International Journal of Sports Physiology and Performance, 2007, 2, 423-438

Caffeine, Carbohydrate, and Cooling Use During Prolonged Simulated Tennis

Daniel J. Hornery, Damian Farrow, Iñigo Mujika, and Warren B. Young

Purpose: To determine the effects of prolonged simulated tennis on performance and the ergogenic potential of caffeine, carbohydrates, and cooling. ***Methods:*** Twelve highly trained male tennis players (age 18.3 ± 3.0 y, height 178.8 ± 8.5 cm, body mass 73.95 ± 12.30 kg, mean ± SD) performed 4 simulated matches (2 h 40 min) against a ball machine on an indoor hard court. The counterbalanced experimental trials involved caffeine supplementation (3 mg/kg), carbohydrate supplementation (6% solution), precooling and intermittent cooling, and placebo control. Physiological markers (core temperature, heart rate, blood lactate, and blood glucose), subjective responses (ratings of perceived exertion and thermal sensation), stroke velocity and accuracy, serve kinematics, and tennis-specific perceptual skill quantified the efficacy of interventions. ***Results:*** Significant effects of time ($P < .01$) reflected increased physiological demand, reduced serve velocity and ground-stroke velocity and accuracy, and a slowing of the serve racket-arm acceleration phase. Caffeine increased serve velocity (165 ± 15 km/h) in the final set of the match ($P = .014$) compared with placebo (159 ± 15 km/h, $P = .008$) and carbohydrate (158 ± 13 km/h, $P = .001$) conditions. Carbohydrate and cooling conditions afforded physiological advantage (increased blood glucose, $P < .01$, and reduced preexercise thermal sensation, $P < .01$) but did not affect performance relative to the placebo condition. ***Conclusions:*** Prolonged simulated tennis induced significant decrements in tennis skills. Caffeine supplementation partly attenuated the effects of fatigue and increased serve velocity. In contrast, carbohydrate and cooling strategies had little ergogenic effect on tennis performance.

Key Words: ergogenic aids, fatigue, performance, kinematics, perceptual skill

Fatigue is a common explanation for overt performance reductions during tennis match play. Several controlled experiments have attempted to quantify the effects of fatigue on tennis skills, but performance deterioration has not been consistently reported.[1,2] At volitional exhaustion Davey et al[1] observed deterioration of ground-stroke accuracy, but after a short rest performance was restored. A

Hornery is with the Dept of Physiology, and Farrow, Skill Acquistion, Australian Institute of Sport, Canberra, Australia. Mujika is with the Dept of Research and Development, Athletic Club Bilbao, 48196 Lezama (Bizkaia) Spain. Young is with the School of Human Movement and Sport Sciences, University of Ballarat, Ballarat, Victoria 3353 Australia.

tennis-skills test, conducted before and after a fatigue intervention, revealed only reduced serve accuracy to the right service box. Vergauwen et al[2] observed reduced serve velocity and accuracy and ground-stroke velocity after 2 hours of strenuous training. The level of fatigue induced in both investigations (ie, beyond that of match play[3]) challenges the application of the findings and encourages examination of performance under matchlike conditions.

Previous investigations that attempted to either determine the locus of fatigue or reduce its influence through ergogenic strategies have typically quantified only performance outcomes such as stroke velocity and accuracy and not the kinematics that underlie these. Evidence from other sports, however, encourages exploration of the mechanics that underlie skill proficiency or decline.[4,5] From a coaching and injury-prevention perspective, stroke kinematics in tennis have received much attention.[6,7] Understanding the mechanics of strokes and their proficiency under duress, however, has comparatively received very little exploration. In baseball, Murray et al[5] reported subtle changes in the pitchers' mechanics and in concert observed slower pitch speed (8 km/h) when comparing early and late innings. Similarly, tennis-specific perceptual skill, evidenced in a player's ability to anticipate the stroke intentions of their opponent, consistently discriminates players of differing skill levels.[8] Little is understood, however, pertaining to the functionality of anticipatory skill under duress or how it is affected by known psychophysiological and central stimulants such as caffeine and carbohydrates.[9,10] The proficiency of cognitive function and motor or physical performance can decrease with thermoregulatory stress,[11,12] a condition not uncommon to tennis players.[13] Despite the challenging environmental conditions often confronting tennis players, few investigators have identified the effects on performance. Similarly, no attempts have been made to counteract the development of heat stress.

