Impact of rapid weight reduction on health and performance related indicators of athletes representing the Olympic combat sports

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B Data Collection
C Statistical Analysis
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Abstract

Background and Study Aim: Rapid weight reduction (RWR) may cause a potential health risk and decreases athletic performance. The cognitive goal of this review is to summarise profound aspects of RWR by Olympic combat sports athletes (boxing, judo, taekwondo and wrestling).

Material & Methods: A comprehensive literature search was performed to identify articles on the specific contexts of RWR in this review. Extensive literature research was conducted using PubMed and Google Scholar with relevant keywords applied.

Results: RWR methods used by the athletes include food restriction, dehydration and intensive exercise. After RWR increased oxidative stress, an imbalance of electrolytes and hormones, decreased glycogen or changes in blood flow, as well as decreased plasma volume, have been reported. Hemorheological properties such as deformability and aggregation of red blood cells are impaired after RWR, which may in part be related to impaired nitric oxide generation. Further, RWR was associated with a peak value of plasminogen activator inhibitor-1 (PAI-1) in the morning of the human circadian system which also damages cardiovascular events and endangers their health. RWR related impairments included impaired oxygen consumption, aerobic and anaerobic capacity, muscle strength, psychological concentration and targeted sport-specific performance of combat sports athletes.

Conclusion: A long-term plan for weight reduction should be individually created, and body weight of athletes should precisely be controlled. If RWR is preferred as weight loss, athletes and coaches should avoid high-intensity training in the morning during RWR due to impaired physiological responses. International, National and Regional federations of Olympic combat sports should control weight cutting.

Key words: health risks • hemorheological properties • microcirculation • performance • nitric oxide • weight loss

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Hemorheological properties – red blood cell deformability and aggregation are important for the microcirculation affecting flow resistance.

RBC deformability – RBC must deform to pass through capillaries and to supply O_2 to the working muscle and organs. Blood fluidity, cell surface area-to-volume ratio and physiological properties of the membrane and cytoskeleton affect RBC deformability.

RBC aggregation – indicated by face-to-face rouleaux formation upon changes in plasma protein concentration.

NO – nitric oxide is produced during the conversion of L-arginine to L-citrulline by red blood cell-NO synthase.

PAI-1 – plasminogen activator inhibitor-1 that inhibits fibrinolysis.

Minimum weight – is determined based on the preseason body fat and body weight.

Health risk – *noun* a situation in which there is a risk to health caused by something such as not following safety procedures [148].

Weight loss – *noun* the act of losing weight or of becoming thinner [148].

Weight reduction – *noun* same as weight loss [148].

INTRODUCTION

Combat sports such as boxing, judo, taekwondo and wrestling are subdivided into various weight categories. Most athletes aim to fight in a lower weight category than their normal weight would allow. For this purpose, athletes of combat sports reduce their body weight by 5-10% in less than one week [1-4], which is referred to as rapid weight reduction (RWR). The main reason for this procedure is to compete against smaller and weaker opponents in the next lighter weight class which may be advantageous in regard to winning the competition [3, 5-11]. Education of trainers and athletes is necessary to avoid potential health risks and decreased athletic performance associated with RWR [3, 4]. RWR is achieved by fasting, dehydration, sauna session, increased training intensity while wearing thermal clothing and prohibited use of diuretic and laxative medication [3, 4, 12-15].

Athletes mostly lose body water which leads to disturbances of the metabolism. Symptoms associated with RWR include increased resting and submaximal heart rate, increased oxidative stress, an imbalance of electrolytes with a lack of sodium and potassium and glycogen or changes in blood flow associated with decreased plasma volume [16-18]. Reduced glucose and glycogen levels might induce hypoinsulinaemia and increased cortisol concentration because the glucose metabolism is associated with the level of circulating insulin and cortisol [14, 19-22]. RWR was also related to reduced serum testosterone and luteinizing hormone levels in wrestlers that may represent a damage of protein nutrition. This impairs the function of hypothalamic-pituitary-gonadal axis and especially impairs the growth of adolescent athletes [21, 23-26].

Dietary restriction (fasting) might negatively affect psychological mood state which includes increased tension, anger, fatigue, depression and decreased vigour (scale values) [4, 14, 19, 27]. Furthermore, a recent study suggests that RWR in taekwondo athletes diminishes hemorheological properties, such as deformability and aggregation of red blood cells (RBC) [28]. This is suggested to impair blood flow through the microcirculation and thus to reduce athletes exercise performance [4, 28, 29]. All these physiological changes may decrease aerobic and anaerobic capacity, muscle strength, and targeted performance of combat sports athletes [4, 16, 23, 30-36]. It is also indicated that RWR reduces mental functions such as concentration, memory or cognition, which additionally negatively affects athletic performance [4, 7, 37-40]. However, study design, study population, form of combat sport and RWR strategies vary between the different studies.

The cognitive goal of this review is to summarise profound aspects of RWR by Olympic combat sports athletes (boxing, judo, taekwondo and wrestling).

This knowledge should help to develop new strategies to reduce weight prior to competition to avoid health risks and a decrease in athlete's performance (application goal).

MATERIAL AND METHODS

Research and review articles regarding RWR or important outcomes of further studies were employed in the present review. The underlying literature research was performed using PubMed and Google Scholar databases using the following keywords (either alone or in combination): combat sports, taekwondo, judo, wrestling, boxing, rapid weight reduction, short-term weight loss, methods of rapid weight loss, dehydration, water loss, hypohydration, fasting, caloric restriction, dietary restriction, physiological performance, psychological performance, athletic performance of weight loss, blood, hemorheological properties, hemorheology of rapid weight reduction, cognitive function, health of weight reduction. A total of 148 publications fit the criteria mentioned above and were summarised. Used publications were published between 1972 and 2017. Study population described included combat athletes.

RESULTS

Strategies for RWR and recovery after weigh-in

Over 60% of combat athletes use RWR in preparation for upcoming competitions [7]. In detail, 89% of Brazilian judo athletes, 89% of Olympic United States (US) wrestlers, 60-70% of high school Olympic US and Iranian wrestlers apply RWR methods [3, 34]. A cross sectional study (questionnaire) showed that 72% of the investigated wrestlers believe that RWR supports their athletic performance, but a similar percentage (77%) of all subjects indicated that RWR has negative side effects [41]. The impact of RWR on athletic performance is controversially discussed in the literature because different RWR protocols were applied which differed in length and percental weight loss of the participants (Table 1). Common strategies of RWR include fasting and increased training volume and intensity while wearing synthetic clothes to prevent heat loss and to increase core body temperature which increases the loss of body water. Also, excessive sauna sessions or hot water baths were applied to dehydrate the body [7, 8, 12, 14, 42]. In this regard, diuretics were also used as a strategy to lose body water although the use of diuretics is prohibited World Anti-Doping Agency due to impaired athlete´s performance [43, 44].

The recovery period between weigh-in and competition depends on the time lapse between weigh-in and competition and varies between different types of sport. Boxers have to absolve weigh-in in the morning of the first competition

Table 1. Studies regarding combat athletes through different subjects, strategies, durations and percentages of rapid weight reduction.

References	Subjects	% of weight reduction and duration	Method	Core results
Artioli et al. [3]	Judo athletes	5% during 5 days + last 3 days (food records)	Usual methods of athletes: severe energy restriction and hypohydration-inducing methods (decreasing fluid intake, exercise with plastic suits and exercising in heated environments)	↓ Relative total work (upper-body Wingate test) → Number of attacks in the judo combats ↓ Glucose concentration
Coufalova et al. [139]	Judo athletes	4.6% during 5 days	Exercise-induced sweating and reduced energy intake	↓ Extracellular water ↓ Intracellular water Maximal isometric strength ↓ (Trunk flexion)
Degoutte et al. [14]	Judo athletes	5% during 1 week	Self-determined methods of athletes: food restriction, resistance training and judo training sessions (2h) and conditioning training per day	↓ Left-hand grip ↑ Tension (POMS) ↑ Anger (POMS) ↓ Vigour (POMS) ↑ Fatigue (POMS) ↓ Testosterone ↓ Insulin ↑ ACTH ↑ Cortisol ↑ DHEA-S ↑ Urea ↑ Uric acid ↑ Glycerol ↑ Free fat acid ↓ Triglycerides
Durkalec-Michalski et al. [138]	Boxers	5.4% during 7.8 days	Caloric restriction and training session	↓ Anaerobic capacity (Wingate test)
Fogelholm et al. [13]	Wrestlers and judo athletes	6% during 2.4 days compared to 5% GWR during 2 months	Fluid and diet restriction and exercise with a plastic suit	↓ Vertical jumps → Anaerobic capacity (Wingate test) Imbalance of electrolytes ↓ (Mg^{2+})
Hickner et al. [137]	Collegiate wrestlers	4.5% during 3 days	Sauna, exercise induced sweating, voluntary fluid restriction and caloric restriction	↓ Upper-body power output ↓ VO_{2max} ↓ Sprint work
Karila et al. [21]	Elite wrestlers	8.2% during 3 week GWR + final RWR (2 days)	Caloric restriction (800-2000 kcal·d^{-1}), dehydration and sweating at heavy physical exercise and in a hot sauna	↓ Hb ↑ Hkt ↑ Creatinine Imbalance of electrolytes ↑ (Na^+) ↓ (K^+) ↑ (Mg^{2+}) ↓ Testosterone ↑ Sex-hormone-binding globulin ↓ Luteinizing hormone

