinction in competition performance decreases the potential to detect a physiological difference between groups. Regardless, when considered together these findings provide strong evidence of greater anaerobic capabilities in more competitive grappling athletes. The limited evidence available indicates mixed findings on the presence of superior short-term performance in these combat athletes. Specifically, while mean power in an 8-s abbreviated Wingate-type test distinguished higher-level competitors [82], superior grapplers in the heavyweight class only performed significantly better in the 10-m sprint, with no differences within the lightweight and middleweight divisions [36]. It is interesting to note that superior change of direction ability was reported in more competitive grapplers [75]. A unique interaction between a number of trainable qualities including reactive strength, maximal force and power in addition to technical factors distinguish this skill than more cyclical efforts [147]. Therefore, this provides evidence that such attributes may be particularly desirable amongst these athletes. Two

studies were reviewed that examined the anaerobic qualities of striking athletes. These investigations provided evidence of superior short- [83] and long-term [89] anaerobic performance. Underpinning these findings is the intermittent nature of combat sport activity. Striking-based sports such as Muay Thai and kickboxing report work to rest ratios of 2:3 and 1:2 [65], respectively. This is represented by 9-s effort periods for Muay Thai and 6-s work periods for kickboxing [65]. A work-to-rest ratio of approximately 3:1 has been determined for grappling sports such as judo [148] and wrestling [149], consisting of work phases of approximately 30 and 37 s, respectively. Taken together, this suggests that while both types of combat sport are intermittent and require expressions of short- and long-term anaerobic efforts, these sports might possess differing profiles. Specially, longer-term high intensity anaerobic qualities lasting approximately 30 s may better define successful grappling athletes, while short-term expressions could be more indicative of higher-level competitors in striking sports. Not unexpectedly, the MMA work to rest ratio of 1:2 to 1:4 [19] falls between what is described for these two categories of combat sport. Thus, while strong evidence is presented for the presence of a superior anaerobic profile in combat sports, the particular measures of this ability that may distinguish more competitive MMA athletes are unknown.

4.3.2 Strength Endurance, Muscular Endurance and Upper-Body Anaerobic Capabilities

In accordance with the findings of lower body anaerobic performance, this review presents strong evidence to support superior levels of this quality in the upper body of higher-level combat athletes also. However, only grappling-based sports were represented in the studies reviewed. A single investigation of the five reviewed failed to report a greater measure of upper-body anaerobic power in higher-caliber competitors [73]. In this case, groups were distinguished not by performance level, but rather by age. As described earlier, because of this stratification method, it is plausible that some competitors in the junior group were of a higher-performance standard than the senior athletes, thereby confounding any attempt to relate level of competition to physiological qualities.

A sports-specific measure of grip muscular endurance was also a differentiator of performance [86]. Although a dynamic component was involved, this test appeared to assess grip muscular capacity while performing the dynamic action rather than the dynamic action itself. As such, this more closely represented a measure of isometric muscular endurance across a single joint only and is therefore constrained by the aforementioned limitations of such testing.

Only grappling sports were represented in tests of strength endurance and dynamic muscular endurance. In the single study where strength endurance was assessed, each of the three relevant measures significantly distinguished the two competitive groups [82]. This is of notable importance considering the low subject numbers in each strata ($n = 5$). However, only one [76] of the three studies quantifying dynamic muscular endurance reported this quality as significantly greater amongst higher-level competitors, while trivial effects existed in the remaining two articles [77, 78]. For each of these reports, bench press repetitions to a metronome were used to assess this capacity. Such a measure requires force production that is augmented or paced so that maximal effort is not applied throughout, or for every action within the test. These findings suggest that the repetitive actions displayed by these athletes might generally not be applied in a paced manner, but rather with maximal intent. As grappling sports formed the entirety of the studies reviewed for strength endurance, muscular endurance and upper body anaerobic capabilities, no conclusions can be reached regarding their influence on striking sports. Taken together there is strong evidence to suggest that superior RFD-based anaerobic capabilities are present in more competitive grappling athletes. This also indicates that it would be worthwhile exploring strength endurance characteristics in both MMA- and striking-based combat sport competitors.

