Original Article

Effects of sodium pyruvate supplementation on repeated sprint exercise performance and recovery in male college soccer players: a randomized controlled trial

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Background: Sodium pyruvate (PYR) has been reported to improve aerobic metabolism and attenuate metabolic acidosis. Aerobic capacity and the ability to remove hydrogen ions affect the recovery from repeated high intensity activities. However, the effects of PYR supplementation on repeated sprint exercise (RSE) performance have not been elucidated. This study explored the effects of PYR ingestion on RSE ability and recovery.

Methods: A total of 14 male soccer athletes (aged 20±2 years) participated in this double-blinded crossover study. The subjects completed two experimental sessions after randomized ingestion of either PYR or the maltodextrin placebo (PLA) for 1 week. At each session, participants completed high-intensity interval exercise (HIIE) and RSE 60 minutes after supplementation. Additionally, acid-base parameters in venous blood, energy system contributions, and power output were assessed.

Results: Compared to PLA, PYR supplementation significantly increased the relative peak power output (PPO) of the first (P=0.034) and fifth (P=0.043) sprints, and the relative mean power output (MPO) of the fifth sprint (P=0.026). In addition, the mean PPO (P=0.031) and MPO (P=0.033) of sprints 1–6 were significantly elevated after PYR supplementation. After PYR administration, the phosphagen energy system [adenosine triphosphate (ATP)-phosphocreatine (PCr)] resynthesis of the fourth (P=0.034) and the overall recovery periods during HIIE (P=0.029) were higher than PLA administration. Additionally, the ATP-PCr resynthesis of the first (P=0.033) and fifth (P=0.019) recovery periods, and the mean of the six recovery periods during RSE (P=0.041) were increased in the PYR group compared to the PLA group. Furthermore, participants on the PYR regimen had higher blood pH, HCO_3^-, and base excess at pre-HIIE, post-HIIE, and pre-RSE (all P<0.05) compared to participants receiving PLA.

Conclusions: PYR supplementation enhanced RSE performance, and the improvement may be attributed to accelerated restoration of the acid-base balance and ATP-PCr regeneration.

Trial Registration: Chinese Clinical Trial Registry ChiCTR2100053936.

Keywords: Exercise-induced metabolic acidosis; repeated sprint exercise (RSE); energy metabolism; performance; sodium pyruvate (PYR)

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Introduction

Typical characteristics of team sports include multiple sets of high-intensity exercise and sprints interspersed with short-term recovery sessions, and these exercise bouts usually last for several hours (1). Repeated sprint exercise (RSE) is generally considered to be the determining part to maintain the possession and shooting rates, despite the fact that sprinting activities only account for 10% of the total distance of team sports (2). However, during high-intensity or sprint exercises, the rate of hydrogen ion (H^+) generation by non-mitochondrial adenosine triphosphate (ATP) far exceeds the rate of neutralization by aerobic ATP (3). Some intracellular H^+ is transported to the blood, where H^+ is mainly neutralized by bicarbonate (HCO_3^-) (4). With repeat exercise, the increased accumulation of H^+ in skeletal muscles and the blood is concomitant with a disturbance of the acid-base balance [i.e., decrease in blood pH, HCO_3^-, and base excess (BE)] (3,5). After bouts of sprinting in the first half of a soccer match, muscle pH was found to drop to 6.96 compared with 7.24 at rest (5). In addition, significant differences in blood pH (7.41–7.25) and HCO_3^- (24.8–13.6 mmol/L) were observed before and after a team sports game (6). This alteration has been described as exercise-induced metabolic acidosis and is believed to cause fatigue by impairing glycolytic, phosphagen energy [ATP-phosphocreatine (PCr)] systems metabolism, and muscle contraction during exercise (7). Additionally, the majority of energy required for sprints is obtained from hydrolysis of the ATP-PCr system. Multiple sprints, however, lead to depletion of PCr which will negatively affect RSE ability (8,9). Throughout a game, RSE capacity of high or ordinary level athletes will gradually decrease (7,10). The ability to recover from these exercise bouts and maintain RSE performance is generally considered to be a crucial factor in winning team sports competitions (2). Interventions that promote ATP-PCr resynthesis and acid-base balance recovery may be therefore beneficial in team sports.

Since the resynthesis of PCr (11) and the removal of intracellular H^+ (3) during recovery sessions rely on aerobic metabolism, the RSE ability may be aided by aerobic capacity. Nutrition supplementation strategies including alkaline buffers (such as sodium bicarbonate and β-alanine) are known to neutralize intracellular or extracellular H^+ and alleviate the inhibition of glycolysis rate-limiting enzymes, but only improve single sprints or RSE performance by about 2–3% (12,13). However, co-ingestion of creatine and sodium bicarbonate has been shown to increase both skeletal muscle PCr content and acid-base recovery, which is more effective in improving RSE performance (14). Therefore, nutritional strategies to improve aerobic metabolic capacity during recovery periods may be beneficial for enhancing RSE performance.

