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Changes in the rheological properties of blood in combat sports athletes (boxing vs MMA)

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Physical exertion causes significant changes in the rheological properties of blood. Combat sports require athletes to engage in dynamic bouts based on direct confrontation. The aim of this study was to compare the rheological properties of blood before and after confrontation (simulated sparring) in combat sports athletes (Boxing vs MMA) and to compare these with a control group of non-training individuals. The study was conducted on a population of 32 combat sports athletes: 82.06 ± 10.22 kg; 177.41 ± 6.74 cm; BMI 26.03 ± 2.61; age 29.35 ± 5.74 years; training experience 9.47 ± 3.14 years (Boxers group n = 16; MMA group n = 16), all of whom exhibited a high level of athletic performance with regular competition participation. Simulated sparring sessions were conducted, and blood samples were taken before and after the intervention. The blood parameter results were also compared with a control group: 86.97 ± 9.47 kg; 177.31 ± 6.91 cm; BMI 27.64 ± 2.39; age 29.65 ± 5.68 years. In the study, comparing the Boxers pre vs. control group and Boxers post vs. control group showed an increase in elongation index at shear stress 4.24, 8.23, 15.95, 30.94, and 60.00 Pa and a decrease in EI at shear stress 0.58, along with an increase in fibrinogen. For blood morphology indices in the Boxers group compared to the control group, there was an increase in MCV, RDW, WBC, LYM, MON, GRA, PCT, and MPV, with higher values noted for Boxers, and a decrease in MCHC and PDW. Similar trends were observed in blood morphology indices when comparing Boxers pre vs. Boxers post simulated sparring. There was an increase in WBC, LYM, MON, PLT, and PCT after simulated sparring and a decrease in EI at shear stress 2.19. Analyzing the results comparing MMA pre vs. control group and MMA post vs. control group, higher values were observed in the MMA group for MCV, WBC, LYM, GRA, PCT, EI at shear stress 30.94 and 60.00, and fibrinogen. Conversely, in the MMA pre vs. control group and MMA post vs. control group, lower values were found for EI at shear stress 0.58 and 1.13. Comparing MMA pre vs. MMA post fight, blood morphology indices were significantly higher in athletes after simulated sparring, with a significant increase in AI after intervention. MMA fights are often longer and more intense than boxing matches, which in turn affects the rheological properties of blood. This is confirmed by the results showing a decrease in red blood cell deformability in the MMA group compared to Boxers, with no changes in AI, AMP, T1/2, blood plasma viscosity, and fibrinogen. The rheological indices of blood indicate that MMA fights have a more negative impact on blood flow compared to boxing matches.

Keywords Blood rheology, Deformability erythrocytes, Erythrocyte aggregation, Blood plasma viscosity, Combat sports

Combat sports require athletes to engage in dynamic bouts based on direct confrontation. These sports can be primarily categorized based on the fighting plane: stand-up striking (e.g., karate, kickboxing, taekwondo, boxing) and stand-up grappling with an additional ground-fighting plane (e.g., judo, Brazilian jiu-jitsu, sport grappling, wrestling)[1]. Mixed Martial Arts (MMA) integrate elements from all these planes. Due to its spectacular nature, the discipline has gained significant popularity on the international stage[2]. From a physiological standpoint, sports such as Kickboxing, Boxing, and MMA rely on anaerobic processes during bouts and generate high

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physiological stress[3,4,18]. Numerous neurophysiological analyses are conducted in scientific research to verify the negative consequences of competition[4]. However, the scientific literature lacks rheological analyses.

The rheological properties of blood are analyzed by examining the tendency of erythrocytes to deform and aggregate at various shear stresses, hematocrit values, blood viscosity, and plasma viscosity[5,6,17]. The main focus of blood rheology studies is red blood cells. The average size of erythrocytes is 7–8 µm, which necessitates their deformation to pass through capillaries with diameters of 3–5 µm, ensuring the transport of oxygen and carbon dioxide. Scientific research indicates that physical exercise can increase or decrease the deformability of red blood cells[7,8]. Regular physical training decreases fibrinogen levels, plasma viscosity, and blood viscosity while increasing blood flow, thus enhancing oxygen delivery to the muscles involved in physical activity[9]. According to El-Sayed et al.[8], physical exertion affects the rheological properties of blood by increasing plasma viscosity and hematocrit due to hemoconcentration caused by fluid shifts from the intravascular space to the working muscle tissues. The rheological properties of blood mainly stem from the characteristics of red blood cells, which significantly modify blood flow in the vessels, and from plasma properties, including plasma proteins. The presence of high-molecular-weight proteins, such as fibrinogen, lipoproteins, and globulins (especially α2-macroglobulin and immunoglobulins), increases plasma viscosity, thereby increasing blood viscosity[5]. Blood rheology is largely dependent on fibrinogen concentration. Elevated fibrinogen levels lead to increased red blood cell aggregation, which results in higher blood viscosity. Factors influencing the formation of red blood cell aggregates, besides fibrinogen, include lipoproteins, macroglobulins, immunoglobulins, hematocrit, red blood cell shape, their deformability, and cell membrane surface properties. In conditions of impaired blood flow, increased erythrocyte aggregation is observed. Just as proteins affect blood viscosity, so do plasma lipids. Studies on potential changes in blood rheology due to prolonged intensive exercise and direct confrontation, including body bruises in combat sports athletes, have been limited. According to Heidari et al.[10], a study involving 12 judokas (with two years of regular training) who performed the Special Judo Fitness Test (SJFT) and had blood drawn before, immediately after, and half an hour after the SJFT, showed that plasma volume and red blood cell count significantly decreased immediately post-exercise ($p < 0.05$), while white blood cell count, platelet count, and hematocrit significantly increased ($p < 0.05$). All studied indicators returned to baseline levels half an hour after SJFT, except for white blood cells. This study demonstrated that intense interval judo activity can effectively influence blood rheology,these changes are transient and likely result from decreased plasma volume and a return to baseline after recovery post-exercise. Therefore, it is worth supplementing blood tests in athletes of other combat sports while conducting tests before and after real fights.

The aim of this study was to compare the rheological properties of blood before and after intervention (simulated sparring) in two groups of combat sports athletes (boxing vs MMA), both intra-group and inter-group, as well as compared to a control group leading a sedentary lifestyle.

The participants from the experimental groups included in the study were characterized by many years of training in combat sports, albeit in disciplines that differ in technical and tactical aspects. Boxing, for instance, is a flagship discipline of striking combat sports, where competition takes place in a standing position using only upper-limb striking techniques. In contrast, MMA is a multi-dimensional discipline in which confrontation occurs both in a standing position and on the ground, utilizing a wide array of technical actions (strikes, kicks, joint locks, and chokes). Based on these distinctions and existing scientific reports, we formulated the hypothesis in our study that, due to the influence of environmental factors in the form of distinct, targeted training, we should expect differences in the profile of blood rheological properties, particularly after the application of an experimental stimulus (a simulated sparring session), between the compared groups.