References	Subjects	% of weight reduction and duration	Method	Core results
Koral et al. [15]	Elite Judo athletes	Combination of GWR (4 weeks) and RWR (6 days) 2-6%	Food restriction, sweating through exercise in plastic suits to dehydration during judo training and conditioning sessions	↓ Judo performance (tokui-waza) ↓ Vigour (POMS) ↓ Confusion (POMS)
Kowatari et al. [90]	College judo athletes	3.6~4.4% 20 and 5 days before the competition	Low energy intake, very-low energy intake, weight training for 1h and judo training for 2.5h every day	↑ Neutrophil oxidative burst ↓ Total phagocytic activity
Kurakake et al. [74]	Judo athletes	<3~≥6%, 4 days before matches	Initiated methods of training and calculated nutrition(carbohydrates, fat and protein)	↑ CK ↑ Total cholesterol ↑ Free fatty acid ↑ Triglyceride ↓ Grip strength
Reljic et al. [100]	Boxers, judo, taekwondo athletes, wrestlers	>5% during 5-7 days	Food and fluid restriction and increased sweat loss in the last 2 days before competition (79% of subjects)	↓ Hb_{mass} ↓ Erythropoietin ↓ Reticulocytes ↓ Haptoglobin ↓ Triiodothyronine ↓ Free androgen index → $VO2_{peak}$
Reljic et al. [49, 60]	Elite amateur boxers	5.6% during 5 days and 1 week after competition	Usual methods of athletes: food and fluid restriction, excessive sweat loss (daily sauna, exercise with warm or rain clothes)	↓ Extracellular water ↓ tHb_{mass} ↓ Blood volume → VO_{2max} → Antioxidants → Oxidative stresses
Tarnopolsky et al. [57]	Wrestlers	5% during >72 h	Energy and fluid restriction, exercise and dehydration with sauna	↓ Muscle glycogen concentration (biopsy)during the simulated match
Timpmann et al. [47]	Trained wrestlers	5% during 3 days	Energy and fluid restriction (high carbohydrate diet), exercise in thermal clothing and sauna sessions	↓ Upper body intermittent sprint performance ↑ Urine specific gravity ↑ Fatigue (PANAS-X scale)
Yang et al. [4, 28]	Taekwondo athletes	5% during 4 days compared to 5% GWR during 4 weeks	Individual method of athletes: higher training intensity, training session with thermal clothing, fasting and dehydration	↓ Kick frequency ↓ Glucose ↑ CK ↑ Urea ↑ Creatinine ↓ Perceived Physical State Imbalance of electrolytes ↑ (Na^+) ↑ (Mg^{2+}) ↓ RBC-NOS ↓ RBC-NO ↓ RBC deformability ↑ RBC aggregation
Silva et al. [50]	Judo athletes	≥2% 1-3 days before competition	Fluid and food restriction, regular judo training sessions (in the morning and evening; each 2 hours)	↓ TBW ↓ ICW ↓ ECW ↓ LST ↓ FMS

VO_{2max} maximal oxygen uptake; **Mg^{2+}** magnesium; **CK** creatine kinase; **Hb** haemoglobin; **Hkt** hematocrit, **Na^+** sodium; **K^+** potassium; **POMS** profile of mood state; **ACTH** adrenocorticotropic hormone; **DHEA-S** dehydroepiandrosterone sulphate; **Hbmass** hemoglobin mass; RBC red blood cell; **NO** nitric oxide; **NOS** nitric oxide synthase; **TBW** total body water; **ICW** intracellular water; **ECW** extracellular water, **LST** lean soft tissue; **FMS** forearm isometric strength; ↓ significant decrease; ↑ significant increase → no.

day followed by repeated weigh-in sessions every morning of every competition day (successive competitions on separate days). Thus, the recovery time ranges from 3 to 12 hours between weigh-in and competition. In judo, taekwondo and wrestling, athletes conduct weigh-ins in the evening before the competition day and the recovery time is about 16 hours. All matches of these combat sports are conducted on the same day which indicates that athletes need to be fit to sustain athletic performance. However, judo athletes are randomly checked in the morning of competition to verify a stable weight. Athletes showing weight differences between weigh-in and competition day of more than 5% can be disqualified [11].

So far, recovery time differs between the different types of sport, and it is unclear whether the athletes are fully recovered from dehydration prior to competition. Up to now guidelines or recovery strategies (e.g. from dehydration) do not exist in practice because a full recovery depends on the level of fluid loss, health situation and the time lapse between weigh-in and competition [45]. Combat athletes aim to restore lost body fluid after weigh-in which usually occurs around 16 hours before competition. However, studies showed that this recovery time is inadequate to restore fluid homeostasis because this takes about 24-48 hours [4, 16, 46, 47].

Loss of body water

The body water is a central component of all cells in the human body and is necessary for various functions such as electrolyte homeostasis [22]. RWR-induced dehydration/loss of body water reduces plasma volume and leads to an imbalance of electrolyte balance [4, 10, 13, 17, 18, 32, 48, 49]. Dehydration through increasing sweating can impair the metabolic system. Passive sweating (sauna session) prior to exercise decreases sweat rate, plasma volume and hence stroke volume, followed by an increase in serum osmolality, hematocrit, heart rate and body heat storage. These changes are less distinctive if the loss of body water is caused by exercise (active sweating) [48]. Therefore, combining fluid restriction and active sweating may reduce performance to a lesser extent compared to passive sweating [11]. The body fluid is differentially reduced in extracellular, interstitial, and intracellular areas by acute dehydration [12, 17]. Costil et al. [17] investigated how acute dehydration affects plasma and muscle water showing that plasma and interstitial water was significantly decreased (−4.0 and −7.8%, respectively) by a 2.2% acute weight reduction. In contrast, the intracellular water was only reduced by 1.5%. Calculation of extracellular and intracellular water losses (ECW and ICW) reported 70% of ECW and 30% of ICW. The difference in the distribution of body water in both areas depends on the osmotic pressure, as well as the oncotic influence of the ions. Most likely the difference in osmotic pressure after dehydration appears to shift fluid from the intracellular area to the extracellular area.

Another study of Silva et al. [50] showed that decreased total-body water (2.7%) in judo athletes was associated with loss of ICW and ECW of 4.5 and 0.3%, respectively and resulted in reduced forearm isometric strength (FMS). Probably, the cellular volume is an important signal for the metabolic orientation. Indeed, cellular swelling affects anabolism, while cellular shrinkage induces catabolism [51-53]. Thus, one reason of decreased FMS observed in the study of Silva et al. may be a higher reduction in ICW [50].

Dietary restriction

RWR includes not only water loss by applying different methods such as sauna sessions, but also extreme food restriction. The hypocaloric diet lasts 4-5 days [4, 19, 28, 54] and carbohydrates are mainly omitted. Largely, extreme food restriction is applied by athletes during RWR such as hypocaloric diet lasting 4-5 days (range of weight reduction: 2.4-4.3 kg, 3.1-6.2%) [4, 19, 28, 55]. This method includes the restriction of carbohydrates. However, glycogen availability is associated with the anaerobic performance during short-term or high-intensity exercise [3, 56]. Glycogen concentration was measured in muscle tissue after RWR (>5% of total body weight in wrestlers) with carbohydrate intake restricted by the athletes to 350 $g \cdot d^{-1}$. The results revealed a significant decrease of biceps brachii glycogen concentration. The results further showed that RWR caused a 54% decrease of muscle glycogen during the simulated match [57]. Another study indicated decreased glycogen levels in the vastus lateralis by nutritional restriction including depletion of carbohydrate [31]. The decreased glycogen storage following a severe weight reduction can last 24 h or longer [16]. Furthermore, fasting also reduced vitamin status (e.g., vitamins A, C, E) which could increase oxidative stress and damage lipids (like cell membrane), proteins and other cell components [58-60]. During RWR, protein intake may also be reduced. This could cause high exercise-induced micro-damage to muscle fibres and impair energy availability during exercise [61, 62]. Through fasting, fat, an essential element of the cell membranes, is barely consumed, which may also impair energy metabolism, transport of fat-soluble vitamins and intake of essential fatty acid [63].