Pyruvate is an important metabolite of glucose and a key metabolic substrate for mitochondrial oxidative metabolism (15). Evidence in numerous preclinical studies suggested that exogenous sodium pyruvate (PYR) supplementation activates pyruvate dehydrogenase (PDH), preserves mitochondrial tricarboxylic acid cycle flux and aerobic metabolism, and can effectively correct metabolic acidosis (16,17). Previous studies found that the blood pH values of the PYR group were higher than the control group after resuscitation in a model of hemorrhagic shock (18,19). Petrat *et al.* found that PYR could increase blood pH and BE after reperfusion in rat model of severe intestinal ischemia-reperfusion injury (20). More importantly, it was indicated that PYR increased pH intracellularly in isolated failing human myocardium and reduced (NH_4Cl)-induced hyperchloremic acidosis in rat model (21,22). Furthermore, Olek *et al.* found that acute PYR intake increased blood pH, HCO_3^-, and BE at rest in healthy adults (23), but these effects were not observed following 6 minutes of high-intensity exercise (24). Two other studies demonstrated that ingestion of PYR for 1 or 2 weeks had no effect on the time to exhaustion during intense exercise (25) or critical power cycle ergometer test performance (26). However, the time-to-exhaustion protocols used in these latter studies may have a high coefficient of variation and are thus not sufficiently accurate for evaluating the effects of PYR in exercise (27). Despite the positive effects of PYR supplementation on aerobic metabolism and acidosis, to date, there have been no studies investigating PYR supplementation on acid-base balance and energy metabolism during high-intensity interval exercise (HIIE) and RSE. Indeed, studies have demonstrated that a 7-day PYR supplementation regimen may have beneficial effects on glucose metabolism during

high-intensity exercise (28). In addition, 1 week of PYR supplementation may be effective in promoting aerobic metabolism and attenuating acidosis, thereby promoting RSE performance. Therefore, further studies are warranted to explore the efficacy of PYR supplementation for energy and H^+ metabolism during exercise so as to provide novel nutritional strategies to enhance RSE performance.

This current investigation examined the effects of 1 week of PYR intake on RSE performance and recovery in male soccer players. We hypothesized that PYR supplementation for 1 week would enhance ATP-PCr regeneration and acid-base recovery, leading to an increase in RSE performance. We present the following article in accordance with the CONSORT reporting checklist (available at https://apm.amegroups.com/article/view/10.21037/apm-21-3862/rc).

Methods

Participants

This is a randomized, double-blinded, crossover trial with a 1:1 allocation ratio. To avoid potential menstrual cycle effects on energy metabolism, only male participants were enrolled (29). Participants were excluded if they were suffering from hypertension, diabetes, cardiovascular or metabolic diseases; if they had taken cigarettes and/or alcohol; and if they had taken buffering agents within the previous 6 months and throughout this study. The inclusion criteria included the following: (I) participants aged 18–24 years; (II) BMI ranged from 18.5 to 23.9 kg/m^2; and (III) participants had at least 5 years of experience in soccer training with VO_{2max} over 50 mL/kg/minute. The study protocol was approved by the Internal Review Board of the Beijing Sport University (No. 2020057H). All procedures performed in this study involving human participants were in accordance with the Declaration of Helsinki (as revised in 2013). Participants were informed of the study aims, possible risks, and signed an informed consent form.

Experimental design

Participants visited the laboratory on 3 separate sessions, including 1 familiarization session and 2 experimental sessions, each session separated by 14 days. At the first visit, personal information, anthropometric measurements (height and body composition), and graded cycling exercise test (GXT) results were collated. All participants completed the exercise protocol familiarization session. After a 7-day washout period, each participant was then assigned to ingest either 0.1 g/kg/d of PYR or the maltodextrin placebo (PLA) in the following 7 days in a counterbalanced randomized design (i.e., 7 participants were supplemented with PYR and 7 participants were administered the PLA).

During the second and third visits (i.e., on the seventh day of supplementation), 45 minutes following the intake of either PYR or PLA, participants completed a 15-minute resting oxygen uptake test. After a 5-minute warmup, a high-intensity interval exercise (HIIE) cycling test was performed, followed by a 6-minute post-exercise oxygen consumption (EPOC) assessment. Participants undertook the RSE test 4 minutes after the EPOC test.

Oxygen uptake was measured breath-by-breath during GXT, 15 minutes before HIIE, during HIIE, 6 minutes after HIIE, and during RSE, using a portable gas analysis system (Cortex Metamax 3B, CORTEX Biophysik, Leipzig, Germany). Participants completed the oxygen uptake test 15 minutes before and 6 minutes after HIIE in a sitting position. Resting oxygen uptake was taken as the average of the last 10 minutes of data (30). Before each test, the gas analyzer was calibrated according to the instructions of the manufacturer.

Before each visit, all participants visited the laboratory 2 hours after a meal and avoided intense exercise and coffee for 24 hours. The diets for the 24 hours prior to the first visit were recorded. Participants were required to replicate the same diet as accurately as possible 24 hours before the next visits. All participants performed all tests at the same time of day and in the same laboratory environment.