Methods

Participants

The study was conducted on a purposefully selected group of 32 male athletes who practiced combat sports at a professional level (boxers group n = 16; MMA group n = 16) and regularly participated in sports competitions. The sample size was calculated using G*Power 3.1.9.7, assuming an effect size of 0.5 (medium effect size) based on previous studies examining the impact of physical exertion on blood rheology[7,8], with a statistical power of 0.8 and an alpha level of 0.05. The primary variables considered for this calculation included red blood cell deformability (elongation index at various shear stresses) and fibrinogen concentration, as these parameters are highly sensitive to the physical demands typical of combat sports. All participants were thoroughly informed about the measurement procedure and its purpose, and provided written consent to participate in the study. Inclusion criteria for the study included: a minimum of 6 years of training experience, no current injuries, up-to-date medical examinations, no history of severe injuries, positive medical recommendation, consent to participate, no use of doping, and active participation in competitions. Exclusion criteria included the opposition of these aspects. The average body mass of the subjects was 82.06 ± 10.22 kg, the average height was 177.41 ± 6.74 cm, and BMI was 26.03 ± 2.61 (Boxers group: BM 82.44 ± 10.12 kg,BH 177.95 ± 7.00 cm; BMI 26.01 ± 2.66 vs. MMA group: BM 81.68 ± 10.63 kg; BH 176.88 ± 6.63 cm; BMI 26.05 ± 2.64). Basic somatic characteristics were assessed using the anthropometer A213 for height measurement and the certified electronic scale TANITA TBF-538 for body mass assessment, following anthropometry guidelines[11]. The global average age of the subjects was 29.35 ± 5.74 years. Training experience ranged from 6 to 16 years (average experience: 9.47 ± 3.14 years) of systematic training, with 4–6 training sessions per week, depending on the training mesocycle (Boxers group: age 28.47 ± 4.73 years,experience 9.24 ± 3.11 years vs. MMA group: age 30.24 ± 6.62 years; experience 9.71 ± 3.24 years). The study was conducted during the preparatory period. The athletes were not on a restrictive diet and did not use supplements or doping. All participants in the experimental groups had competed in local, national, and international events throughout their athletic careers. As of the start of this project, all athletes demonstrated an elite level of performance, regularly participating in master-class competitions (both internationally and nationally). . Information regarding chronological age, activity, and training experience was obtained through a diagnostic survey method, utilizing direct interviews with the athletes and coaching staff. Subsequently, thematic federation rankings and protocols from selected sports events were verified.

The third study group (n = 14) consisted of non-training men leading a sedentary lifestyle. The average body mass of these subjects was 86.97 ± 9.47 kg, the average height was 177.31 ± 6.91 cm, BMI 27.64 ± 2.39, and the average age was 29.65 ± 5.68 years.

Experimental set-up

Simulated sparring

Both groups, the Boxers and MMA athletes, performed a standard set of exercises to prepare their bodies for exertion (warm-up). Immediately afterward, each participant engaged in a simulated sparring session within their respective group, organized specifically for this project. Sixteen bouts were conducted, with eight in each group (boxers n = 8; MMA n = 8). Each athlete completed one three-round sparring match, with each round lasting 3 min and a 1-min break between rounds. The boxers followed the official sports regulations established by the Polish Boxing Association (PZB) (Polish Boxing Association, 2023), while the MMA athletes sparred according to the sports regulations set by the MMA Polish Association[12]. The athletes were matched according to their weight categories. Both groups, the Boxers and MMA athletes, performed a standard set of exercises to prepare their bodies for exertion (warm-up) in controlled environmental conditions. The sparring sessions took place in a neutral setting with a stable indoor temperature of approximately 20–21 °C, relative humidity of 50–60%, and conducted during the late morning hours. These environmental conditions were maintained to minimize external factors that could affect physical performance and blood rheology.

Blood sample collection

Blood samples were taken from the antecubital vein the participants before and after fighting in an amount of 10 mL into Vacuette EDTAK2 tubes. The blood samples were collected by a qualified nurse at the Blood Physiology Laboratory of the University of Physical Education in Krakow.

Morphological analyses

The measurement of basic haematological indicators was performedin a HORIBA ABX Micros 60 blood analyser with the impedance method (ABX Micros 60, HORIBA Medical, Montpellier, France): RBC [× 10^12/l],HGB [g/dl], HCT [%], MCV [fl], MCH [pg], MCHC [g/dl], RDW[%], WBC [× 10^9/l], neutrophils[× 10^9/l], eosinophils [× 10^9/l], basophils [× 10^9/l], lymphocytes[× 10^9/l], monocytes [× 10^9/l], PLT [× 10^9/l], MPV [fl], PCT [%]and PDW [%].

Rheological assessments

The blood rheology parameters, such as erythrocyte aggregation (aggregation index (AI) [%], amplitude andtotal extent of aggregation (AMP) [arbitrary units], half-time of total aggregation (T1/2)[s]) and deformability (EI,elongation index) were measured with the Laser-Assisted Optical Rotational Red Cell Analyzer (Lorrca) MaxSis(Lorrca®, RR Mechatronics, the Netherlands) using the method described by Baskurt et al.[5]. Mean EI values were determined at the shear stress values of 0.30–60.00 Pa, using the automatic analysis function ofLorrca system, which allows assessing erythrocyte deformability as a function of shear stress and erythrocyte aggregation.

Blood protein analysis

Fibrinogen (g/L) was determined using the coagulometric method with a Chrom 7 coagulometer (Bioksel, Poland).

Viscosity plasma

Viscosity was measured using a DVNext-LV cone/plate rheometer from AMETEK Brookfield (Middleborough, USA) with a speed (RPM) 100,00, temperature (°C) 35,8, Sh Rate (1/s) 750,00), Shear Stress 8,23 (dyn/cm^2).

Plasma volume changes

Plasma volume changes were calculated using the following formula[16]:

$$Percentage\ Plasma\ Volume\ Change = \left(\frac{Hbpre}{Hbpost} \times \frac{(100 - Hctpost)}{(100 - Hctpre)} - 1\right) \times 100$$

where Hb_{pre} and Hb_{post} are the hemoglobin concentrations before and after sparring, Hct_{pre} and Hct_{post} are the hematocrit values before and after sparring.

Statistical analysis

The statistical analysis of the collected data was performed using the PQStat v.1.8.4 software package (PQStat Poland). Basic descriptive statistics were calculated: arithmetic mean and standard deviation. The significance of differences between paired data was tested using repeated measures analysis of variance (ANOVA) for dependent variables. For independent comparisons, one-way ANOVA was used for independent groups. The choice of tests was conditioned by meeting the assumption of normal distribution, which was confirmed by the Shapiro–Wilk test, and homogeneity of variances confirmed by Levene's test. Cohen's *d* was calculated to measure the effect size between groups, using pooled standard deviations to standardize the mean differences. A significance level of $p < 0.05$ was adopted for statistically significant differences.