4.4 Aerobic Capabilities

The scheduled duration of a typical MMA bout is considerably longer than the other combat sports investigated. In particular, matches are generally allocated three rounds of 3 min and two 3-min rounds, for amateur boxing and international wrestling respectively, while a continuous 5-min match for international judo competitors is commonplace. It is likely for this reason that $\dot{V}O_{2\max}$ was often not superior amongst higher-level competitors in this present review. This is further reinforced by magnitude-based inferences that indicate a range of only trivial to moderate effects towards higher performing wrestlers, while small positive or negative effects were mostly present in more successful judokas and karatekas. In contrast to this, one recent study did report a significant difference between groups underpinned by a very large positive ES amongst international judo competitors [82]. Although limited conclusions can be drawn from these findings in relation to MMA, the unique physiological responses to the extended HIA within this sport can still be understood. With work periods of approximately 10 s combined with active recovery phases of 15–36 s [19], MMA closely resembles the activity-time structure of repeated sprint sequences

[150]. Such a mode of HIA has been reported to elicit periods of $\dot{V}O_{2\max}$ during work intervals in elite athletes [54], and may do so to an even greater extent in MMA athletes owing to the extensive ballistic and agility actions applied during the activity cycles. Additionally, conditioning training recommendations for MMA consider this demand and suggest high volumes of HIA based on this work-to-rest ratio [9]. This activity would likely lead to several minutes per session at $>90\%$ $\dot{V}O_{2\max}$ [54], resulting in considerable stress on the mechanisms underpinning this quality and thus provides a powerful stimulus for adaptation [151–153]. Such a metabolic stimulus promotes recruitment of type II muscle fibres [154, 155] in combination with greater cardiac output, which is driven by increased stroke volume and associated myocardium enlargement [151]. Accordingly, superior aerobic power values have been reported for MMA athletes. In an assessment of five mixed martial artists, who were described as elite but with competition level otherwise not defined, an average value of $62.75 \pm 4.86 \text{ mL}\cdot\text{kg}^{-1}\text{min}^{-1}$ was reported [156]. This is similar to that of a professional boxer [157] and considerably greater than values reported for regional level MMA fighters in a separate investigation ($55.5 \pm 7.3 \text{ mL}\cdot\text{kg}^{-1}\text{min}^{-1}$) [99]. The elite MMA values are substantially higher than those produced by the higher-level competitors in this review, including international karate fighters ($57.6 \pm 3 \text{ mL}\cdot\text{kg}^{-1}\text{min}^{-1}$) [89] wrestlers who were national champions ($54.9 \pm 6.7 \text{ mL}\cdot\text{kg}^{-1}\text{min}^{-1}$) [84] or medalled in international competition ($57.1 \pm 5.7 \text{ mL}\cdot\text{kg}^{-1}\text{min}^{-1}$) [84], elite amateur boxers ($57.52 \pm 4.7 \text{ mL}\cdot\text{kg}^{-1}\text{min}^{-1}$) [69], and international Brazilian judo players ($48.3 \pm 8.17 \text{ mL}\cdot\text{kg}^{-1}\text{min}^{-1}$) [72]. This provides evidence of a distinction between MMA and the other reviewed combat sports, represented by increased aerobic power capabilities. However, differing modes and methods of quantification across studies and a small sample of elite representatives ($n = 5$) limit the ability to draw solid conclusions from these findings. Additionally, despite the intermittent nature of combat sport activity, only one of the reviewed studies assessed aerobic capacity using an intermittent test. This article reported a significantly superior performance by more successful competitors [90] and provides further evidence that such intermittent-activity measures may provide a more valid method of quantifying endurance capabilities in these athletes.