The physiological stresses of combat sports athletes are caused by acute dehydration and fasting during RWR. Decreased levels of glucose and glycogen stores during reduced intake of carbohydrates can negatively affect the metabolic system and may cause hormonal imbalance, e.g. of the cortisol balance. RWR alters lipid profiles with a decrease in triglycerides leading to an increase in fat-free acid and glycerol concentration. This may increase lipolysis in adipose tissue and circulating triglycerides. Increased cortisol sensitivity and secretion improves lipid utilisation [14, 20]. However, increased lipolysis of adipose tissue in combat athletes of light weight class can impair their health because of the reduced percentage of body fat. In this regard, the low percentage of body fat can lead to decreased testosterone levels in male athletes and menstrual dysfunction in female athletes [1, 16, 64, 65].

Adenosine triphosphate (ATP) resynthesis was shown to be impaired when muscle glycogen levels decreased and associated with reduction of muscular performance of athletes [16, 54, 57]. Also, adenosine monophosphate (AMP) accumulation and ammonia production are increased in conditions of reduced glycogen, which also impairs the performance of the exercising muscles [4, 57, 66]. Hypoglycemia triggers a decrease in insulin (hypoinsulinemia) that in turn increases the levels of growth hormone, cortisol, adrenocorticotropic hormone (ACTH) and dehydroepiandrosterone sulfate (DHEA-S) which are stress hormones and influenced by physical and psychical stress. ACTH and DHEA-S affect adrenal glands and used to suppress ovarian or testicular origin of excess androgen [14, 19, 21, 22, 67]. Furthermore, reduced testosterone levels were found in wrestlers after RWR [21, 23]. Thus, RWR-induced undernourishment impairs testosterone levels, [14] and this hormonal imbalance may especially impair the athletic performance and the growth of adolescent athletes [23].

Mechanical impairments of muscle function

An imbalance in sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) levels shown after RWR alters the muscle action potential (AP) [12, 17]. AP is affected by multifunctional factors, e.g. membrane potential and intracellular and extracellular Na^+ and K^+ concentrations [68]. Impaired AP including displacements of the threshold potential can favour K^+ accumulation in the extracellular area that may reduce muscle excitability and force development [69, 70]. Decreased ATP (ATPase) levels caused by the reduction of glycolysis may also negatively affect the activity of Na^+-K^+ pumps in the transverse tubule [70-73]. These dysfunctions further reduces the release and Ca^{2+}-contraction through triad junction between the t-system and the sarcoplasmic reticulum (SR) and intracellular Ca^{2+} handling such as Ca^{2+} release from SR. This may also be inhibited by reduced ATP and increased Mg^{2+}, Ca^{2+} sensitivity of the contractile proteins and thus impair muscle contraction and favour muscle fatigue [70].

Moreover, RWR increases creatine kinase (CK), urea and creatinine levels [4, 14, 74, 75]. Increased CK levels are caused by increased training intensity but also by dehydration during RWR. High CK level impairs Z-band muscle fibres. The condition of hydration affects CK level because lowed muscle K^+ may be caused by dehydration [76]. This may increase the muscle susceptibility to injury [4, 77]. Elevated urea concentrations provoke an imbalance in protein metabolic homeostasis and increase protein catabolism which can also lead to tissue damage and fatigue [14, 74, 75, 78]. During RWR, increased ammonia caused by high-intensity training infers from the first area of the purine nucleotide cycle catalysed by adenylate deaminase. This occurs in all muscle fibres in relation to the intensity of the metabolic stress and glycogen availability [14, 78]. Few studies also describe an increased level of creatinine caused by a hypocaloric diet which was associated with damages of the muscle tissue. This relation was shown by changes of heart fatty acid binding protein, troponin, and myosin heavy chain [21, 79, 80].

Oxidative stress

Increased exercise intensity and decreased nutritional status may result in overproduction of reactive oxygen species (ROS) thus favouring oxidative stress. ROS are produced by physiological metabolism or external stimuli and include superoxide anion radical (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radical (·OH). ROS can cause cell and tissue damages and lipid peroxidation that is correlated with skeletal muscle damage [81-84]. Antioxidants such as uric acid, glutathione and melatonin but also vitamin A, C, E can reduce the effects of ROS [58, 63, 85]. High-intensity exercise is known to damage lipids, proteins and other cell properties which can lead to accelerated ageing and various diseases, including cardio vascular diseases, cancer, Alzheimer´s disease and Parkinson´s disease [58, 86-88]. Furthermore, Lipid peroxidation of the RBC membrane can be induced by the exercise [81, 83]. Oxidative stress was shown to reduce nitric oxide (NO) bioavailability which can impair hemorheological properties (see below) [28, 89]. The relation between RWR and oxidative stress is controversially discussed. Reljic et al. [60] were unable to show significant changes in antioxidants and oxidative stress markers after RWR in judo athletes. In contrast, thereto, other studies reported an accumulation of oxidative stress in judo athletes and a significant increase of 8-hydroxy-2´-deoxyguanoxine (8-OHdG) in wrestlers after RWR. 8-OHdG is a predominant marker indicating oxidative damage of DNA molecules and assessed in urine samples [82, 90]. The differing outcomes may be the result of differing study design including varying duration of food restriction, vitamin intake during the study, sweating status or exercise intensity [60].

Hematology and hemorheology

Dehydration not only reduces plasma volume but also increases hematocrit (Hct). High Hct levels increase blood viscosity and decrease cardiac output which can impair oxygen (O_2) supply to the muscle cells and thus muscular function [29, 91, 92]. Increased blood viscosity increases blood flow resistance in capillaries, including muscle capillaries [93]. However, Hct levels are not necessarily increased during the loss of body water or dehydration [28, 94, 95]. Studies have shown that loss of more than 3% of body mass is necessary to affect plasma volume [95, 96] and thus hematocrit. The plasma volume is dependent in an attempt to maintain the cardiovascular stability. This can be activated by homeostatic mechanisms such as stroke volume, arterial blood pressure and hormones (vasopressin, angiotensin and aldosterone) that retain body fluids [96, 97].

Other hematological indicators like RBC count, hemoglobin concentration (Hb), mean corpuscular volume (MCV), mean cellular hemoglobin (MCH), and mean cellular hemoglobin concentration (MCHC) were shown to be negatively affected by RWR and this correlated with impaired performance capacity [28, 29, 89, 93, 98, 99]. According to Reljic et al. [49, 100], haemoglobin mass (Hb_{mass}) was reduced by 4.1% and 5.3%, respectively after RWR of >5% body weight in combat athletes. The reduction in Hb_{mass} was a determining factor of reduced peak oxygen uptake (VO_{2peak}). Also, reduced erythropoietin, reticulocytes, haptoglobin and triiodothyronine levels were found after >5% RWR within 5-7 days finally leading to decreased erythropoiesis. Moreover, food and fluid restriction during RWR decreased erythropoiesis, erythropoietin (EPO) concentration and increased hemolysis which is associated with the reduced aerobic performance [100-102].

RBC deformability and aggregation are important for the microcirculation affecting flow resistance, oxygen supply and finally exercise performance [28, 29, 103, 104]. RBC must deform to pass through capillaries and to supply O_2 to the working muscle and organs. Blood fluidity, cell surface area-to-volume ratio and physiological properties of the membrane and cytoskeleton were shown to affect RBC deformability [105, 106]. RBC deformability is also influenced by NO availability. NO is produced during the conversion of L-arginine to L-citrulline by RBC-NO synthase (RBC-NOS) [107, 108]. Thus, RBC-NOS activity affects deformability and may thus affect the O_2 supply of the muscle and organs within the microcirculation [109-111]. Variables associated to RWR including reduced nutrition, increased exercise and loss of body water, leading to reduced blood and plasma volume, increase in Hct, and reduction in NO availability, were all shown also to alter hemorheological properties [29].