Results

Boxers pre vs. Boxers post simulated sparring [intra-group diversity (Table 1)]

In terms of assessing morphological parameter composition, a significant differentiation of selected indicators was observed in the community of boxers (Table 1). A significant increase was shown in relation to the values of WBC ($p = 0.001$), LYM ($p = 0.005$), MON ($p = 0.003$), PLT ($p = 0.008$), and PCT ($p = 0.004$) after simulated sparring sessions. Regarding the other parameters, athletes did not exhibit significant differentiation.

With respect to indicators of red blood cell elongation, at a shear stress level of EI 2.19 ($p = 0.01$), a significant decrease in values was recorded after intervention (simulated sparring).

Boxers pre vs. control group [intergroup comparison (Table 1)]

Comparison with the control group revealed significant differentiation of selected blood morphology parameters among athletes, such as: MCV ($p = 0.002$), RDW ($p < 0.001$), WBC ($p < 0.001$), LYM ($p < 0.001$), MON ($p = 0.005$), GRA ($p = 0.005$), PCT ($p < 0.001$), and MPV ($p < 0.001$), with higher values noted for boxers, and a decrease in MCHC ($p > 0.001$) and PDW ($p < 0.001$) (Table 1).

Analyzing the mean EI values of the study group (boxers) compared to the control group, statistically significant differences were found at shear stresses of 4.24 ($p = 0.01$), 8.23 ($p = 0.002$), 15.95 ($p < 0.001$), 30.94 ($p < 0.001$), and 60.00 Pa ($p < 0.001$). It was shown that the mean value was higher in the boxer group, with a decrease observed at 0.58 Pa shear stress ($p < 0.001$) (Table 1).

Parameters	Boxers (pre)	Boxers (post)	Control group	*p* (Boxers pre vs post)	d Cohen's	*p* (Boxers pre vs Control)	d Cohen's	*p* (Boxers post vs Control)	d Cohen's
RBC [T/l]	5.175 ± 0.519	5.195 ± 0.446	5.326 ± 0.973	0.59	0.04	0.71	0.19	0.68	0.17
HGB [g/dl]	15.340 ± 0.853	15.360 ± 0.957	16.171 ± 2.771	0.90	0.02	0.40	0.41	0.38	0.39
HCT [%]	51.410 ± 4.512	51.580 ± 4.320	50.086 ± 9.497	0.83	0.04	0.66	0.18	0.70	0.20
MCV [fl]	99.500 ± 3.028	99.400 ± 3.534	94.000 ± 1.826	0.79	0.03	**0.002**	2.20	**< 0.001**	1.92
MCH [pg]	29.840 ± 2.558	29.720 ± 1.921	30.443 ± 0.791	0.60	0.05	0.36	0.32	0.55	0.49
MCHC [g/dl]	29.950 ± 2.005	29.890 ± 1.398	32.400 ± 0.648	0.81	0.03	**< 0.001**	1.64	**0.007**	2.30
RDW [%]	14.160 ± 0.700	14.240 ± 0.636	12.900 ± 0.526	0.52	0.12	**< 0.001**	2.04	**0.001**	2.30
WBC [g/l]	7.110 ± 1.443	8.560 ± 2.679	3.886 ± 0.715	**0.001**	0.67	**< 0.001**	2.83	**< 0.001**	2.38
LYM [µl]	2.100 ± 0.400	3.010 ± 0.962	1.286 ± 0.302	**0.005**	1.24	**< 0.001**	2.30	**< 0.001**	2.42
MON [µl]	0.470 ± 0.134	0.660 ± 0.280	0.229 ± 0.076	**0.003**	0.87	**0.001**	2.21	**< 0.001**	2.10
GRA [µl]	4.540 ± 1.490	4.890 ± 1.980	2.371 ± 0.602	0.09	0.20	**0.005**	1.91	**0.002**	1.72
PLT [g/l]	286.400 ± 72.765	324.600 ± 99.566	240.571 ± 55.593	**0.008**	0.44	0.06	0.71	0.18	1.04
PCT [%]	219.100 ± 51.804	250.900 ± 71.437	0.164 ± 0.044	**0.004**	0.51	**< 0.001**	5.98	**< 0.001**	4.96
MPV [fl]	7.680 ± 0.286	7.760 ± 0.363	6.786 ± 0.488	0.15	0.24	**< 0.001**	2.24	**< 0.001**	2.26
PDW [fl]	12.080 ± 1.302	12.480 ± 0.783	19.929 ± 1.906	0.16	0.37	**< 0.001**	4.81	**< 0.001**	5.11
AMP [au]	35.668 ± 2.050	35.434 ± 0.964	37.943 ± 4.214	0.58	0.15	0.08	0.69	0.15	0.82
AI [%]	57.636 ± 6.425	56.829 ± 5.316	53.450 ± 4.323	0.60	0.14	0.18	0.76	0.16	0.70
T1/2 [s]	3.034 ± 0.829	3.136 ± 0.658	3.534 ± 0.716	0.63	-0.14	0.25	0.65	0.21	0.58
EI 0,30 [Pa]	0.056 ± 0.007	0.056 ± 0.008	0.059 ± 0.009	0.74	0.00	0.46	0.37	0.53	0.35
EI 0,58 [Pa]	0.123 ± 0.011	0.122 ± 0.010	0.163 ± 0.012	0.47	0.10	**< 0.001**	3.47	**< 0.001**	3.71
EI 1,13 [Pa]	0.246 ± 0.016	0.245 ± 0.011	0.248 ± 0.012	0.57	0.07	0.54	0.14	0.78	0.26
EI 2,19 [Pa]	0.354 ± 0.012	0.349 ± 0.009	0.349 ± 0.011	**0.01**	0.47	0.95	0.43	0.40	0.00
EI 4,24 [Pa]	0.453 ± 0.011	0.452 ± 0.010	0.439 ± 0.008	0.31	0.10	**0.01**	1.46	**0.009**	1.44
EI 8,23 [Pa]	0.526 ± 0.010	0.528 ± 0.012	0.511 ± 0.003	0.48	-0.18	**0.002**	2.03	**0.001**	1.94
EI 15,95 [Pa]	0.576 ± 0.009	0.577 ± 0.008	0.559 ± 0.004	0.84	-0.12	**< 0.001**	2.44	**< 0.001**	2.85
EI 30,94 [Pa]	0.613 ± 0.006	0.614 ± 0.006	0.596 ± 0.005	0.16	0.17	**< 0.001**	3.08	**< 0.001**	3.26
EI 60,00 [Pa]	0.643 ± 0.005	0.644 ± 0.004	0.625 ± 0.004	0.28	0.22	**< 0.001**	3.98	**< 0.001**	4.75
Fibrynogen [g/dl]	3.263 ± 1.106	3.266 ± 1.069	1.493 ± 0.165	0.99	0.0	**< 0.001**	2.24	**< 0.001**	2.32
plasma viscosity [mPas]	1.491 ± 0.057	1.480 ± 0.056	1.464 ± 0.076	0.29	0.19	0.63	0.40	0.42	0.24

Table 1. Mean values ($\bar{X} \pm SD$) of blood morphology indicators, aggregation indicators, of red blood cell elongation indexes (EI) at various levels of shear stress, fibrinogen concentration and plasma viscosity in the Boxers group before and after simulated sparring and in the control group. RBC red blood cells count; HGB haemoglobin; HCT haematocrit; MCV mean corpuscular volume; MCH mean corpuscular haemoglobin; MCHC mean corpuscular haemoglobin concentration; RDW red blood cell distribution width standard deviation; WBC white blood cells count; LYM lymphocytes; MON monocytes; GRA granulocytes; PLT platelets; PCT procalcitonin; MPV mean platelet volume; PDW platelet distribution width; AMP erythrocyte aggregation amplitude; AI aggregation index; T1/2 half-time; EI elongation index. Statistically significant values have been bolded.