Because of the highly competitive nature of elite tennis (and other sports), players seek out strategies or devices to enhance performance and provide an advantage over opponents. Nutritional supplements, such as caffeine and carbohydrates, and cooling modalities are examples currently used by tennis players. The application of caffeine and carbohydrate supplementation in tennis is contended because their capacity to prevent fatigue and enhance performance has not been well established.[14-16] Likewise, further investigation of cooling strategies in tennis is required to confirm the thermoregulatory and performance benefits afforded to other modes of exercise.[17] Methodological shortcomings such as the protocols used to induce fatigue and test sensitivity are suggested reasons for the current equivocal nature of findings. The purpose of this investigation was to examine the potential for carbohydrate supplementation to counteract tennis-induced hypoglycemia, caffeine supplementation to override central fatigue, and precooling and intermittent cooling to attenuate thermal strain. In addition to stroke velocity and accuracy quantification, measurement of serve kinematics, perceptual skill, and a matchlike experimental protocol were key methodological features designed to extend the existing literature.

Methodology

Participants

Twelve highly trained male tennis players (mean ± SD age 18.3 ± 3.0 years, height 178.8 ± 8.5 cm, body mass 73.95 ± 12.30 kg, sum of 7 skinfolds 62.3 ± 20.9 mm) participated in the investigation. They trained at least 15 to 20 h/week and had at least 5 years of competitive tournament experience. Participants (and parents) received explicit details of the experimental protocol before voluntarily providing written informed consent. The study was reviewed and approved by the Australian Institute of Sport Ethics Committee and the University of Ballarat Ethics Committee.

Testing Protocol

Participants performed a prolonged simulated tennis match of 4 sets (~2 hours 40 minutes) on 4 occasions. The 4 trials (placebo control and 3 interventions) were performed in a single-blinded and counterbalanced manner. Trials were separated by 48 hours to 7 days. Diet and exercise were standardized for 24 hours before each trial. Participants were not habitual caffeine users and were not allowed to consume caffeine in the 24 hours preceding trials. Matches were conducted indoors on hard courts. Figure 1 illustrates the timeline of the experimental design.

Simulated Match

The protocol commenced with the ball machine (SAM Millennium II, Maximum Sports, Victoria, Australia) projecting 17 consecutive tennis balls in a preprogrammed sequence over 40 seconds. The balls landed approximately 1.5 m to the left and right of the center mark of the baseline and at the approximate midpoint between the baseline and service line. The participants' role was to return each ball to designated areas at the opposite end of the court. Participants were given a different hitting sequence before each game (eg, cross-court only, 1 shot to the left, 2 shots to the right). On completing the rally, participants rested at the baseline for 20 seconds, after which the next 40-second rally immediately commenced. This process continued until 10 rallies had been completed (10 minutes). Thereafter, players served 6 first serves then sat and recovered courtside for 90 to 120 seconds. During this time participants performed a computer-based return-of-serve test to examine perceptual skill, and physiological variables were recorded (core body temperature, heart rate, rating of perceived exertion, and thermal sensation). Blood lactate and blood glucose was measured during set breaks only (every third break in play). Once all variables had been recorded, participants were informed of the next hitting sequence, walked to the baseline, and commenced the subsequent 10-minute ground-stroke assessment. Therefore, 1 "game" (~13-minute block) comprised ground-stroke-performance assessment (~10-minute 40-second rally, 20 seconds rest), first-serve analysis (6 serves, ~1 minute), and a perceptual-skill test (12 trials, ~90 to 120 seconds, also recovery). Three completed games constituted 1 "set," and 4 sets constituted the simulated match. The successive sets replicated the format of the first set, with the only variation being the instructions to players regarding the direction in which balls were to be returned. Participants were instructed to attempt to maintain an intensity equivalent to that during match play.

Performance Assessment

There were 3 facets to performance assessment: serve and ground-stroke velocity and accuracy, serve kinematics, and perceptual skill.