Plasma macromolecules and fibrinogen affect RBC aggregation indicated by face-to-face rouleaux formation upon changes in plasma protein concentration [104]. RBC aggregation can affect hemodynamics, RBC distribution, and flow dynamics in the microcirculation. Accordingly, low protein intake through caloric restriction appears to relate to the increase of fibrinogen and aggregation [81]. Brun et al. [89] described a negative correlation between fibrinogen and protein intake. Also, a further negative correlation between RBC disaggregation threshold and protein intake was indicated [81]. Pathological increase in RBC aggregation may reduce tissue perfusion, which leads to a reduction in performance capacity [28, 29, 112, 113].

Yang et al. [28] recently investigated how a 5% RWR within 4 days and 5% gradual weight reduction (GWR) within 4 weeks affect the hemorheological indicators deformability and aggregation in taekwondo athletes. In contrast to GWR, RWR led to a significant reduction of RBC-NOS activation, reduced NO production and RBC deformability. Reduction of RBC-NOS activation may be caused by a reduced intracellular calcium level because calcium and its binding to calmodulin were described to be essential for NOS activity [114, 115]. Another reason for decreased NO levels measured during RWR is a reduced nitrate/nitrite uptake. The main dietary source of nitrate and nitrite is green leafy vegetables such as lettuce and spinach [116]. Nitrite represents an important NO storage pool which is converted from nitrate by the oral cavity commensal facultative bacteria using specific nitrate reductase enzymes [116, 117]. Yang et al. [28] calculated that only 6.4 ± 8.9% of the ingested calories during RWR originated from mixed vegetables. Under normal conditions 12.3 ±13.4% of ingested calories originate from green vegetables. A decrease in RBC deformability was associated with decreased glucose and thus reduced ATP levels, which results in membrane loss and alterations in rheological properties such as deformability [28, 110, 118, 119].

Blood lactate is also a critical factor for the rheological properties [89, 93, 120]. However, the relationship between increased lactate and rheological parameters is still controversially discussed. Some studies indicated that lactate impairs RBC deformability in untrained subjects but increased deformability in trained individuals [120]. Lactate scavenges radicals such as OH and O_2 which are generated in hepatocytes by Fenton and Haber-Weiss reactions. These radicals initiate membrane lipid peroxidation [121]. Thus, accumulation of lipid peroxidation might be prevented by lactate as a potential antioxidant [83, 121].

RWR was shown to increase RBC aggregation and aggregate strength [28]. Dehydration observed during RWR may increase blood viscosity finally leading to hyper-aggregation which in a current study was also emphasised by the result of increased disaggregation threshold during RWR [28]. Hyper-aggregation in the microvascular circulation decreases arteriolar blood flow velocity and reduces perfusion of capillaries [122]. Ultimately, these impaired rheological indicators in RWR can reduce tissue perfusion and thus decrease muscle strength, anaerobic power, and endurance capacity of athletes [16, 19, 23, 122].

The fibrinolytic activity, which reduces thrombus in blood vessels, is decreased in the morning because of an increase in plasminogen activator inhibitor-1 (PAI-1) with peak values of PAI-1 in the morning (~6:30 $_{AM}$) [123]. PAI-1 was shown to inhibit fibrinolysis [55, 123, 124]. Thus, athletes should avoid high-intensity exercise sessions in the morning during RWR because this may increase the risk for occlusive thrombus development and increases the risk of cardiovascular events in the morning.

Psychological effects during RWR

RWR also affects the psychological performance of athletes and should be considered during preparation of the competition. Weight loss significantly alters the neuroendocrine and sympathetic nervous systems. Loss of body water may adversely affect psychological performances [11, 125, 126]. Reduced acute memory, vigour, concentration and increased confusion, rage, fatigue, depression and isolation were associated with RWR conducted by wrestlers and judo athletes [14, 35, 54, 127]. Dietary restriction and high-intensity training sessions during RWR can trigger a feeling of weakness before the competition [14, 38-40, 128]. Another study of Escobar-Molina et al. [129] with different judo athletes indicated that female athletes were more concerned about their weight reduction and showed higher anxiety: they received higher scores on the emotion scale and showed more eating disorders symptomatology although weight reduction was lower than male athletes. Anxiety and eating disorders symptomatology differences were more pronounced in juniors and cadets, respectively, with higher scale values in female athletes [129, 130]. Women may worry more about what they eat which associates with negative mood state. Thus, mainly cadet, junior and senior female judoka suffer more from the psychological-related states associated with weight reduction [131]. Furthermore, boxers seem to have significantly higher score values regarding anger and tension after RWR [39]. Wrestlers also reported that the weight reduction was one of the most stressful parts of their sport [132].

In contrast to 5% GWR within 4 weeks, the scale values of Perceived Physical State (scale values) such as perceived physical energy (e.g., flabby, washed out), physical fitness (e.g., well trained, strong), physical health (e.g., sick, injured) and physical flexibility (e.g., flexible, elastic) were significantly decreased after 5% RWR within 4 days of taekwondo athletes [4, 133]. The development of brain structure and function is affected by the nutrition which sustains the appropriate components for the brain to generate and defend neural connections. This is the determining factor for the improvement of cognitive function such as processing speed, short-term memory, working memory, and long-term memory [134, 135]. Cognitive functions are essential for the maximal performance of elite athletes. Once again, restricted glucose availability and hypoglycemia (<2.2 mmol·L^{-1}) account for impaired cerebral functions such as cognitive ability [136].

Athletic performances

Various studies investigated the impact of RWR on athletic performance, and conclusive evidence exists regarding the finding that RWR negatively affects athletic performance. In detail, three days of RWR (4.5%) reduced VO_{2max} and sprint in wrestlers compared to a control group [137]. Contrary, VO_{2peak} was not affected by a ~5% RWR lasting 5 to 7 days in several combat athletes [100]. Further results showed different performance outcome between 3 weeks GWR and 2.4-day RWR (59 h) with an average weight loss of 5-6%. Vertical jump height was decreased in wrestlers and judo athletes after RWR compared to GWR. Through Wingate test, anaerobic performance was not altered after RWR while this parameter was increased after 3 week GWR [13]. However, another result showed that anaerobic performance through Wingate test of boxers was reduced (average 5.4%) during 7.8 days RWR [138]. Moreover, studies indicated decreased maximal muscular strength, upper body strength, maximal isometric strength, sprinting, cycling performance, grip strength and vertical jump after 5% RWR during 7 days and ≥6% RWR during 4 days in wrestlers or judo athletes. The results predominantly indicate a reduction in physiological performance after RWR. [14, 74, 139]. Recent studies with sport-specific measurements indicated that RWR (5% and 2-6%, respectively) induced significant decreases in the sport-specific performance such as kick-frequency of taekwondo athletes and 30 s tokui-waza of judo athletes [4, 15].