5 Constructing the MMA Profile

This review concluded that maximal isometric and dynamic strength, in addition to high-force neuromuscular power is often greater in superior grappling athletes, and

that this causes a shift of the force–velocity relationship through to dominance under velocity-based conditions in many cases also. When compared with these competitors, successful combat athletes from striking sports may show a less pronounced increase in high-force efforts, with a more clear distinction from lower-tier competitors in rapid expressions of force under lighter loads. Because of the requirements for both methods of combat in MMA, it is likely that higher-level competitors in this sport possess enhanced capabilities throughout the loading spectrum. Additionally, differences may also be present within competition grade between striking dominant and grappling dominant MMA athletes. Despite the possibility of enhanced aerobic performance in elite MMA athletes, such qualities could not definitively be established as a marker of superior combat sport competitors in the context of this review. For this reason, evidenced-based conclusions cannot be drawn. However, this review has revealed anaerobic capabilities as a defining characteristic of more successful combat sports athletes. Considering the similarities between the reviewed combat sports and MMA, in addition to time-motion and technical-tactical analysis [19], it is reasonable to conclude that such capacities are also a defining characteristic of the more competitive mixed martial artist. Like strength and neuromuscular power, it appears that anaerobic profiles also differ between grappling and striking athletes. It is possible that both short- and long-term anaerobic performance are markers of higher-level MMA competitors, and these enhanced attributes may be present to differing magnitudes depending upon combat sport history and strategy. Specifically, MMA athletes with a predominantly striking background or who more effectively use these methods of attack might possess physiological characteristics that more closely resemble striking-based combat athletes. This would include heightened short-term anaerobic traits, which may be expressed at a work-to-rest ratio that is near the shorter values of the range reported for MMA competition. In contrast, grappling-dominant MMA competitors might

display abilities that are skewed towards athletes from grappling sports. Such a profile would contain superior longer-term anaerobic qualities applied at an extended work to rest ratio within the window reported for MMA. Taken together, it is plausible that two separate yet inter-related performance profiles define the elite mixed martial artist, and these differences extend from strength-power qualities to metabolic adaptations (Table 7). However, this raises the question of whether one profile is more successful than the other. An examination of technical and tactical analysis of MMA bouts provides insight into this. Del Vecchio et al. [19] reported that approximately twice as many fights ended during high-intensity groundwork sequences (50 %) than as intense striking exchanges (26.9 %). In conjunction with the aforementioned lactate levels, which more closely resemble grappling than striking sports, this provides support to the suggestion that MMA might hold greater similarities to grappling than striking disciplines [9]. Such findings indicate that a grappling dominant physiological profile might more often define higher-level performance in this sport. However, to better understand the combat methods that contribute the greatest to MMA success, a detailed performance analysis on elite bouts is needed to support this notion.

6 Conclusion

This review represents a step towards a determination of the physiological characteristics that differentiate higher- from lower-level MMA athletes. While a number of markers indicated superior competition performance in combat athletes, there is evidence to suggest that grappling and striking disciplines have differing metabolic and mechanical demands. Considering the requirement for both combat methods in MMA, this leads to the conclusion that a spectrum of specific physiological markers likely define higher-level performance. Additionally, it gives rise to the possibility of two alternate, yet associated, performance

Table 7 Proposed physiological profiles of higher-level mixed martial artists

Physiological quality	Profile type	
	Grappling dominant	Striking dominant
Neuromuscular power	Force emphasis underpinning a shift through to unloaded conditions	Velocity emphasis, with lesser increases under higher force conditions
Maximal force	Both isometric and dynamic strength attributes, with greater overall force capabilities than a striking profile	Greater dynamic than isometric strength capabilities
Anaerobic capabilities	Longer-term anaerobic performance (~30 s). Superior strength endurance	Short-term anaerobic performance (~10 s)
Intermittent anaerobic capabilities	1:2 work-to-rest ratio	1:4 work-to-rest ratio

profiles within more successful mixed martial artists. However, these findings should be considered within the limitations of this review. Specifically, the reliance on separate, although related, sports prevents solid conclusions from being drawn. Primary investigations into the physiological determinants of higher- vs. lower-level MMA performance are needed to confirm the suggestions of this analysis. Regardless, these findings are drawn from the scientific evidence available via the process of systematic review and therefore represent the most accurate conclusions to date on this topic. Such information can assist sports scientists in directing training interventions to the qualities that are most likely to enhance performance, while forming the foundation of athlete performance monitoring and physiological diagnoses. This review has also highlighted the considerable gaps in the literature across all combat sports reviewed. It is recommended that thorough investigations are conducted to accurately determine which mechanical and metabolic attributes distinguish more successful competitors in each of these sports.

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