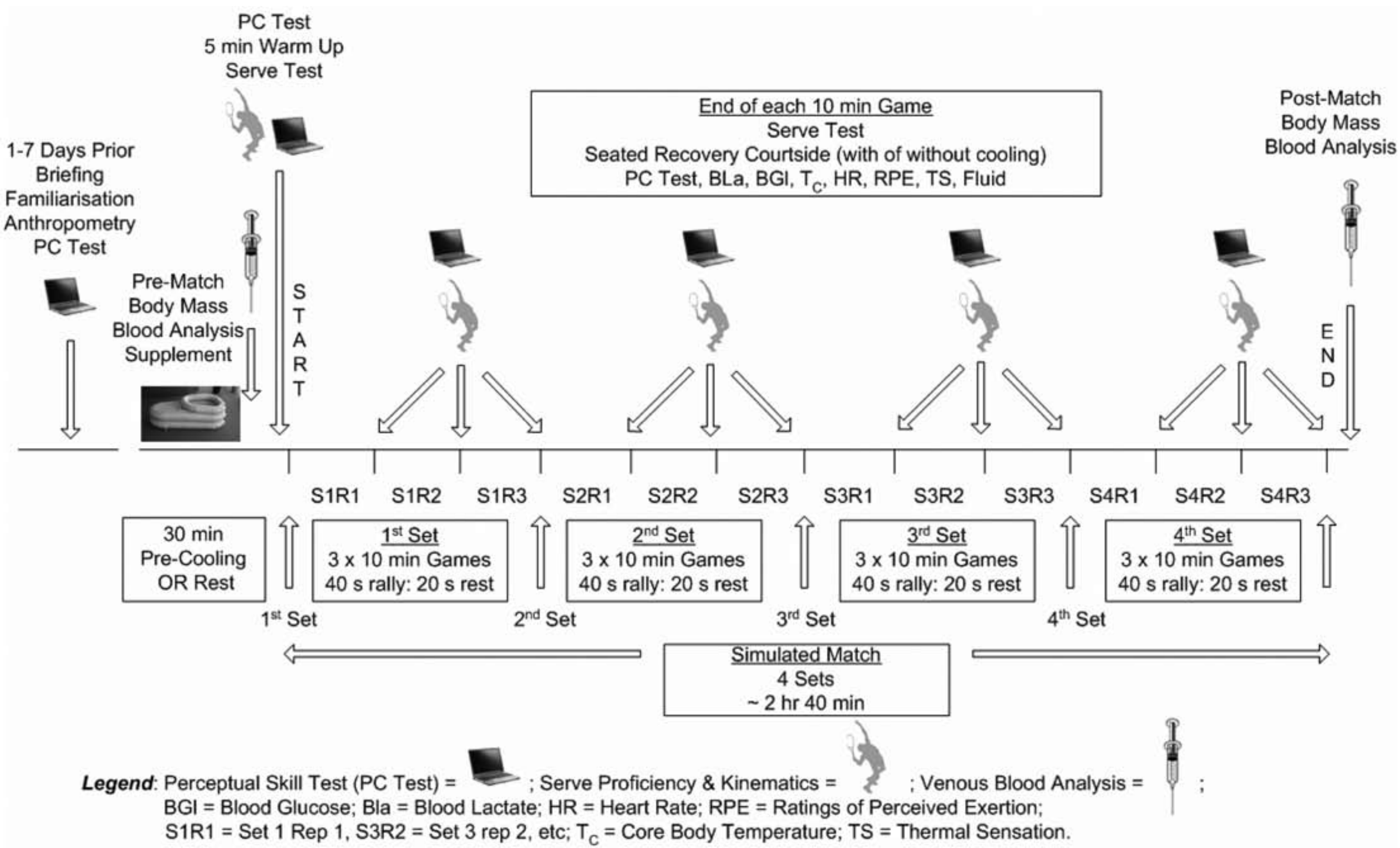

Figure 1 — A schematic illustration of the experimental design.

Serve and Ground-Stroke Velocity and Accuracy. Two radar guns (Stalker Professional Sports Radar, Radar Sales, Plymouth, MN) were used to measure first-serve and forehand ground-stroke velocity. The radar recording serve velocity was positioned on the center of the baseline at the end of the court opposite the server, aligned with the approximate height of ball contact and pointing down the center of the court. The radar recording forehand groundstroke velocity was positioned on the forehand side of the court, behind the participant, pointed at net height down the singles' sideline. Accuracy scores were determined, using a 3, 2, 1, 0 scoring system, by counting the number of times the ball landed within the designated target areas (see Figure 2). A total score, expressed as a percentage of the maximum, was recorded for each game. The intertrial reliabilities for first-serve velocity and accuracy and ground-stroke velocity and accuracy were 3.1%, 46.6%, 1.9%, and 8.3%, respectively.