A significant difference in fibrinogen concentration was demonstrated between the studied groups, with a higher mean value in the boxer cohort ($p < 0.001$) (Table 1).

Boxers post vs. control group [intergroup comparison (Table 1)]

Comparison with the control group revealed significant differentiation of selected blood morphology parameters among athletes, such as: MCV ($p < 0.001$), RDW ($p = 0.001$), WBC ($p < 0.001$), LYM ($p < 0.001$), MON ($p < 0.001$), GRA ($p = 0.002$), PCT ($p < 0.001$), and MPV ($p < 0.001$), with higher values observed for boxers. Meanwhile, the control group predominated in MCHC ($p = 0.007$) and PDW ($p < 0.001$) (Table 1).

Analyzing the mean EI values of the study group (boxers) compared to the control group, statistically significant differences were found at shear stresses of 4.24 ($p = 0.009$), 8.23 ($p = 0.001$), 15.95 ($p < 0.001$), 30.94 ($p < 0.001$), and 60.00 Pa ($p < 0.001$). It was shown that the mean value was higher in the boxer group, whereas a decrease in EI at shear stress of 0.58 Pa was observed ($p < 0.001$) (Table 1).

A significant difference in fibrinogen concentration ($p < 0.001$) was demonstrated between the studied groups, with a higher mean value in the boxer cohort (Table 1).

MMA pre vs. MMA post fight [intra-group diversity (Table 2)]

Based on the results from Table 2, it can be concluded that in terms of morphology variables and their differentiation (before vs. after simulated sparring), the studied MMA athletes showed significant differences in selected parameters. Comparative analysis showed that for: RBC ($p = 0.001$), HGB ($p = 0.003$), MCH ($p = 0.005$), MCHC ($p = 0.019$), WBC ($p = 0.001$), LYM ($p < 0.001$), MON ($p = 0.003$), GRA ($p = 0.004$), PLT ($p = 0.002$), PCT ($p < 0.001$), and MPV ($p < 0.001$), athletes exhibited significantly higher levels after simulated sparring, with a decrease observed for HCT ($p = 0.001$).

Regarding red blood cell aggregation indices, a significant increase in aggregation index AI ($p = 0.003$) was noted, along with a decrease post-intervention for indices T1/2 ($p = 0.003$) and AMP ($p = 0.006$).

For the remaining parameters (EI, fibrinogen concentration, and blood plasma viscosity), no significant changes were observed.

MMA pre vs. control group [intergroup comparison (Table 2)]

Significant differences in morphological parameters were found when comparing MMA athletes with the control group (Table 2). Higher values of MCV ($p = 0.003$), WBC ($p < 0.001$), GRA ($p = 0.002$), LYM ($p = 0.007$), and PCT ($p < 0.001$) were noted in the MMA group, while a decrease was observed for MCHC ($p = 0.04$).

The mean EI values of the MMA group compared to the control group showed significant differences at selected shear stresses. An increase in mean EI was observed at shear stresses of 15.95 ($p = 0.04$) and 30.94 ($p = 0.001$) in the MMA group, while a decrease was noted at shear stresses of 0.58 ($p = 0.002$) and 1.13 Pa ($p = 0.005$) compared to the control group.

Regarding fibrinogen concentration, a significant difference was found between the studied groups, with a higher mean value in the MMA cohort ($p < 0.001$).

MMA post vs. control group [intergroup comparison (Table 2)]

Comparative analysis of the studied groups revealed significant differentiation in blood morphology variables, such as: MCV ($p = 0.03$), WBC ($p < 0.001$), LYM ($p < 0.001$), MON ($p < 0.001$), GRA ($p < 0.001$), and PCT ($p < 0.001$), with higher values registered for the MMA group (Table 2).

A decrease in red blood cell deformability at shear stresses of EI 0.58 ($p = 0.002$), 1.13 ($p = 0.01$), and 2.19 ($p = 0.04$) was observed in the MMA group, while an increase in EI at shear stresses of 30.94 ($p = 0.03$) and 60.00 Pa ($p = 0.04$) was noted (Table 2).

There was a significant difference in fibrinogen concentration ($p < 0.001$) between the studied groups, with a higher mean value in the MMA cohort (Table 2).

Boxers pre vs. MMA pre [intergroup comparison pre simulated sparring (Table 3)]

Before intervention, the studied groups significantly differed in the levels of selected blood morphology indicators (Table 3). In the boxer group, significantly higher levels were registered for: HCT ($p = 0.03$), RDW ($p = 0.002$), WBC ($p = 0.01$), MON ($p = 0.005$), PCT ($p = 0.04$), and MPV ($p < 0.001$). In the MMA group, this trend was observed for PDW ($p < 0.001$).

Regarding aggregation indices, significant differentiation was found for AMP ($p = 0.002$), with a higher mean in the MMA group, and for AI ($p = 0.05$), although with a predominance in the boxer group.

Variables of EI reflecting red blood cell deformability showed significant differentiation, particularly at shear stress of 0.58 Pa ($p = 0.006$), with a predominance in the MMA group. The same trend of difference favoring the boxer group was observed for shear stresses of: 1.13 ($p = 0.02$), 2.19 ($p = 0.009$), 4.24 ($p = 0.001$), 8.23 ($p = 0.005$), 15.95 ($p = 0.004$), 30.94 ($p = 0.003$), and 60.00 Pa ($p < 0.001$).

Additionally, fibrinogen concentration ($p = 0.02$) was significantly higher in the boxer cohort.

No significant intergroup differences were observed for the remaining variables studied.

Boxers post vs. MMA post [intergroup comparison post simulated sparring (Table 3)]

After intervention, significant differentiation was observed in the mean levels of indicators: RDW ($p = 0.005$) and MPV ($p = 0.02$), which again were higher for the boxer group. However, in contrast to the pre-test where boxers had higher levels of HCT, WBC, MON, and PCT, no significant disparities were found post-test. For the MMA group, significantly higher mean PDW ($p < 0.001$) and MCHC ($p < 0.001$) were again observed, which was not seen in the pre-test.