Preliminary assessment and familiarization

At the first laboratory visit, the participant's height and body composition was measured with a calibrated electronic scale (GMCS-SGJ3, Jianmin, Beijing, China) and a multifrequency bioelectrical impedance measurement device (Inbody 230, Biospace, Seoul, Korea), respectively. Thereafter, each participant performed GXT on an electromagnetically braked cycle ergometer (EC 3000e, CUSTO Med, Ottobrunn, Germany) to determine peak power (W_{max}) and VO_{2max}. After adjusting the seat, participants warmed up for 3 minutes at 50 W, the load was then increased by 30 W/minute with pedal frequency maintained at around 75–80 rpm. During the test, Polar V800 (Polar Electro Oy, Oulu, Finland) was used to measure the heart rate. The standards for exhaustion included at least 3 of the following criteria: (I) failure to

maintain 75 rpm for 5 seconds; (II) oxygen uptake (VO_2) changes ≤2.1 mL/kg/minute in 2 consecutive workloads; (III) respiratory exchange rate (VCO_2/VO_2) ≥1.10; and (IV) maximal heart rate ≥90% of the predicted maximal value. VO_{2max} is the average oxygen consumption within the final 30 seconds (31). W_{max} is determined as the load of the last completed stage plus the fraction of time spent in the final uncompleted stage multiplied by 30 W (32). After a short rest period, all participants completed familiarization with the experimental exercise protocol. Familiarization sessions included performing a HIIE and an RSE. All familiarization protocols were designed to eliminate the effects of learning and training.

Experimental trials

Supplementation protocol

High quality PYR (≥99.0% pure PYR, Lianlu industrial Co., Ltd., Shanghai, China) and maltodextrin were randomly packaged into capsule A or B by an independent staff. The capsules were similar in appearance, size, and weight. Supplementation with PYR in humans can result in significant blood alkalinization within 1–2 hours (23). Studies have suggested that supplementation with multiple smaller doses may prevent gastrointestinal intolerance (33). Therefore, for the first 6 days, participants took 0.1 g/kg/d PYR or maltodextrin at 25% dose after breakfast, 25% after lunch, 25% after dinner, and 25% before bed. On the 7th day, the capsules were all ingested at once (23,25). Each 1-day dose was given in a separate plastic bag labeled with a date, and participants were required to consume supplements on time and provide videos. Participants who took capsule A were switched over to capsule B and vice versa during the test. During the study, participants and test personnel were blind and reported similar appearance and taste of the PYR and PLA capsules. Furthermore, none of the participants reported gastrointestinal discomfort with either capsule (23,25).

Primary outcome

HIIE and RSE tests

HIIE was conducted on a cycle (Ergoline Ergoselect 100K, Ergoline, Bitz, Germany). During the test, participants undertook a 5-minute warm-up at 60 W. Then, the HIIE protocol was performed, consisting of 4 sessions of 1-minute cycling at 110% of their W_{max}, interspersed with 1-minute recovery periods. Cadence was constant (90–100 rpm) during each high-intensity bout (34).

Following HIIE, participants rested for 10 minutes, and then completed 6 sessions of 6-second maximal cycling, interspersed with 24 seconds passive recovery on a mechanically-braked Monark cycle ergometer (894E, Monark, Vansbro, Sweden). Each sprint exercise was started with a "3, 2, 1, go" countdown. Once cadence reached 110 rpm, the 0.087 kp/kg body mass load was added to the ergometer, and the 6-second sprint was started (35). All participants were encouraged to exert maximum effort possible during each sprint. The seat height and handlebar position for each participant was adjusted prior to the initial HIIE and RSE tests and remained the same for subsequent tests. The RSE test protocol has been reported to be valid and reliable (36), and has been previously used to measure exercise performance in soccer players (37).

All data were calculated via Monark Anaerobic Testing software (version 3.3.0.0, developed in cooperation with HUR Labs) (38). The software automatically recorded the power output per second and calculated the relative peak power output (PPO) and relative mean power output (MPO) for each sprint. The mean PPO and MPO were calculated by taking the average of PPO and MPO for sprints 1–6, respectively (38).

Blood collection and analysis

Venous blood samples (1.0 mL) obtained from the ulnar vein at baseline, pre-HIIE, post-HIIE, pre-RSE, and post-RSE were collected in sodium heparin tubes (YA1430, Solarbio, Beijing, China) and immediately assessed for blood pH, HCO_3^-, and BE using a blood gas analyzer (Radiometer ABL80, FLEX CO-OX, Willich, Germany) (39).

Capillary blood samples (10 μL) taken by finger prick were collected with Biosen capillary tubes (EKF Diagnostics, Barleben, Germany) at baseline, immediately after each bout of HIIE, and at 3, 5, 7, and 10 minutes after HIIE. The samples were used to measure blood lactate concentrations with a lactate analyzer (Biosen C-Line, EKF Diagnostics, Barleben, Germany).

Secondary outcome

Estimation of energy system contributions

Contributions of the aerobic energy system were estimated by subtracting the resting oxygen uptake from the oxygen consumption obtained during each 110% W_{max} bout. All oxygen used during HIIE was converted to energy assuming one liter of oxygen is equal to 20.92 kJ (40). The lactate

accumulated during each 110% W_{max} bout was used to evaluate the contributions of the glycolytic energy system of each bout of HIIE (1 mmol/L of lactate equals to 3 mL/kg of oxygen) (40). The ATP-PCr resynthesis were calculated by subtracting resting oxygen from the oxygen consumption obtained during each HIIE and RSE recovery periods, and the fast component of post-exercise oxygen consumption ($EPOC_{fast}$) accessed during the 6 minutes after HIIE. The $EPOC_{fast}$ was determined by the product of the amplitude and time constant of the first exponential decay (OriginPro 8.0, OriginLab, Microcal, Massachusetts, USA) (41,42).