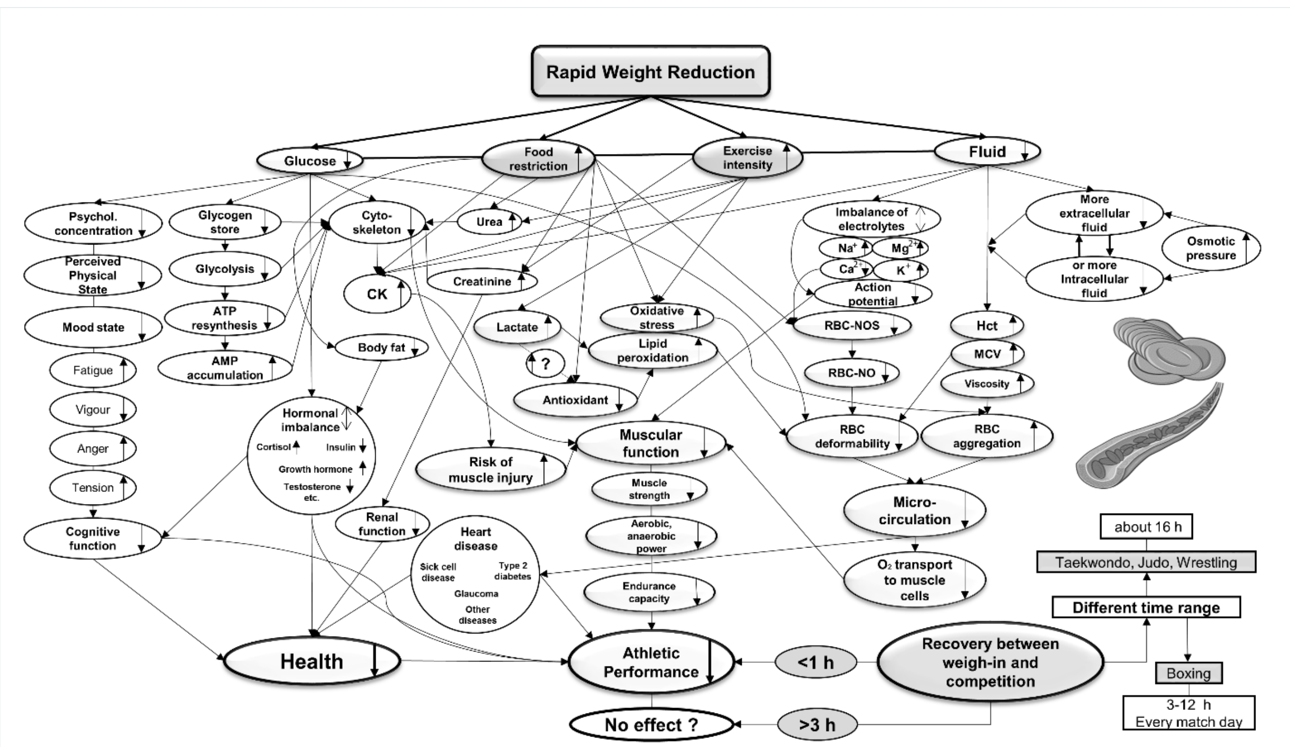

Figure 1. Summarized fluxogram of rapid weight reduction (physiological, psychological and hemorheological factors): **ATP** adenosine triphosphate; **AMP** adenosine monophosphate; **Mg^{2+}** magnesium; **Na^{+}** sodium; **K^{+}** potassium; **Ca^{2+}** calcium; **RBC-NO** red blood cell-nitric oxide; **RBC-NOS** red blood cell-nitric oxide synthase; **CK** creatine kinase.

Several outcomes of the athletic performance after RWR (Table 1) appear to be still controversially discussed because of different phases and percentages of RWR and diverse measurements of athletic performances. Moreover, there is an important difference between physical performance in laboratory tests and athletic performance. Studies showed that strength and power were not affected by RWR in laboratory tests [15, 140, 141]. Inversely, the effects of aerobic and anaerobic performance highly depends on the period between weigh-in and performance test [142, 143]. Different studies allowed no or very short recovery periods (<1 h) which indicated negative effects of RWR on physical performance [19, 39, 137, 141, 144, 145]. Compared thereto, when the recovery periods are longer (>3 h), RWR typically does not impair physical performance [3, 13, 26, 33, 140]. Indirect analyses as the association between RWR and performance (winner/loser and finalists/non-finalists) also showed no relationship between RWR and performance in wrestler and boxers, which was performed after recovery period 20 and 3-12 h of RWR, respectively [5, 11]. A lot of scientific investigations describe the effect of RWR in combat athletes, but to access the effects of RWR on athletic performance and health status with results being valid for all combat athletes it is necessary to examine the sport-specific performance during RWR and after the real recovery time.

DISCUSSION

Previous studies showed that RWR negatively affects metabolic responses, hemorheological properties, psychological condition, resulting in impaired health and performance of the athlete (Fig. 1). Different outcomes of athletic performance after RWR were described with differences being caused by various study designs such as percentages and duration of body weight reduction. Indeed, various sport-specific characteristics of the combat sport should significantly be considered in further studies to assess the individual risk for each sport. The time between weigh-in and competition day after RWR may play a key role for the successful competition of athletes, but this was rarely considered in previous studies. Negative physiological and psychological responses after RWR can lead to a potential deterioration of athletic performance during the competition. Also, recent aspects of hemorheological properties during RWR are associated with athlete´s health and performance.

CONCLUSIONS

Trainers and athletes should work with physiologists and nutritionists to prevent the potential reduction in performance during RWR, and thus an alternative period of weight reduction should be scheduled such as GWR based on, e.g. continuous consideration of nutrient status and training activity as optimal preparation before the official competition. Thereby, a long-term plan for weight reduction should be individually created. Oppliger et al. [16] emphasize that the minimal caloric intake should be between 1700 and 2500 $kcal \cdot d^{-1}$ and intensive training may increase the requirement up to an additional 1000 $kcal \cdot d^{-1}$.

Yang et al. [4, 28] suggest that a weight reduction by ≤5% should be scheduled at least four weeks prior to competition to avoid impairments of athletic performance.

The National Collegiate Athletic Association (NCAA) recommends that athletes should not reduce more than 1.5% of their weight per week. Thus, they introduced the minimum weight. It is regarded as the lightest weight class in which an athlete would compete without decreasing his or her body fat percentage to less than 7% or 12%, respectively. The minimum weight is determined based on the preseason body fat and body weight; both evaluated in euhydrated status via hydration test. After this determined minimum weight, athletes are not able to fight in a given weight class if means that the athlete has to reduce more than 1.5% of the body weight per week [46, 146]. International, national and regional federations of Olympic combat sports should control weight cutting such as hydration control through a test of urine colour or urine specific gravity (simple, portable, fast and inexpensive technique; calibrated refractometer) to decrease risks of an extreme weight reduction [46, 147]. However, athletes have to control their nutrition status prior to this test on the competition day because a high concentrating vitamin or other dietary supplements can manipulate their urine trial.

Especially, if RWR is applied prior to the competition, athletes and coaches should avoid sessions with high-intensity training in the morning hours during RWR because of impaired physiological responses, and they have to control and schedule precisely the body weight of athletes prior to the official competition.

HIGHLIGHTS

The literature indicates that rapid weight reduction (RWR) impairs several metabolic and psychological functions which associate with decreased athletic performance and health in athletes of Olympic combat sports. Therefore, a long-term schedule of weight reduction should be proposed to prevent a potential decline of athletic performance.

Regarding the microcirculation during RWR, deformability and aggregation of red blood cells (RBC) is mainly impaired because of altered nitric oxide synthase activation of RBC which is also the important factor for health and athletic performance.

The recent literature showed that plasminogen activator inhibitor-1 (PAI-1) highly inhibit fibrinolysis in the morning which can endanger the cardiovascular system and thus athletes should avoid high-intensity training during the RWR.

The recovery period between weigh-in and competition after RWR is very important for the successful competition of athletes, but this is rarely considered in previous studies. Therefore, it is necessary to examine the direct sport-specific performance during RWR and after the real recovery time in Olympic combat sports.

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REFERENCES

1. Brownell KD, Steen SN, Wilmore JH. Weight regulation practices in athletes: analysis of metabolic and health effects. Med Sci Sports Exerc 1987; 19(6): 546-56
2. Perriello Jr VA. Aiming for healthy weight in wrestlers and other athletes. Contemp Pediatr 2001; 18(9): 55-74
3. Artioli GG, Iglesias RT, Franchini E et al. Rapid weight loss followed by recovery time does not affect judo-related performance. J Sports Sci 2010; 28(1): 21-32
4. Yang WH, Grau M, Kim P et al. Physiological and psychological performance of taekwondo athletes is more affected by rapid than by gradual weight reduction. Arch Budo 2014; 10: 169-77
5. Horswill CA, Scott JR, Dick RW et al. Influence of rapid weight gain after the weigh-in on success in collegiate wrestlers. Med Sci Sports Exerc 1994; 26(10): 1290-4
6. Alderman BL, Landers DM, Carlson J et al. Factors related to rapid weight loss practices among international-style wrestlers. Med Sci Sports Exerc 2004; 36(2): 249-52
7. Brito CJ, Roas AF, Brito IS et al. Methods of body mass reduction by combat sport athletes. Int J Sport Nutr Exerc Metab 2012; 22(2): 89-97
8. Pettersson S, Ekström MP, Berg CM. Practices of weight regulation among elite athletes in combat sports: a matter of mental advantage? J Athl Train 2013; 48(1): 99-108
9. Daniele G, Weinstein RN, Wallace PW et al. Rapid weight gain in professional boxing and correlation with fight decisions: analysis from 71 title fights. Phys Sportsmed 2016:1-6
10. Reale R, Slater G, Burke LM. Acute Weight Loss Strategies for Combat Sports and Applications to Olympic Success. Int J Sports Physiol Perform 2016:1-30
11. Reale R, Cox GR, Slater G et al. Weight Re-Gain is Not Linked to Success in a Real Life Multi-Day Boxing Tournament. Int J Sports Physiol Perform 2016:1-26
12. Costill DL, Sparks KE. Rapid fluid replacement following thermal dehydration. J Appl Physiol 1973; 34(3): 299-303
13. Fogelholm GM, Koskinen R, Laakso J et al. Gradual and rapid weight loss: effects on nutrition and performance in male athletes. Med Sci Sports Exerc 1993; 25(3): 371-7
14. Degoutte F, Jouanel P, Begue RJ et al. Food restriction, performance, biochemical, psychological, and endocrine changes in judo athletes. Int J Sports Med 2006; 27(1): 9-18
15. Koral J, Dosseville F. Combination of gradual and rapid weight loss: effects on physical performance and psychological state of elite judo athletes. J Sports Sci 2009; 27(2): 115-20
16. Oppliger RA, Case HS, Horswill CA et al. American College of Sports Medicine position stand. Weight loss in wrestlers. Med Sci Sports Exerc 1996; 28(6): 9-12
17. Costill DL, Cote R, Fink W. Muscle water and electrolytes following varied levels of dehydration in man. J Appl Physiol 1976; 40(1): 6-11
18. Maughan RJ, Shirreffs SM. Recovery from prolonged exercise: restoration of water and electrolyte balance. J Sports Sci 1997; 15(3): 297-303