Parameters	MMA (pre)	MMA (post)	Control group	*p* (MMA pre vs post)	d Cohen's	*p* (MMA pre vs Control)	d Cohen's	*p* (MMA post vs Control)	d Cohen's
RBC [T/l]	4.824 ± 0.361	4.991 ± 0.396	5.326 ± 0.973	**0.001**	0.44	0.22	0.68	0.41	0.45
HGB [g/dl]	14.686 ± 0.834	15.643 ± 1.036	16.171 ± 2.771	**0.003**	1.02	0.19	0.73	0.64	0.25
HCT [%]	46.786 ± 3.348	48.543 ± 3.717	50.086 ± 9.497	**0.001**	0.50	0.40	0.46	0.69	0.21
MCV [fl]	97.000 ± 2.769	97.143 ± 3.024	94.000 ± 1.826	0.60	0.05	**0.003**	1.28	**0.03**	1.26
MCH [pg]	30.471 ± 1.630	31.357 ± 1.128	30.443 ± 0.791	**0.005**	0.63	0.007	0.02	0.10	0.94
MCHC [g/dl]	31.400 ± 1.007	32.229 ± 0.519	32.400 ± 0.648	**0.019**	1.03	**0.04**	1.18	0.59	0.29
RDW [%]	12.986 ± 0.540	13.314 ± 0.474	12.900 ± 0.526	0.06	0.65	0.76	0.16	0.15	0.83
WBC [g/l]	5.600 ± 0.374	9.129 ± 1.586	3.886 ± 0.715	**0.001**	3.06	**< 0.001**	3.00	**< 0.001**	4.26
LYM [µl]	1.771 ± 0.269	3.914 ± 0.904	1.286 ± 0.302	**< 0.001**	3.21	**0.007**	1.70	**< 0.001**	3.90
MON [µl]	0.286 ± 0.069	0.614 ± 0.157	0.229 ± 0.076	**0.003**	2.70	0.16	0.79	**< 0.001**	3.12
GRA [µl]	3.543 ± 0.535	4.600 ± 1.036	2.371 ± 0.602	**0.004**	1.28	**0.002**	2.06	**< 0.001**	2.63
PLT [g/l]	241.857 ± 49.687	305.143 ± 73.361	240.571 ± 55.593	**0.002**	1.01	0.96	0.02	0.08	0.99
PCT [%]	170.143 ± 29.430	222.429 ± 45.376	0.164 ± 0.044	**< 0.001**	1.37	**< 0.001**	8.17	**< 0.001**	6.93
MPV [fl]	7.057 ± 0.251	7.329 ± 0.298	6.786 ± 0.488	**< 0.001**	0.99	0.21	0.70	**0.02**	1.34
PDW [fl]	18.914 ± 0.463	20.000 ± 0.993	19.929 ± 1.906	0.06	1.40	0.19	0.73	0.93	0.05
AMP [au]	40.459 ± 3.438	35.674 ± 4.420	37.943 ± 4.214	**0.006**	1.21	0.24	0.65	0.34	0.53
AI [%]	51.900 ± 3.808	57.131 ± 3.090	53.450 ± 4.323	**0.003**	1.51	0.49	0.38	0.09	0.98
T1/2 [s]	3.786 ± 0.579	2.990 ± 0.436	3.534 ± 0.716	**0.003**	1.55	0.48	0.39	0.11	0.92
EI 0,30 [Pa]	0.121 ± 0.181	0.053 ± 0.008	0.059 ± 0.009	0.35	0.53	0.38	0.48	0.25	0.70
EI 0,58 [Pa]	0.140 ± 0.010	0.141 ± 0.009	0.163 ± 0.012	0.69	0.11	**0.002**	2.08	**0.002**	2.07
EI 1,13 [Pa]	0.229 ± 0.009	0.233 ± 0.007	0.248 ± 0.012	0.11	0.50	**0.005**	1.79	**0.01**	1.53
EI 2,19 [Pa]	0.338 ± 0.009	0.337 ± 0.009	0.349 ± 0.011	0.72	0.11	0.07	1.09	**0.04**	1.19
EI 4,24 [Pa]	0.434 ± 0.008	0.436 ± 0.010	0.439 ± 0.008	0.47	0.22	0.26	0.63	0.50	0.33
EI 8,23 [Pa]	0.512 ± 0.005	0.513 ± 0.006	0.511 ± 0.003	0.82	0.18	0.52	0.24	0.48	0.42
EI 15,95 [Pa]	0.564 ± 0.004	0.564 ± 0.004	0.559 ± 0.004	0.59	0.00	**0.04**	1.25	0.07	1.25
EI 30,94 [Pa]	0.603 ± 0.004	0.602 ± 0.004	0.596 ± 0.005	0.51	0.25	**0.001**	1.55	**0.03**	1.33
EI 60,00 [Pa]	0.625 ± 0.009	0.629 ± 0.003	0.625 ± 0.004	0.30	0.60	0.85	0.00	**0.04**	1.13
Fibrinogen [g/dl]	2.209 ± 0.256	2.397 ± 0.369	1.493 ± 0.165	0.30	0.59	**< 0.001**	3.32	**< 0.001**	3.16
Plasma viscosity [mPas]	1.503 ± 0.133	1.493 ± 0.054	1.464 ± 0.076	0.78	0.10	0.51	0.36	0.43	0.44

Table 2. Mean values (X ± SD) of blood morphology indicators, aggregation indicators, of red blood cell elongation indexes (EI) at various levels of shear stress, fibrinogen concentration and plasma viscosity in the MMA group before and after simulated sparring and in the control group. RBC red blood cells count; HGB haemoglobin; HCT haematocrit; MCV mean corpuscular volume; MCH mean corpuscular haemoglobin; MCHC mean corpuscular haemoglobin concentration; RDW red blood cell distribution width standard deviation; WBC white blood cells count; LYM lymphocytes; MON monocytes; GRA granulocytes; PLT platelets; PCT procalcitonin; MPV mean platelet volume; PDW platelet distribution width; AMP erythrocyte aggregation amplitude; AI aggregation index; T1/2 half-time; EI elongation index. Statistically significant values have been bolded.

Indices of red blood cell deformability showed a similar pattern of intergroup differentiation, as observed in the first measurement (pre-test).

Interestingly, in the second measurement (opposite trend to the first measurement), no significant differentiation was found in aggregation indices, namely AMP and AI, between the studied groups of athletes.

Furthermore, the mean fibrinogen concentration did not show significant differentiation between the studied cohorts in the second measurement, unlike the first measurement.

Significant plasma volume reductions were observed in both combat sports groups following sparring. The Boxing group demonstrated a mean plasma volume decrease of 1.59%, whereas the MMA group exhibited a more pronounced reduction of 8.97%. These reductions reflect the intensity and duration of sparring, with MMA sessions imposing greater physiological stress. These changes were associated with increases in hemoconcentration markers, such as hemoglobin (Hb) and hematocrit (Hct), and alterations in rheological properties, including erythrocyte aggregation and deformability.