Statistical analysis

A priori analysis with the G*Power software (version 3.1.9.6, Universitat Kiel, Germany) indicated a required sample size of 13 to detect significant differences in acid-base balance values. The following parameters were applied: repeated measures ANOVA within factors; effect size (f) =0.24; α=0.05; power (1–β) =0.8; and correction among repeated measures =0.5 (43). Data analyses were performed using SPSS software (version 22.0, SPSS Inc. Chicago, IL, USA) and presented as the mean ± standard deviation (SD). The Shapiro-Wilk test was used to determine the data normality. Two-way repeated-measures ANOVA was performed to assess the interaction between time and the two groups, and *post-hoc* analysis was performed using Fisher's least significant difference test. Effect sizes were calculated as partial eta-squared [η_p^2; small effect (0.01–0.059), medium effect (0.06–0.139), and large effect (≥0.14)]. Independent samples *t*-tests were used to measure average PPO and MPO, and average contributions of the energy system during HIIE and RSE. Effect sizes were expressed as Cohen's d, where Cohen's d =0.20–0.49 indicates a small effect, Cohen's d =0.50–0.79 indicates a medium effect, and Cohen's d ≥0.80 indicates a large effect. The significance level was set at P<0.05.

Results

Between October and December 2020, 15 national-level male soccer athletes from the China Football College were enrolled in this study. *Figure 1* shows the enrollment and follow-up of the participants. One participant dropped out after completing the first visit due to personal reasons. Fourteen athletes completed all the sessions and were included in the data analysis. The baseline characteristics of participants are shown in *Table 1*.

RSE performance

Post-hoc analysis showed significant differences between PYR and PLA groups in the PPO of the first sprint (P=0.034, η_p^2 =0.161) and fifth sprints (P=0.043, η_p^2 =0.149) (*Figure 2A*). In addition, the MPO of the fifth sprint (P=0.026, η_p^2 =0.177) was significantly improved after PYR administration compared to PLA administration (*Figure 2B*).

The mean PPO (P=0.031, Cohen's d =0.86) (*Figure 2C*) and the mean MPO of the 6 sets of sprints (P=0.033, Cohen's d =0.85) (*Figure 2D*) were higher after PYR administration compared to PLA administration.

Energy system contributions

During HIIE, there were no difference between PYR and PLA groups in the aerobic energy system contributions (P=0.275, η_p^2 =0.046) (*Figure 3A*). Compared with the PLA group, the ATP-PCr resynthesis of the fourth recovery period (P=0.034, η_p^2 =0.161) during HIIE was significantly improved in the PYR group (*Figure 3B*). For contributions of the glycolytic energy during HIIE, a significant reduction was observed during repeated high-intensity exercise in both groups (P<0.0001, η_p^2 =0.802). However, no changes were observed in the contributions of glycolytic energy between PYR and PLA groups (P=0.410, η_p^2 =0.026) (*Figure 3C*).

The total contribution of aerobic energy (P=0.275; *Figure 3D*) during HIIE was not changed between the two groups. PYR supplementation enhanced the total ATP-PCr resynthesis during HIIE (P=0.029, Cohen's d =0.874; *Figure 3E*). However, the total contribution of glycolytic energy (P=0.411; *Figure 3F*) during HIIE did not differ between the two groups.

During RSE, compared with the PLA group, the ATP-PCr resynthesis of the first (P=0.033, η_p^2 =0.163) and fifth (P=0.019, η_p^2 =0.193) recovery periods were significantly improved in the PYR group (*Figure 4A*). In addition, the total ATP-PCr resynthesis was significantly improved by PYR than PLA supplement (P=0.041, Cohen's d =0.81) during RSE (*Figure 4B*).

Blood gas analysis

Table 2 shows the changes in blood pH, HCO_3^-, and BE at baseline, during pre- and post-HIIE and RSE. There was no effect of supplementation order on blood pH, HCO_3^-, nor BE at baseline (all P>0.05). However, blood pH, HCO_3^-, and BE decreased from baseline to pre-HIIE and post-