19. McMurray RG, Proctor CR, Wilson WL. Effect of caloric deficit and dietary manipulation on aerobic and anaerobic exercise. Int J Sports Med 1991; 12(2): 167-72

20. Anderson RA, Bryden NA, Polansky MM et al. Effects of carbohydrate loading and underwater exercise on circulating cortisol, insulin and urinary losses of chromium and zinc. Eur J Appl Physiol Occup Physiol 1991; 63(2): 146-50

21. Karila TA, Sarkkinen P, Marttinen M et al. Rapid weight loss decreases serum testosterone. Int J Sports Med 2008; 29(11): 872-7

22. Benton D. Dehydration influences mood and cognition: a plausible hypothesis? Nutrients 2011; 3(5): 555-73

23. Roemmich J, Sinning W. Sport-seasonal changes in body composition, growth, power and strength of adolescent wrestlers. Int J Sports Med 1996; 17(2): 92-9

24. Roemmich JN, Sinning WE. Weight loss and wrestling training: effects on growth-related hormones. J Appl Physiol 1997; 82(6): 1760-4

25. Saarni S, Rissanen A, Sarna S et al. Weight cycling of athletes and subsequent weight gain in middleage. Int J Obes 2006; 30(11): 1639-44

26. Mendes SH, Tritto AC, Guilherme JPL et al. Effect of rapid weight loss on performance in combat sport male athletes: does adaptation to chronic weight cycling play a role? Br J Sports Med 2013: bjsports-2013-092689

27. Wells AS, Read NW, Laugharne JD et al. Alterations in mood after changing to a low-fat diet. Br J Nutr 1998; 79(01): 23-30

28. Yang WH, Heine O, Pauly S et al. Rapid Rather than Gradual Weight Reduction Impairs Hemorheological Parameters of Taekwondo Athletes through Reduction in RBC-NOS Activation. PLoS One 2015; 10(4): e0123767

29. Connes P, Simmonds MJ, Brun JF et al. Exercise hemorheology: classical data, recent findings and unresolved issues. Clin Hemorheol Microcirc 2013; 53(1-2): 187-99

30. Jacobs I. The effects of thermal dehydration on performance of the Wingate anaerobic test. Int J Sports Med 1980; 1 (01): 21-4

31. Houston M, Marrin D, Green H et al. The effect of rapid weight loss on physiological functions in wrestlers. Physician Sportsmed 1981; 9(11): 73-8

32. Caldwell J, Ahonen E, Nousiainen U. Differential effects of sauna-, diuretic-, and exercise-induced hypohydration. J Appl Physiol 1984; 57(4): 1018-23

33. Klinzing JE, Karpowicz W. The effects of rapid weight loss and rehydratation on a wrestling performance test. J Sports Med Phys Fitness 1986; 26(2): 149-56

34. Park SH, Roemmich JN, Horswill CA. A season of wrestling and weight loss by adolescent wrestlers: effect on anaerobic arm power. J Strength Cond Res 1990; 4(1): 1-4

35. Steen SN, Brownell KD. Patterns of weight loss and regain in wrestlers: has the tradition changed? Med Sci Sports Exerc 1990; 22(6): 762-8

36. Melby CL, Schmidt WD, Corrigan D. Resting metabolic rate in weight-cycling collegiate wrestlers compared with physically active, noncycling control subjects. Am J Clin Nutr 1990; 52(3): 409-14

37. Choma CW, Sforzo GA, Keller BA. Impact of rapid weight loss on cognitive function in collegiate wrestlers. Med Sci Sports Exerc 1998; 30(5): 746-9

38. Nieman DC, Custer WF, Butterworth DE et al. Psychological response to exercise training and/or energy restriction in obese women. J Psychosom Res 2000; 48(1): 23-9

39. Hall C, Lane AM. Effects of rapid weight loss on mood and performance among amateur boxers. Br J Sports Med 2001; 35(6): 390-5

40. Finn KJ, Dolgener FA, Williams RB. Effects of carbohydrate refeeding on physiological responses and psychological and physical performance following acute weight reduction in collegiate wrestlers. J Strength Cond Res 2004; 18(2): 328-33

41. Kordi R, Ziaee V, Rostami M et al. Patterns of weight loss and supplement consumption of male wrestlers in Tehran. BMC Sports Sci Med Rehabil 2011; 3(1): 4

42. Bigard A-X, Sanchez H, Claveyrolas G et al. Effects of dehydration and rehydration on EMG changes during fatiguing contractions. Med Sci Sports Exerc 2001; 33(10): 1694-700

43. Halabchi F. Doping in combat sports. Combat sports medicine: Springer; 2009: 55-72

44. Maughan RJ, Shirreffs SM. Dehydration and rehydration in competative sport. Scand J Med Sci Sports 2010; 20 Suppl 3: 40-7

45. Pettersson S, Berg CM. Hydration status in elite wrestlers, judokas, boxers, and taekwondo athletes on competition day. Int J Sport Nutr Exer Metab 2014; 24(3): 267-75

46. Artioli GG, Franchini E, Nicastro H et al. The need of a weight management control program in judo: a proposal based on the successful case of wrestling. J Int Soc Sports Nutr 2010; 7: 15

47. Timpmann S, Burk A, Medijainen L et al. Dietary sodium citrate supplementation enhances rehydration and recovery from rapid body mass loss in trained wrestlers. Appl Physiol Nutr Metab 2012; 37(6): 1028-37

48. Walsh R, Noakes T, Hawley J et al. Impaired high-intensity cycling performance time at low levels of dehydration. Int J Sports Med 1994; 15(07): 392-8

49. Reljic D, Hässler E, Jost J et al. Rapid weight loss and the body fluid balance and hemoglobin mass of elite amateur boxers. J Athl Train 2013; 48(1): 109-17

50. Silva AM, Fields DA, Heymsfield SB et al. Relationship between changes in total-body water and fluid distribution with maximal forearm strength in elite judo athletes. J Strength Cond Res 2011; 25(9): 2488-95

51. Häussinger D, Gerok W, Roth E et al. Cellular hydration state: an important determinant of protein catabolism in health and disease. Lancet 1993; 341(8856): 1330-2

52. Haussinger D, Lang F, Gerok W. Regulation of cell function by the cellular hydration state. Am J Physiol Endocrinol Metab 1994; 267(3): E343-E55

53. Lang F, Busch GL, Ritter M et al. Functional significance of cell volume regulatory mechanisms. Physiol Rev 1998; 78(1): 247-306

54. Horswill C, Hickner R, Scott J et al. Weight loss, dietary carbohydrate modifications, and high intensity, physical performance. Med Sci Sports Exerc 1990; 22(4): 470-6

55. Angleton P, Chandler WL, Schmer G. Diurnal variation of tissue-type plasminogen activator and its rapid inhibitor (PAI-1). Circulation 1989; 79(1): 101-6

56. Hawley JA, Hopkins WG. Aerobic glycolytic and aerobic lipolytic power systems. Sports Med 1995; 19(4):240-50

57. Tarnopolsky M, Cipriano N, Woodcroft C et al. Effects of rapid weight loss and wrestling on muscle glycogen concentration. Clin J Sport Med 1996; 6(2): 78-84