Serve Kinematics. First-serve actions were captured using a high-speed (100 frames per second) digital video camera (Phantom, USA), downloaded, and converted to video files. The files were subsequently viewed using a sport-analysis tool (Swinger Plus, Webbsoft Solutions) and divided into 5 distinct temporal phases (phase 1, preparation to ball release; phase 2, ball release to maximum height of the ball toss; phase 3, maximum height of the ball toss to racket–ball impact; phase 4, racket–ball impact to follow-through; and phase 5, entire serve sequence, preparation to follow-through). The duration of each phase was determined by counting the number of frames. This method of analysis was simplified from previous analyses of angular momentum.[18]

Perceptual Skill. Participants viewed 12 clips, displayed on a laptop computer screen, of a professional player serving. The footage was captured from the perspective of a player attempting to return the serve. The participant was instructed to assume the role of a receiving player and attempt to anticipate the direction of a serve from the footage shown. Two temporal occlusion conditions were presented to manipulate the exposure time available to the participant to predict the direction of the serve. One condition occluded the vision at the point of racket–ball contact, and the other presented the complete service action, including ball flight. Participants used the computer mouse to click on the side of the service box they believed was the intended service direction. A response-accuracy percentage was generated from the 12 trials presented (6 randomly ordered trials of each occlusion condition). The test took approximately 90 seconds, which is equivalent to the allocated time between games in a tournament match.

Simulated Match Experimental Strategies

Participants performed the simulated match on 4 occasions, each time using a different experimental strategy. Participants were blinded to 3 of the 4 trials performed (placebo control, caffeine, and carbohydrates), but the selected cooling intervention did not permit complete masking.

Precooling and Intermittent Cooling. Before commencing the simulated match, participants sat submersed in water for 30 minutes. They were immersed to the level of the sternum in an inflatable plastic plunge pool (Portacovery, Canberra