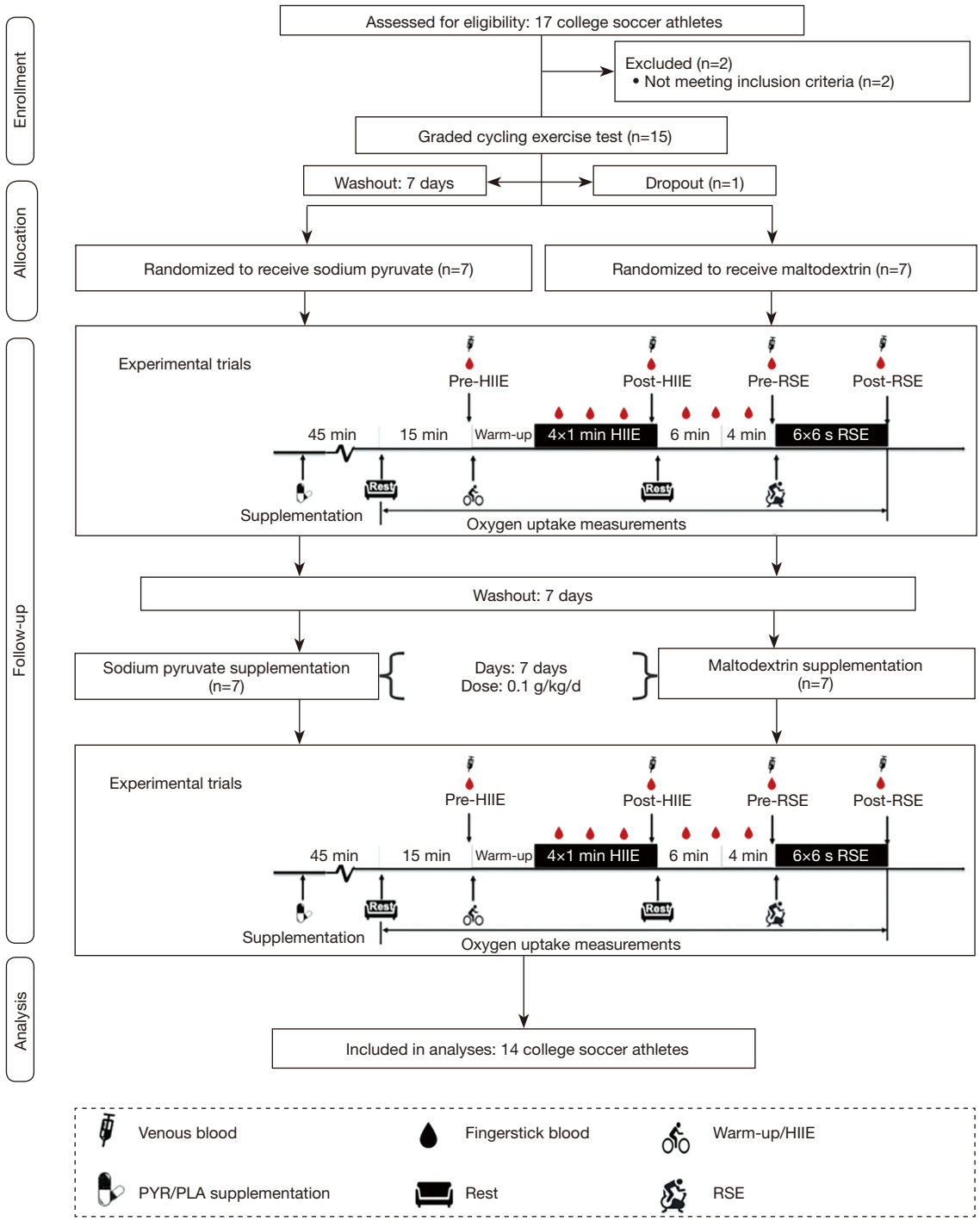

Figure 1 A timeline of the supplementation and exercise tests. HIIE, high-intensity interval exercise; RSE, repeated sprint exercise; PYR, sodium pyruvate; PLA, placebo.

Table 1 Baseline characteristics of participants (n=14)

Characteristics	Value, mean ± SD
Age (year)	20±2
Height (cm)	178.3±6.4
Weight (kg)	69.58±7.22
Body fat (%)	13.11±3.50
VO_{2max} (mL/kg/min)	55.93±5.36
W_{max} (W)	298.54±41.70
Training year (year)	9±3

SD, standard deviation; VO_{2max}, maximal oxygen uptake; W_{max}, maximal power output.

HIIE levels, as well as from pre-RSE to post-RSE levels in both groups (all P<0.05). Furthermore, compared with the PLA group, blood pH was significantly higher at pre-HIIE (P=0.018, η_p^2 =0.198), post-HIIE (P=0.041, η_p^2 =0.15), and pre-RSE (P=0.032, η_p^2 =0.165) following PYR ingestion. Blood HCO_3^- levels were significantly higher at pre-HIIE (P=0.002, η_p^2 =0.316), post-HIIE (P=0.01, η_p^2 =0.238), and pre-RSE (P=0.019, η_p^2 =0.195) with PYR supplementation compared to PLA. PYR administration also resulted in higher blood BE at pre-HIIE (P=0.002, η_p^2 =0.323), post-HIIE (P=0.047, η_p^2 =0.143), pre-RSE (P=0.036, η_p^2 =0.158), and post-RSE (P=0.021, η_p^2 =0.189) compared to PLA administration.