58. Packer L. Oxidants, antioxidant nutrients and the athlete. J Sports Sci 1997; 15(3):353-63

59. Mastaloudis A, Morrow JD, Hopkins DW et al. Antioxidant supplementation prevents exercise-induced lipid peroxidation, but not inflammation, in ultramarathon runners. Free Radic Biol Med 2004; 36(10): 1329-41

60. Reljic D, Jost J, Dickau K et al. Effects of pre-competitional rapid weight loss on nutrition, vitamin status and oxidative stress in elite boxers. J Sports Sci 2015; 33(5): 437-48

61. Butterfield GE. Whole-body protein utilization in humans. Med Sci Sports Exerc 1987; 19(5 Suppl): 157-65

62. Lemon PW. Effects of exercise on dietary protein requirements. Int J Sport Nutr 1998; 8: 426-47

63. Medicine ACoS, Association AD. Joint Position Statement: nutrition and athletic performance. American College of Sports Medicine, American Dietetic Association, and Dietitians of Canada. Med Sci Sports Exerc 2000; 32(12): 2130

64. Stern J, Schultz C, Mole P et al. Effect of caloric restriction and exercise on basal metabolism and thyroid hormone. Aliment Nutr Metab 1980; 1: 361

65. Kukidome T, Shirai K, Kubo J et al. MRI evaluation of body composition changes in wrestlers undergoing rapid weight loss. Br J Sports Med 2008; 42(10): 814-8

66. Sahlin K, Tonkonogi M, Soderlund K. Plasma hypoxanthine and ammonia in humans during prolonged exercise. Eur J Appl Physiol Occup Physiol 1999; 80(5): 417-22

67. Somani N, Harrison S, Bergfeld WF. The clinical evaluation of hirsutism. Dermatol Ther 2008; 21(5): 376-91

68. Bezanilla F, Caputo C, Gonzalez-Serratos H et al. Sodium dependence of the inward spread of activation in isolated twitch muscle fibres of the frog. J Physiol 1972; 223(2): 507-23

69. Zhang SJ, Bruton JD, Katz A et al. Limited oxygen diffusion accelerates fatigue development in mouse skeletal muscle. J Physiol 2006; 572(2): 551-9

70. Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. Physiol Rev 2008; 88(1): 287-332

71. Okamoto K, Wang W, Rounds J et al. ATP from glycolysis is required for normal sodium homeostasis in resting fast-twitch rodent skeletal muscle. Am J Physiol Endocrinol Metab 2001; 281(3): E479-E88

72. Clausen T. Na+-K+ pump regulation and skeletal muscle contractility. Physiol rev 2003; 83(4): 1269-324

73. Dutka TL, Lamb GD. Na+-K+ pumps in the transverse tubular system of skeletal muscle fibers preferentially use ATP from glycolysis. Am J Physiol Cell Physiol 2007; 293(3): C967-C77

74. Kurakake S, Umeda T, Nakaji S et al. Changes in physical characteristics, hematological parameters and nutrients and food intake during weight reduction in judoists. Environ Health Prev Med 1998; 3(3): 152-7

75. Brancaccio P, Maffulli N, Limongelli FM. Creatine kinase monitoring in sport medicine. Br Med Bull 2007; 81-82: 209-30

76. Knochel JP. Mechanisms of rhabdomyolysis. Curr Opin Rheumatol 1993; 5(6): 725-31

77. Fielding RA, Violan MA, Svetkey L et al. Effects of prior exercise on eccentric exercise-induced neutrophilia and enzyme release. Med Sci Sports Exerc 2000; 32(2): 359-64

78. Hellsten Y, Sjodin B, Richter EA et al. Urate uptake and lowered ATP levels in human muscle after high-intensity intermittent exercise. Am J Physiol 1998; 274(4 Pt 1): E600-6

79. Greenleaf JE. Problem: thirst, drinking behavior, and involuntary dehydration. Med Sci Sports Exerc 1992; 24(6): 645-56

80. Sorichter S, Puschendorf B, Mair J. Skeletal muscle injury induced by eccentric muscle action: muscle proteins as markers of muscle fiber injury. Exerc Immunol Rev 1998; 5: 5-21

81. Gaudard A, Varlet-Marie E, Bressolle F et al. Nutrition as a determinant of blood rheology and fibrinogen in athletes. Clin Hemorheol Microcirc 2004; 30(1): 1-8

82. Yanagawa Y, Morimura T, Tsunekawa K et al. Oxidative stress associated with rapid weight reduction decreases circulating adiponectin concentrations. Endocr J 2010; 57(4): 339-45

83. Kilic-Toprak E, Ardic F, Erken G et al. Hemorheological responses to progressive resistance exercise training in healthy young males. Med Sci Monit 2012; 18(6): CR351

84. Rhyu H-S, Cho S-Y, Roh H-T. The effects of ketogenic diet on oxidative stress and antioxidative capacity markers of Taekwondo athletes. J Exerc Rehabil 2014; 10(6): 362-6

85. Ji L. Oxidative stress during exercise: implication of antioxidant nutrients. Free Radic Biol Med 1995; 18(6): 1079-86

86. Sen CK. Oxidants and antioxidants in exercise. J Appl Physiol 1995; 79(3): 675-86

87. Fruehauf JP, Meyskens FL. Reactive oxygen species: a breath of life or death? Clin Cancer Res 2007; 13(3): 789-94

88. Weinberg F, Chandel NS. Reactive oxygen species-dependent signaling regulates cancer. Cell Mol Life Sci 2009; 66(23): 3663-73

89. Brun JF, Varlet-Marie E, Connes P et al. Hemorheological alterations related to training and overtraining. Biorheology 2010; 47(2): 95-115

90. Kowatari K, Umeda T, Shimoyama T et al. Exercise training and energy restriction decrease neutrophil phagocytic activity in judoists. Med Sci Sports Exerc 2001; 33(4): 519-24

91. Brun JF, Bouchahda C, Chaze D et al. The paradox of hematocrit in exercise physiology: which is the "normal" range from an hemorheologist's viewpoint? Clin Hemorheol Microcirc 2000; 22(4): 287-303

92. Ahmadizad S, El-Sayed MS, MacLaren DP. Effects of water intake on the responses of haemorheological variables to resistance exercise. Clin Hemorheol Microcirc 2006; 35(1-2): 317-27

93. Brun JF. Exercise hemorheology as a three acts play with metabolic actors: is it of clinical relevance? Clin Hemorheol Microcirc 2002; 26(3): 155-74

94. Armstrong LE, Soto JA, Hacker FT, Jr. et al. Urinary indices during dehydration, exercise, and rehydration. Int J Sport Nutr 1998; 8(4): 345-55

95. Shirreffs S. Markers of hydration status. Eur J Clin Nutr 2003; 57: S6-S9

96. Francesconi RP, Hubbard RW, Szlyk PC et al. Urinary and hematologic indexes of hypohydration. J Appl Physiol 1987; 62(3): 1271-6

97. Fogarty AL, Armstrong KA, Gordon CJ et al. Cardiovascular and thermal consequences of protective clothing: a comparison of clothed and unclothed states. Ergonomics 2004; 47(10): 1073-86

98. Schmidt W, Prommer N. The optimised CO-rebreathing method: a new tool to determine total haemoglobin mass routinely. Eur J Appl Physiol 2005; 95(5-6): 486-95

99. Michalska-Malecka K, Slowinska-Lozynska L. Aggregation and deformability of erythrocytes in primary open-angle glaucoma (POAG); the assessment of arterial hypertension. Clin Hemorheol Microcirc 2012; 51(4): 277-85

100. Reljic D, Feist J, Jost J et al. Rapid body mass loss affects erythropoiesis and hemolysis but does not impair aerobic performance in combat athletes. Scand J Med Sci Sports 2016; 26(5): 507-17

101. Dunn C. Effect of food or water restriction on erythropoiesis in mice: relevance to" anemia" of space flight. Am J Physiol Regul Integr Comp Physiol 1980; 238(5): R301-R5

102. Gunga H-C, Wittels P, Günther T et al. Erythropoietin in 29 men during and after prolonged physical stress combined with food and fluid deprivation. Eur J Appl Physiol Occup Physiol 1996; 73(1-2): 11-6

