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

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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 • 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 147 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 waterMaximal 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 dayscompared to 5% GWRduring 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 ↑ CreatinineImbalance 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 beforematches	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 comparedto 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 StateImbalance 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].

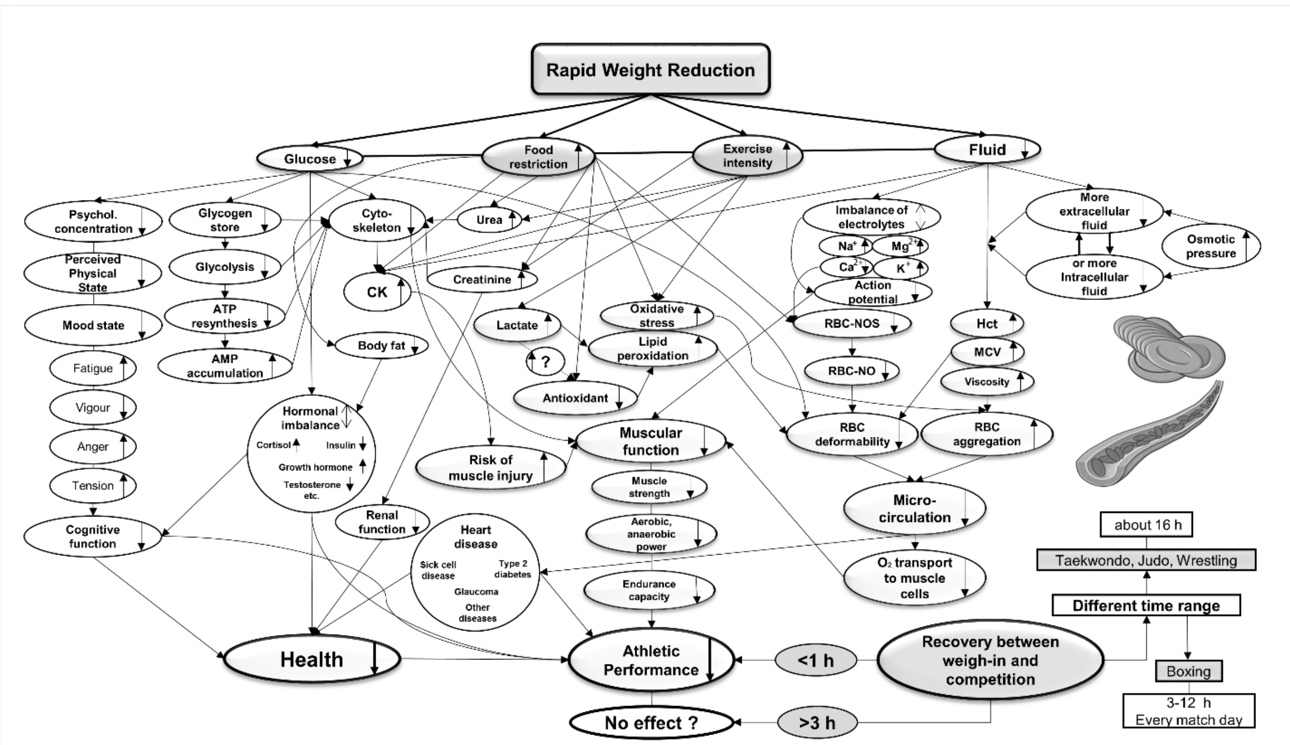

Figure 1. Summarized fluxogram of rapid weight reduction (physiological, psychological and hemorheological factors): **ATP** adenosine triphosphate; **AMP** adenosine monophosphate; **Mg^{2+}** magnesium; **Na^{+}** sodium; **K^{+}** potassium; **Ca^{2+}** calcium; **RBC-NO** red blood cell-nitric oxide;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