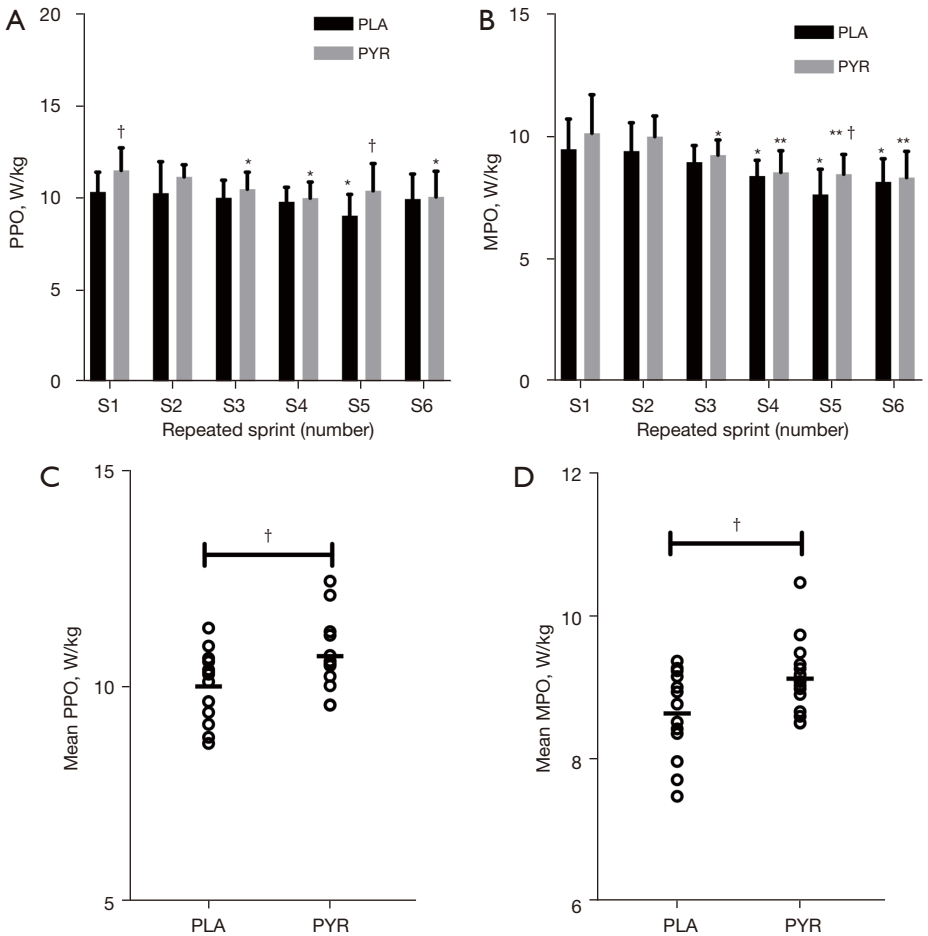

Figure 2 Effects of PYR and PLA supplementation on RSE performance. The PPO (A) and MPO (B) of each sprint. The mean PPO (C) and mean MPO (D) of sprints 1–6. *, P<0.05; **, P<0.01 *vs.* S1 of the same group; †, P<0.05 *vs.* PLA at the same time point. PPO, peak power output; MPO, mean power output; PYR, sodium pyruvate; PLA, placebo; RSE, repeated sprint exercise.

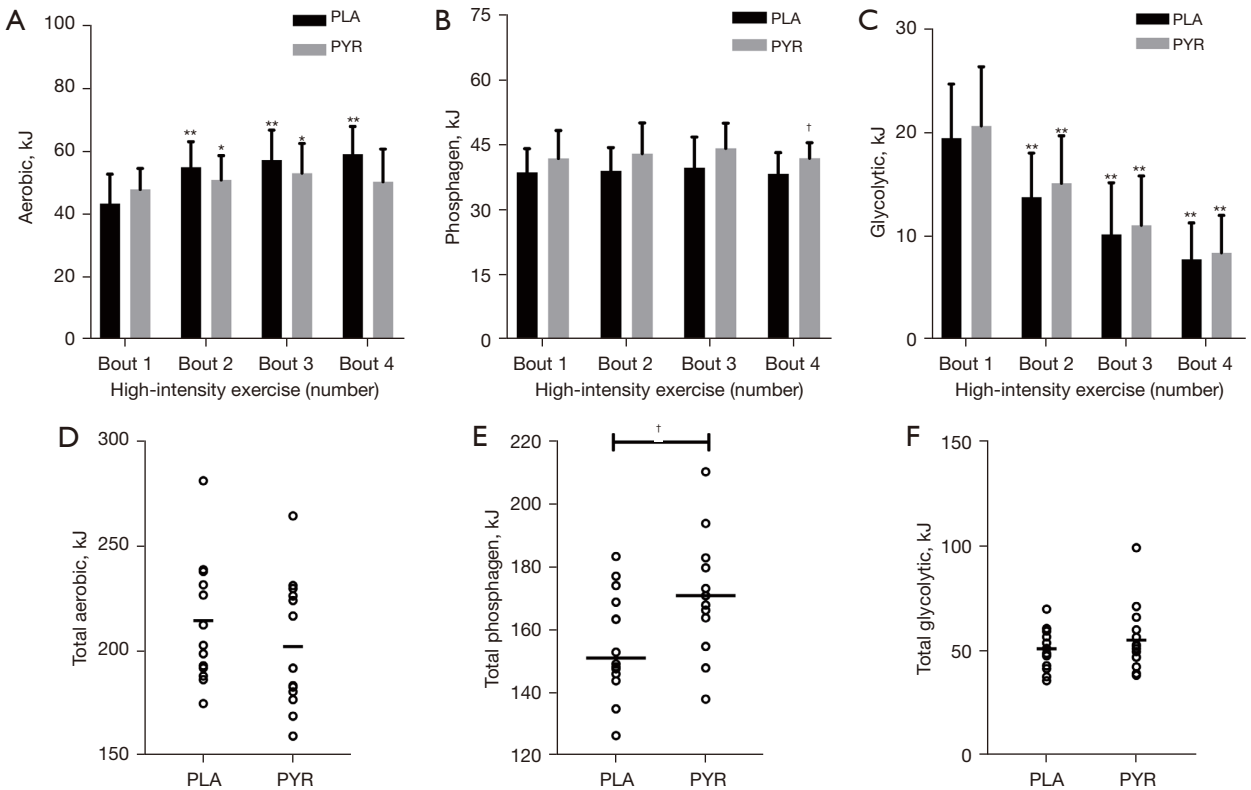

Figure 3 Effects of PYR and PLA supplementation on the contributions of the energy systems. Contributions of the aerobic (A,D) and glycolytic (C,F) energy systems during HIIE. The phosphagen energy system resynthesis (B,E) during HIIE. *, P<0.05; **, P<0.01 *vs.* bout 1 of the same group; †, P<0.05 *vs.* PLA at the same time point. PLA, placebo; HIIE, high-intensity interval exercise; PYR, sodium pyruvate.