Discussion

Physical exercise induces significant changes in the rheological properties of blood. Hemorheological effects of exercise can be divided into three phases: short-term effects indicating excessive viscosity, mainly caused by fluid shifts and changes in red blood cell deformability and aggregation; medium-term effects (reversal of acute

Parameters	Boxers (pre)	Boxers (post)	MMA (pre)	MMA (post)	MMA Pre vs Boxing pre	d Cohen's	MMA post vs Boxing post	d Cohen's
RBC [T/l]	5.175 ± 0.519	5.195 ± 0.446	4.824 ± 0.361	4.991 ± 0.396	0.14	0.79	0.34	0.48
HGB [g/dl]	15.340 ± 0.853	15.360 ± 0.957	14.686 ± 0.834	15.643 ± 1.036	0.13	0.78	0.57	-0.28
HCT [%]	51.410 ± 4.512	51.580 ± 4.320	46.786 ± 3.348	48.543 ± 3.717	**0.03**	1.16	0.15	0.75
MCV [fl]	99.500 ± 3.028	99.400 ± 3.534	97.000 ± 2.769	97.143 ± 3.024	0.10	0.86	0.19	0.69
MCH [pg]	29.840 ± 2.558	29.720 ± 1.921	30.471 ± 1.630	31.357 ± 1.128	0.57	– 0.29	0.06	– 1.04
MCHC [g/dl]	29.950 ± 2.005	29.890 ± 1.398	31.400 ± 1.007	32.229 ± 0.519	0.10	– 0.91	**< 0.001**	– 2.22
RDW [%]	14.160 ± 0.700	14.240 ± 0.636	12.986 ± 0.540	13.314 ± 0.474	**0.002**	1.88	**0.005**	1.65
WBC [g/l]	7.110 ± 1.443	8.560 ± 2.679	5.600 ± 0.374	9.129 ± 1.586	**0.01**	1.43	0.62	-0.26
LYM [µl]	2.100 ± 0.400	3.010 ± 0.962	1.771 ± 0.269	3.914 ± 0.904	0.07	0.97	0.07	-0.97
MON [µl]	0.470 ± 0.134	0.660 ± 0.280	0.286 ± 0.069	0.614 ± 0.157	**0.005**	1.73	0.70	0.20
GRA [µl]	4.540 ± 1.490	4.890 ± 1.980	3.543 ± 0.535	4.600 ± 1.036	0.11	0.89	0.72	0.18
PLT [g/l]	286.400 ± 72.765	324.600 ± 99.566	241.857 ± 49.687	305.143 ± 73.361	0.18	0.71	0.66	0.22
PCT [%]	219.100 ± 51.804	250.900 ± 71.437	170.143 ± 29.430	222.429 ± 45.376	**0.04**	1.16	0.36	0.48
MPV [fl]	7.680 ± 0.286	7.760 ± 0.363	7.057 ± 0.251	7.329 ± 0.298	**< 0.001**	2.32	**0.02**	1.30
PDW [fl]	12.080 ± 1.302	12.480 ± 0.783	18.914 ± 0.463	20.000 ± 0.993	**< 0.001**	– 6.99	**< 0.001**	– 8.41
AMP [au]	35.668 ± 2.050	35.434 ± 0.964	40.459 ± 3.438	35.674 ± 4.420	**0.002**	– 1.69	0.86	– 0.08
AI [%]	57.636 ± 6.425	56.829 ± 5.316	51.900 ± 3.808	57.131 ± 3.090	**0.05**	1.09	0.89	– 0.07
T1/2 [s]	3.034 ± 0.829	3.136 ± 0.658	3.786 ± 0.579	2.990 ± 0.436	0.06	– 1.05	0.61	0.26
EI 0,30 [Pa]	0.056 ± 0.007	0.056 ± 0.008	0.121 ± 0.181	0.053 ± 0.008	0.26	– 0.51	0.57	0.38
EI 0,58 [Pa]	0.123 ± 0.011	0.122 ± 0.010	0.140 ± 0.010	0.141 ± 0.009	**0.006**	-1.62	**< 0.001**	-2.00
EI 1,13 [Pa]	0.246 ± 0.016	0.245 ± 0.011	0.229 ± 0.009	0.233 ± 0.007	**0.02**	1.31	**0.03**	1.30
EI 2,19 [Pa]	0.354 ± 0.012	0.349 ± 0.009	0.338 ± 0.009	0.337 ± 0.009	**0.009**	1.51	**0.01**	1.33
EI 4,24 [Pa]	0.453 ± 0.011	0.452 ± 0.010	0.434 ± 0.008	0.436 ± 0.010	**0.001**	1.98	**0.003**	1.60
EI 8,23 [Pa]	0.526 ± 0.010	0.528 ± 0.012	0.512 ± 0.005	0.513 ± 0.006	**0.005**	1.77	**0.006**	1.58
EI 15,95 [Pa]	0.576 ± 0.009	0.577 ± 0.008	0.564 ± 0.004	0.564 ± 0.004	**0.004**	1.72	**0.001**	2.06
EI 30,94 [Pa]	0.613 ± 0.006	0.614 ± 0.006	0.603 ± 0.004	0.602 ± 0.004	**0.003**	1.96	**< 0.001**	2.35
EI 60,00 [Pa]	0.643 ± 0.005	0.644 ± 0.004	0.625 ± 0.009	0.629 ± 0.003	**< 0.001**	2.47	**< 0.001**	4.24
Fibrinogen [g/dl]	3.263 ± 1.106	3.266 ± 1.069	2.209 ± 0.256	2.397 ± 0.369	**0.02**	1.31	0.06	1.09
Plasma viscosity [mPas]	1.491 ± 0.057	1.480 ± 0.056	1.503 ± 0.133	1.493 ± 0.054	0.80	– 0.12	0.64	– 0.24

Table 3. Inter-group comparison (Boxers vs MMA, before and after simulated sparring) mean values ($\bar{X} \pm SD$) of blood morphology indicators, aggregation indicators, of red blood cell elongation indexes (EI) at various levels of shear stress, fibrinogen concentration and plasma viscosity. RBC red blood cells count; HGB haemoglobin; HCT haematocrit; MCV mean corpuscular volume; MCH mean corpuscular haemoglobin; MCHC mean corpuscular haemoglobin concentration; RDW red blood cell distribution width standard deviation; WBC white blood cells count; LYM lymphocytes; MON monocytes; GRA granulocytes; PLT platelets; PCT procalcitonin; MPV mean platelet volume; PDW platelet distribution width; AMP erythrocyte aggregation amplitude; AI aggregation index; T1/2 half-time; EI elongation index. Statistically significant values have been bolded.

effects due to increased plasma volume, known as auto-hemodilution); and long-term effects, which additionally improve blood fluidity and correspond to classical hormonal and metabolic changes induced by training[7]. The most common hemorheological change during physical training is a significant increase in whole blood viscosity. Whole blood viscosity is determined by hematocrit, plasma viscosity, red blood cell deformability, and aggregation. The increase in these indicators depends on: redistribution of red blood cells in the vascular system, spleen contraction increasing the number of circulating red blood cells, increased protein concentration in the plasma, water loss through sweat for thermoregulation, and water delivery to muscle cells[7,13].