103. Stuart J, Nash G. Red cell deformability and haematological disorders. Blood Rev 1990; 4(3): 141-7

104. Rampling MW, Meiselman HJ, Neu B et al. Influence of cell-specific factors on red blood cell aggregation. Biorheology 2004; 41(2): 91-112

105. Lipowsky HH, Cram LE, Justice W et al. Effect of erythrocyte deformability on in vivo red cell transit time and hematocrit and their correlation with in vitro filterability. Microvasc Res 1993; 46(1): 43-64

106. Mohandas N, Chasis JA. Red blood cell deformability, membrane material properties and shape: regulation by transmembrane, skeletal and cytosolic proteins and lipids. Semin Hematol 1993; 30(3): 171-92

107. Gladwin MT, Crawford JH, Patel RP. The biochemistry of nitric oxide, nitrite, and hemoglobin: role in blood flow regulation. Free Radic Biol Med 2004; 36(6): 707-17

108. Malan D, JI GJ, Schmidt A et al. Nitric oxide, a key signaling molecule in the murine early embryonic heart. FASEB J 2004; 18(10): 1108-10

109. Suhr F, Brenig J, Muller R et al. Moderate exercise promotes human RBC-NOS activity, NO production and deformability through Akt kinase pathway. PLoS One 2012; 7(9): e45982

110. Grau M, Pauly S, Ali J et al. RBC-NOS-dependent S-nitrosylation of cytoskeletal proteins improves RBC deformability. PLoS One 2013; 8(2): e56759

111. Grau M, Friederichs P, Krehan S et al. Decrease in red blood cell deformability is associated with a reduction in RBC-NOS activation during storage. Clin Hemorheol Microcirc 2014: http://dx.doi.org/10.3233/CH-141850

112. McArdle WD, Katch FI, Katch VL. Exercise physiology: nutrition, energy, and human performance: Lippincott Williams & Wilkins; 2010.

113. Brun JF, Varlet-Marie E, Raynaud de Mauverger E. Relationships between insulin sensitivity measured with the oral minimal model and blood rheology. Clin Hemorheol Microcirc 2012; 51(1): 29-34

114. Kleinbongard P, Schulz R, Rassaf T et al. Red blood cells express a functional endothelial nitric oxide synthase. Blood 2006; 107(7): 2943-51

115. Ozuyaman B, Grau M, Kelm M et al. RBC NOS: regulatory mechanisms and therapeutic aspects. Trends Mol Med 2008; 14(7): 314-22

116. Lundberg JO, Weitzberg E. NO-synthase independent NO generation in mammals. Biochem Biophys Res Commun 2010; 396(1): 39-45

117. Lauer T, Preik M, Rassaf T et al. Plasma nitrite rather than nitrate reflects regional endothelial nitric oxide synthase activity but lacks intrinsic vasodilator action. Proc Natl Acad Sci U S A 2001; 98(22): 12814-9

118. Beutler E, Kuhl W. Volume control of erythrocytes during storage. The role of mannitol. Transfusion 1988; 28(4): 353-7

119. Henkelman S, Dijkstra-Tiekstra MJ, de Wildt-Eggen J et al. Is red blood cell rheology preserved during routine blood bank storage? Transfusion 2010; 50(4): 941-8

120. Connes P, Bouix D, Py G et al. Opposite effects of in vitro lactate on erythrocyte deformability in athletes and untrained subjects. Clin Hemorheol Microcirc 2004; 31(4): 311-8

121. Groussard C, Morel I, Chevanne M et al. Free radical scavenging and antioxidant effects of lactate ion: an in vitro study. J Appl Physiol 2000; 89(1): 169-75

122. Vicaut E. Opposite effects of red blood cell aggregation on resistance to blood flow. J Cardiovasc Surg (Torino) 1995; 36(4): 361-8

123. Scheer FA, Shea SA. Human circadian system causes a morning peak in prothrombotic plasminogen activator inhibitor-1 (PAI-1) independent of the sleep/wake cycle. Blood 2014; 123(4): 590-3

124. Andreotti F, Davies GJ, Hackett DR et al. Major circadian fluctuations in fibrinolytic factors and possible relevance to time of onset of myocardial infarction, sudden cardiac death and stroke. Am J Cardiol 1988; 62(9): 635-7

125. Montain SJ, Smith SA, Mattot RP et al. Hypohydration effects on skeletal muscle performance and metabolism: a 31P-MRS study. J Appl Physiol 1998; 84(6): 1889-94

126. Nybo L, Nielsen B. Hyperthermia and central fatigue during prolonged exercise in humans. J Appl Physiol 2001; 91(3): 1055-60

127. Franchini E, Brito CJ, Artioli GG. Weight loss in combat sports: physiological, psychological and performance effects. J Int Soc Sports Nutr 2012; 9(1): 52

128. Chaouachi A, Coutts AJ, Chamari K et al. Effect of Ramadan intermittent fasting on aerobic and anaerobic performance and perception of fatigue in male elite judo athletes. J Strength Cond Res 2009; 23(9): 2702-9

129. Escobar-Molina R, Rodríguez-Ruiz S, Gutiérrez-García C et al. Weight loss and psychological-related states in high-level judo athletes. Int J Sport Nutr Exerc Metab 2015; 25(2): 110-8

130. Yoshioka Y, Umeda T, Nakaji S et al. Gender differences in the psychological response to weight reduction in judoists. Int J Sport Nutr Exerc Metab 2006; 16(2): 187-98

131. Thompson JK, Stice E. Thin-ideal internalization: Mounting evidence for a new risk factor for body-image disturbance and eating pathology. Curr Dir Psychol Sci 2001; 10(5): 181-3

132. Kristiansen E, Roberts GC, Abrahamsen FE. Achievement involvement and stress coping in elite wrestling. Scand J Med Sci Sports 2008; 18(4): 526-38

133. Kleinert J. Mood states and perceived physical states as short term predictors of sport injuries: two prospective studies. Int J Sport Exerc Psychol 2007; 5(4): 340-51

134. Hillman CH, Motl RW, Pontifex MB et al. Physical activity and cognitive function in a cross-section of younger and older community-dwelling individuals. Health psychol 2006; 25(6): 678-87

135. Meeusen R. Exercise, nutrition and the brain. Sports Med 2014; 44(1): 47-56

136. Draelos MT, Jacobson AM, Weinger K et al. Cognitive function in patients with insulin-dependent diabetes mellitus during hyperglycemia and hypoglycemia. Am J Med 1995; 98(2): 135-44

137. Hickner R, Horswill C, Welker J et al. Test development for the study of physical performance in wrestlers following weight loss. Int J Sports Med 1991; 12(6): 557-62

138. Durkalec-Michalski K, Goscianska I, Jeszka J. Does conventional body weight reduction decreasing anaerobic capacity of boxers in the competition period? Arch Budo 2015; 11: 251-8

139. Coufalova K, Cochrane DJ, Maly T et al. Changes in body composition, anthropometric indicators and maximal strength due to weight reduction in judo. Arch Budo 2014; 10: 161-8

140. Serfass RC, Stull GA, Alexander JF et al. The effects of rapid weight loss and attempted rehydration on strength and endurance of the hand gripping muscles in college wrestlers. Res Q Exerc Sport 1984; 55(1): 46-52

141. Webster S, Rutt R, Weltman A. Physiological effects of a weight loss regimen practiced by college wrestlers. Med Sci Sports Exerc 1990; 22(2): 229-34

142. Artioli GG, Saunders B, Iglesias RT et al. It is time to ban rapid weight loss from combat sports. Sports Med 2016; 46(11): 1579-84

143. Artioli GG, Saunders B, Iglesias RT et al. Authors' Reply to Davis: "It is Time to Ban Rapid Weight Loss from Combat Sports". Sports Med 2017: 1-5

144. Smith M, Dyson R, Hale T et al. The effects in humans of rapid loss of body mass on a boxing-related task. Eur J Appl Physiol 2000; 83(1): 34-9

145. Filaire E, Maso F, Degoutte F et al. Food restriction, performance, psychological state and lipid values in judo athletes. Int J Sports Med 2001; 22(06): 454-9

146. Artioli GG, Gualano B, Franchini E et al. Prevalence, magnitude, and methods of rapid weight loss among judo competitors. Med Sci Sports Exerc 2010; 42(3): 436-42

147. Armstrong LE. Assessing hydration status: the elusive gold standard. J Am Coll Nutr 2007; 26(5 Suppl): 575S-584S

148. Dictionary of Sport and Exercise Science. Over 5,000 Terms Clearly Defined. London: A & B Black; 2006

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