Discussion

The main findings of this study suggested that 1 week of PYR ingestion enhanced the power output during RSE. In support of our initial hypothesis, the resynthesis of PCr and acid-base balance recovery during HIIE and RSE were improved in the PYR group.

Many team sports (such as soccer and basketball) consist of HIIE sessions and repeated bouts of sprints with short recovery (1). A large accumulation of H^+ and the depletion of skeletal muscle PCr content are evident in subsequent bouts of exercise, leading to fatigue during RSE (8). Consistent with previous findings, we observed that the decline in PPO and MPO was accompanied by the repetition of sprints in both the PYR and PLA groups (44).

In the present study, PYR ingestion elevated the PPO in the first (+11.41%) and fifth (+14.92%) sprints, and the MPO in the fifth sprint (+10.72%). Additionally, the mean PPO (+7.06%) and mean MPO (+5.56%) of the 6 sets of sprints were significantly improved following PYR administration compared to PLA administration (*Figure 2*). Although, previous studies showed that PYR supplementation did not enhance aerobic exercise capacity (25,26), the current study demonstrated that for intense exercise, PYR supplementation resulted in a stronger ergogenic effect on RSE performance compared to other common buffers that only obtained a 2–3% increase in power output during single sprints or RSE (12,13). Indeed, the stronger ergogenic effect may be attributed to the fact that PYR ingestion promotes phosphagen metabolism and attenuates acidosis during RSE. The beneficial effects of PYR observed in this study confirmed the findings of Sarshin *et al.* The latter study demonstrated that a combined improvement in PCr content and acid-base balance may be more beneficial for RSE ability (14).

The ergogenic effects of PYR intake may be explained by enhanced aerobic metabolism. Although PCr hydrolysis and anaerobic glycolysis are rapid pathway for ATP production during sprint exercise, the aerobic system plays an increasingly important role in maintaining performance

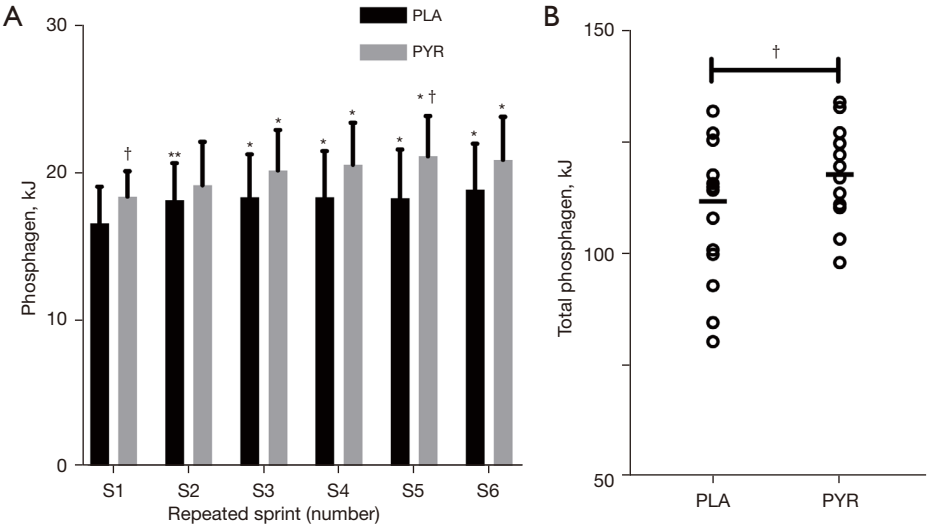

Figure 4 Effects of PYR and PLA supplementation on the phosphagen energy system resynthesis during RSE. (A) The phosphagen energy system resynthesis during each recovery session. (B) Total phosphagen energy system resynthesis of the 6 sets of recovery sessions. *, P<0.05; **, P<0.01 *vs.* S1 of the same group; †, P<0.05 *vs.* PLA at the same time point. PLA, placebo; PYR, sodium pyruvate; RSE, repeated sprint exercise.

Table 2 Comparison of blood pH, HCO_3^-, and BE between the two groups

Time point	pH, mean ± SD		HCO_3^- (mmol/L), mean ± SD		BE (mmol/L), mean ± SD	
	PLA	PYR	PLA	PYR	PLA	PYR
Baseline	7.36±0.03	7.38±0.04	24.52±0.96	24.55±1.15	1.16±1.30	1.06±1.15
Pre-HIIE	7.37±0.03	7.40±0.03†	24.86±1.03	26.09±0.82**††	2.00±1.11	3.39±0.86**††
Post-HIIE	7.14±0.08**	7.20±0.05**†	12.57±1.86**	14.56±1.83**†	−15.61±4.39**	−12.58±3.24**†
Pre-RSE	7.17±0.09**	7.24±0.06**†	13.02±2.05**	15.24±2.10**,†	−14.98±4.37**	−11.68±3.49**†
Post-RSE	7.18±0.07**	7.23±0.07**	12.52±1.61**	14.04±2.32**	−16.56±3.07**	−13.64±3.50**†