During boxing matches, the primary objective is to deliver punches with fists, which often leads to injuries to the head, face, and upper body. Punches are typically more precise and targeted, which can cause specific micro-injuries. In our own studies comparing Boxers pre vs. control group and Boxers post vs. control group, we observed an increase in elongation index at shear stresses of 4.24, 8.23, 15.95, 30.94, and 60.00 Pa, as well as fibrinogen levels, and a decrease in EI at shear stress 0.58. Regarding blood morphology indicators, the Boxer group compared to the control group showed increases in MCV, RDW, WBC, LYM, MON, GRA, PCT, and MPV, with higher values observed among the boxers, and decreases in MCHC and PDW. We know that fibrinogen is a protein produced in the liver, it is an acute phase protein, which allows to evaluate the risk of thrombotic complications. Increased fibrinogen concentration during physical exertion leads to increased red blood cell aggregation. However, in our own studies, no statistically significant changes were found for AI, hematocrit, and blood plasma viscosity. Boxing is a combat sport that may seem demanding and brutal on the surface, but in our studies, an increase in red blood cell deformability was observed in Boxers at shear stresses of 4.24, 8.23, 15.95, 30.94, and 60.00 Pa, indicating a shortened red blood cell lifespan in athletes, as faster hemolysis occurs, which in turn affects the turnover of old red blood cells for new ones and improves red blood cell deformability, leading to better tissue oxygenation during fights. In addition to boxing and MMA, studies on other combat sports, such as taekwondo, have also shown significant rheological and physiological changes in response to physical exertion. For instance, Yang et al.[14] found that rapid weight loss in taekwondo athletes leads to decreased erythrocyte deformability and increased aggregation, likely due to oxidative stress and inflammatory responses similar to those observed in MMA and boxing[14]. Similarly, Roh et al.[15] analyzed the impact of regular taekwondo training on oxidative stress markers and noted improvements in the oxidative balance, with increased superoxide dismutase (SOD) activity and reduced malondialdehyde (MDA) levels, indicating an adaptive response to training intensity[15]. Additionally, Markovic et al. (2008) documented significant increases in heart rate and blood lactate during taekwondo bouts in elite female athletes, reflecting the high physical demands of these fights and the potential for similar hemorheological changes as those observed in boxing and MMA (Markovic et al. 2008). These findings align with the present study's observations on combat-induced hemorheological changes, highlighting the impact of physical exertion and combat sport-specific demands on blood rheology.

New erythrocytes are larger and more efficient in transporting oxygen to tissues. The decrease in EI at shear stress 0.58 in the Boxer groups compared to the control group indicates minor red blood cell deformability disorders, which according to [Brunoetal.] [7] affects oxidative stress caused by the production of free radicals, which may originate from mitochondria, leukocytes, or temporary tissue hypoxia. Confirmation of Bruno et al.'s theory[7] comes from our own studies, where an increase in leukocytes such as WBC, LYM, MON, and GRA was demonstrated. Similar trends were observed in blood morphology indicators comparing Boxers pre vs. Boxers post simulated sparring. An increase in WBC, LYM, MON, PLT, and PCT was observed after simulated sparring, along with a decrease in EI at shear stress 2.19. Activated leukocytes can interact with erythrocytes through reactive oxygen species and inflammatory cytokines, thereby reducing red blood cell deformability. Considering the increased number of leukocytes, this phenomenon indicates white blood cell activation, which in turn are stiffer and can directly affect circulatory hemodynamics.

Analyzing the results of our own studies comparing MMA pre vs. control group and MMA post vs. control group, higher values were observed in the MMA group for: MCV, WBC, LYM, GRA, PCT, EI at shear stress 30.94 and at shear stress 60.00, and fibrinogen. However, in the MMA group compared to the control group pre and post fights, decreased values were found for EI at shear stress 0.58 and EI at shear stress 1.13. Comparing MMA pre vs. MMA post-fight, blood morphology indicators were significantly higher in athletes after simulated sparring, and a significant increase in AI was observed post-intervention. Increased fibrinogen concentration during physical exertion leads to increased erythrocyte aggregation. Disorders in erythrocyte aggregation may also be associated with metabolic changes such as elevated lactate levels and reactive oxygen species[7]. The above results indicate disturbances in blood hemorheology, evidenced by changes in blood morphology, minor alterations in erythrocyte deformability, and an increase in red blood cell aggregation index. This suggests that the dynamic and comprehensive fighting techniques in MMA (both standing and ground positions), exposing the entire body to strikes, grappling techniques (including clinching, throws, joint locks, chokes), and head strikes, negatively affect blood rheology indicators in MMA athletes. MMA encompasses a wide range of techniques, including punches, kicks, knee strikes, grips, and chokes. Therefore, injuries are more extensive and involve larger areas of the body, including limbs and torso. The observed reductions in plasma volume following simulated sparring align with established physiological responses to intense physical activity, where fluid shifts from the intravascular space to working muscle tissues result in hemoconcentration. The greater plasma volume reduction in the MMA group (8.97%) compared to the Boxing group (1.59%) likely reflects the prolonged duration and higher intensity of MMA sparring, which includes diverse technical actions and engages multiple muscle groups. These findings are consistent with studies by Dill and Costill[16], which highlight the role of plasma volume shifts in hemorheological changes. The marked plasma volume reduction in MMA athletes may exacerbate hemoconcentration-related alterations in rheological properties, such as increased erythrocyte aggregation and reduced deformability, potentially impairing blood flow and oxygen delivery. This underscores the need for tailored hydration and recovery strategies in MMA to mitigate the adverse effects of hemoconcentration on athletic performance and recovery. In MMA, due to the greater diversity of techniques, vascular injuries—both superficial and deep—are more frequent. Fractures, bruises, and even internal bleeding are more common, which can impact the rheological properties of blood. The higher incidence of injuries and tissue damage in MMA can lead to stronger inflammatory reactions, which also affect blood rheology. MMA fights are often longer and more intense than boxing matches, which in turn affect blood rheological properties. This is confirmed by the results of red blood cell deformability in the MMA group compared to boxers (Table 3). In the MMA group, decreased red blood cell deformability at shear stresses of 1.13, 2.19, 4.24, 8.23, 30.94, and 60.00 was observed, with no changes in AI, AMP, T1/2, blood plasma viscosity, and fibrinogen, indicating blood flow disorders.

Limitations and future research directions

The results of this study may be somewhat limited due to the focus on simulated sparring. However, within the inevitable constraints of our experimental design, we recruited high-level athletes from the studied disciplines and followed a strict protocol that simulated conditions akin to real sports matches, thereby scientifically justifying our findings. Future exploratory efforts should expand the study to encompass the specifics of tournament fights. To provide a broader clinical context, future research should also include samples from female populations and representatives of other combat sports disciplines (e.g., grappling sports like BJJ, judo, wrestling).

Conclusion
The practiced discipline of combat sports had an impact on the profile of changes in blood rheological properties following the intervention. Indicators of blood rheology suggest that MMA fights have a more negative impact on blood flow compared to boxing matches. Changes in blood rheology after MMA fights indicate decreased deformability of erythrocytes, which can lead to impaired blood flow and increased risk of cardiovascular complications.

Applicatory conclusions
Boxers are advised to employ training strategies that minimize oxidative stress to reduce the negative effects of accelerated erythrocyte hemolysis. This may include appropriate recovery strategies and antioxidant supplementation.

Adept MMA, due to their demonstrated condition, are advised to adopt intensified and multifaceted prevention strategies aimed at improving erythrocyte deformability under low shear stress to reduce susceptibility to oxidative stress. This includes: exercises enhancing circulation and vascular flexibility (such as yoga, HIIT training, aerobic endurance), a diet rich in antioxidants (fruits, vegetables, healthy fats, glutathione-containing foods), supplementation optimizing erythrocyte function (iron, vitamin B12, folic acid, vitamin C, E, coenzyme Q10, resveratrol) and effective regeneration and stress reduction (adequate sleep, relaxation techniques).

Furthermore, in high-level combat sports, systematic health monitoring, including blood parameter monitoring after intense training periods, is crucial.

These actions can aid in early detection of potential pathologies and provide valuable insights into the physiological status of athletes and their adaptive capacity to the specific physical demands of the discipline.

Availability of data and materials
The original contributions presented in the study are included in the article/supplementary material,, and further inquiries can be directed to the corresponding author/s.

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References
1. Tropin, Y. et al. Analyzing predictive approaches in martial arts research. *Pedagogy Phys. Cult. Sports* **27**, 321–330. https://doi.org/10.15561/26649837.2023.0408 (2023).
2. Aryowiloto, J. & Rofiyarti, F. The power of united states in dominating mixed martial arts sports through ultimate fighting championship. *Acitya Wisesa (J. Multidiscip. Res.)* **2**, 71–85. https://doi.org/10.56943/jmr.v2i3.416 (2023).
3. Gonçalves, A. F. et al. Enhancing performance: Unveiling the physiological impact of submaximal and supramaximal tests on mixed martial arts athletes in the−61 kg and−66 kg weight divisions. *Front. Physiol.* **14**, 1257639. https://doi.org/10.3389/fphys.2023.1257639 (2024).
4. Rydzik, Ł et al. The effect of physical exercise during competitions and in simulated conditions on hormonal-neurophysiological relationships in kickboxers. *Biol. Sport* **41**, 61–68. https://doi.org/10.5114/biolsport.2024.133662 (2024).
5. Baskurt, O. K. et al. (eds) *Handbook of hemorheology and hemodynamics* Vol. 69 (IOS Press, 2007).
6. Nader, E. et al. Blood rheology: Key parameters, impact on blood flow, role in sickle cell disease and effects of exercise. *Front. Physiol.* **10**, 1329. https://doi.org/10.3389/fphys.2019.01329 (2019).
7. Brun, J. F. et al. The triphasic effects of exercise on blood rheology: Which relevance to physiology and pathophysiology?. *Clin. Hemorheol. Microcirc.* **19**, 89–104 (1998).
8. El-Sayed, M. S., Ali, N. & Ali, Z. E. S. Haemorheology in exercise and training. *Sports Med.* **35**, 649–670. https://doi.org/10.2165/00007256-200535080-00001 (2005).
9. Yalcin, O., Bor-Kucukatay, M., Senturk, U. K. & Baskurt, O. K. Effects of swimming exercise on red blood cell rheology in trained and untrained rats. *J. Appl. Physiol.* **88**, 2074–2080. https://doi.org/10.1152/jappl.2000.88.6.2074 (2000).
10. Heidari, N., Dortaj, E., Karimi, M., Karami, S. & Kordi, N. The effects of acute high intensity interval exercise of judo on blood rheology factors. *Turk. J. Kinesiol.* **2**, 6–10 (2016).
11. Marfell-Jones, M. J., Stewart, A. D. D. & Ridder, J. H. *International standards for anthropometric assessment* (International Societyfor the Advancement of Kinanthropometry, 2012).
12. MMA Polska (2023) Regulamin sportowy. Available from URL: https://mmapolska.org/download/regulamin1.pdf [Accessed 24 June 2024] (in Polish).
13. El-Sayed, M. S. Effects of exercise and training on blood rheology. *Sports Med.* **26**, 281–292. https://doi.org/10.2165/00007256-199826050-00001 (1998).
14. Yang, W. H. et al. Rapid rather than gradual weight reduction impairs hemorheological parameters of taekwondo athletes through reduction in RBC-NOS activation. *PLoS ONE* **10**(4), e0123767. https://doi.org/10.1371/journal.pone.0123767 (2015).
15. Roh, H.-T., Cho, S.-Y. & So, W.-Y. Effects of regular taekwondo intervention on oxidative stress biomarkers and Myokines in overweight and Obese adolescents. *Int. J. Environ. Res. Public Health* **17**(7), 2505. https://doi.org/10.3390/ijerph17072505 (2020).
16. Dill, D. B. & Costill, D. L. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J. Appl. Physiol.* **37**(2), 247–248. https://doi.org/10.1152/jappl.1974.37.2.247 (1974).
17. Teległów A., Review: Zbigniew Dąbrowski, Anna Marchewka, Aneta Teległów (eds.), Sports Haematology, Wydawnictwo Lekarskie PZWL, Warsaw 2022, *Health Promotion and Physical Activity 2024*; **29**(4), 37–39. https://doi.org/10.55225/hppa.642 (2024)
18. Rydzik, Ł, İlbak, İ, Ouergui, I., Podrighalo, L. & Pałka, T. Analysis of cortisol concentration changes induced by stress in Kickboxing K1 competition. *J. Sports Res. Innov.* **1**, 1–8 (2024). (http://creativecommons.org/licenses/by-sa/4.0/)

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Author contributions
Conceptualization, A.T., T.A., W.M.; methodology, A.T.,T.A., Ł.R.,W.W., P.S., P.R. formal analysis, Ł.R., W.W., ; investigation, A.T.,T.A.W.W., ; resources, A.T., T.A., W.W., P.S.; data curation, A.T., W.W., P.S., writing—original draft preparation, A.T., Ł.R., W.W..; writing—review and editing, A.T., Ł.R., W.W., T.A. supervision: A.T., T.A.; project administration, A.T., E.M.; funding acquisition, E.M., A.T., W.M., T.A. All authors haveread and agreed to the published version of the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Ethics approval
The study was conducted according to the Declaration of Helsinki and approved by the Bioethics Committee at the District Medical Chamber in Krakow (No. 226/KBL/OIL/2023).

Informed consent
Informed consent was obtained from all subjects involved in the study.

Additional information
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