**, P<0.01: significantly different *vs.* baseline of the same group; †, P<0.05; ††, P<0.01: significantly different *vs.* PLA at the same time point. SD, standard deviation; BE, base excess; PLA, placebo group; PYR, pyruvate group; HIIE, high-intensity interval exercise; RSE, repeated sprint exercise.

during repeated sprints (38). As shown in previous studies, large amounts of PCr are consumed in multiple sprints, and short recovery periods may not afford sufficient time for the PCr values to restore to resting levels, thus leading to RSE fatigue (8). In fact, the resynthesis of PCr is dependent on aerobic metabolism, and therefore, higher levels of aerobic metabolism accelerate ATP-PCr resynthesis during the recovery periods and maintains subsequent sprint ability (45). According to our results, PYR significantly enhanced the ATP-PCr regeneration in the fourth bout of HIIE (+9.39%, η_p^2 =0.161) (*Figure 3B*) and increased the total ATP-PCr regeneration during HIIE (+9.72%, Cohen's d =0.874) (*Figure 3E*) with large effect sizes. In addition, the ATP-PCr regeneration was improved in the first (+10.99%) and fifth (+15.54%) (*Figure 4A*) recovery periods during RSE. Consistent with the findings of Knott et al, administration of PYR upon reperfusion after cardioplegic arrest could protect mitochondrial enzymes and increase phosphorylation potential and ATP content (46). In addition, although previous studies did not find a positive effect of PYR on improving aerobic metabolism during exercise, Sharma and Zhang showed

that PYR activated PDH activity and promoted more ATP production by mitochondrial aerobic metabolism (17,47). In summary, as PCr resynthesis capacity is a limiting factor for RSE performance, it may also account for the greater beneficial effects of pyruvate supplementation on exercise performance in the present study.

Furthermore, the improvement of RSE ability by PYR supplementation may also be related to the increased acid-base recovery capacity in the blood. It has been suggested that the rapid restoration of acid-base balance during exercise reduces the inhibition of energy metabolism and muscle contraction by H^+ (7). In the current study, following 1 week of PYR ingestion, blood pH (+0.03 units), HCO_3^- (+1.23 mmol/L), and BE (+1.39 mmol/L) were significantly higher before HIIE in the PYR group compared to the PLA group. Additionally, blood pH (+0.07 units), HCO_3^- (+2.22 mmol/L), and BE (+2.92 mmol/L) were elevated before the start of RSE in the PYR group compared to the PLA group. Although the mechanisms of improved buffering capacity with 1 week of PYR ingestion remain unknown, the enhanced PCr resynthesis capacity may provide some insight (3). Compared with sodium bicarbonate ingestion (12), PYR supplementation in the present study had a mild alkalization effect on blood pH and HCO_3^-, which is consistent with the results observed by Olek *et al.* (23). Common buffering agents (e.g., sodium bicarbonate) have been shown to maintain glycolytic metabolism during high-intensity exercise primarily through a stronger regulation of acid-base homeostasis (48). In our study, the blood lactate concentrations and glycolytic metabolism did not differ between PYR administration and PLA administration. The possible reason is that the mild regulation of acid-base recovery by PYR supplementation may not be sufficient to alleviate the inhibitory effect of H^+ accumulation on glycolytic metabolism (1,12). Also, previous studies have similarly found that 1 week of PYR supplementation failed to boost the glycolytic energy supply during high-intensity exercise (25). Nevertheless, the modulation of acid-base balance recovery by PYR may achieve benefits for exercise performance by reducing the inhibition of PCr resynthesis and muscle contraction through the reduction of H^+ concentration (7).

This study had some limitations. First, since the differences in muscle anatomy and physiology between males and females, our findings should not be extrapolated to females. Second, as the athletes in this study had a training commitment, we only calculated the contribution of energy systems. Collecting skeletal muscle for assessing intracellular pH, PCr, ATP levels, and PDH activity could provide further insights on the effects of PYR on acid-base homeostasis and aerobic energy metabolism. Additionally, considering the inconvenience of gas metabolism and venous blood collection in the field test, the bicycle task was used in this study. However, there are differences between the bicycle task and field tests, and therefore, it is necessary to extrapolated the results of this study to team sports with caution.

Conclusions

This study demonstrated that PYR supplementation (0.1 g/kg/d for 1 week) can improve power output during RSE in male college soccer players. This improvement in exercise performance may result from the accelerated restoration of acid-base balance and increased ATP-PCr resynthesis. However, future research is still warranted to confirm our findings and to elucidate the mechanisms that may be responsible for the ergogenic effects of PYR.

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Footnote

Reporting Checklist: The authors have completed the CONSORT reporting checklist. Available at https://apm.amegroups.com/article/view/10.21037/apm-21-3862/rc

Trial Protocol: Available at https://apm.amegroups.com/article/view/10.21037/apm-21-3862/tp

Data Sharing Statement: Available at https://apm.amegroups.com/article/view/10.21037/apm-21-3862/dss

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at https://apm.amegroups.com/article/view/10.21037/apm-21-3862/coif). Dr. FQZ is from Shanghai Sandai Pharmaceutical R&D Co. Ltd. The

other authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All procedures performed in this study involving human participants were in accordance with the Declaration of Helsinki (as revised in 2013). The study protocol was approved by the Internal Review Board of the Beijing Sport University (No. 2020057H). All participants signed written informed consent prior to participating in this study.

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