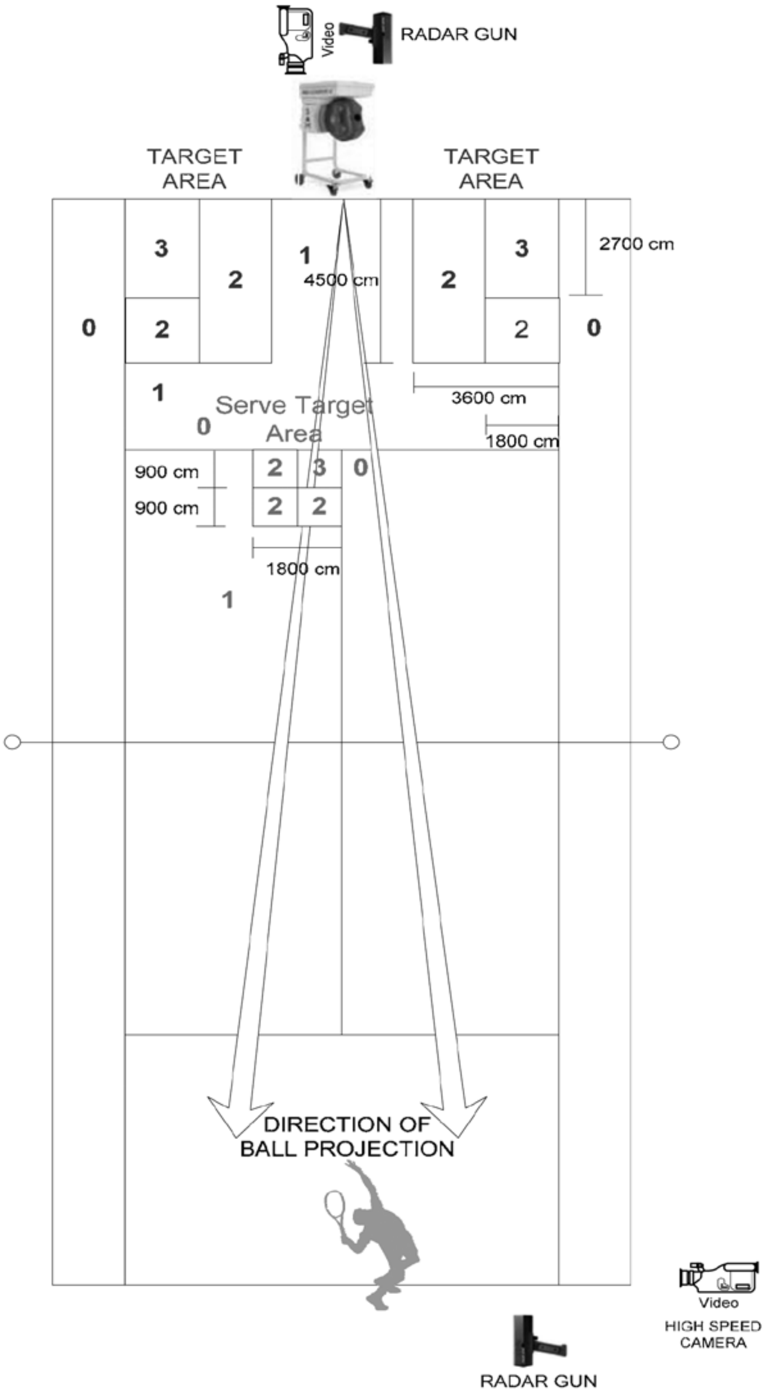

Figure 2 — A schematic representation of the tennis performance test and target-area dimensions.

ACT, Australia). The water temperature, continuously monitored with a Testo 781 thermometer (Testo Term, Germany), was progressively reduced over the 30-minute period from 29 to 24 °C by adding ice to the bath. During breaks in play, participants wore a waist-length, sleeveless cooling jacket and hood (RMIT, Melbourne, Australia).

Caffeine Supplementation. Before commencing the simulated match (30 minutes) participants ingested No-Doz Awakeners (Key Pharmaceuticals Pty Ltd, Rhodes, Australia). The ingested dose (3 mg/kg of body mass) was administered crushed inside a gelatin capsule.

Carbohydrate Supplementation. Before commencing the simulated match and during every break in play, participants consumed approximately 14 $mL \cdot kg^{-1} \cdot h^{-1}$ of a commercially available carbohydrate-loaded beverage (6%), lemon-lime-flavored Gatorade (PepsiCo Australia Holdings Pty Ltd, Sydney, Australia).

Placebo Control. To mask caffeine supplementation, participants ingested a powder placebo (Polycose, Ross Nutrition, Abbott Laboratories, OH, USA). The volume of the placebo, identical to the amount of caffeine, was administered in a gelatin capsule. To mask carbohydrate ingestion participants consumed a carbohydrate-free, flavored placebo (Gatorade lemon-lime placebo, PepsiCo Australia Holdings Pty Ltd, Sydney, Australia).

Materials and Physiological Measures

Venous blood samples (10 mL) were extracted from a superficial vein from the cubital fossa of the nondominant forearm. Samples were later centrifuged, and the supernatant was analyzed for prolactin concentration using Immulite (Diagnostic Products Corp, Los Angeles, CA, USA). Peripheral prolactin concentration has formerly been acknowledged as a surrogate index on central serotonergic activity and an indirect measure of central fatigue.[19] Blood lactate, blood glucose, and creatine kinase were analyzed from capillary samples using a Lactate Pro (Arkray Factory Inc, Shiga, Japan), HemoCue (Angelholm, Sweden), and Reflotron (Roche Diagnostics, Indianapolis IN, USA), respectively. Core body temperature was measured via short-range telemetry, from a single-use capsule to a data logger BCTM3 (Fitsense Technology, USA). The capsule was ingested at least 3 hours before each trial commenced. A Polar S610 (Polar Electro Oy, Finland) was used to monitor heart rate.

Statistical Analyses

The experiment used a repeated-measures design (with each participant undertaking 1 trial under each condition), with longitudinal data collected throughout each trial. The data were analyzed using linear mixed modeling, with provision for fixed effects of trials and time, random effects for participants, and either constant or autoregressive correlation between the random errors within each trial. When overall significant differences were detected, subsequent Bonferroni-adjusted post hoc analyses were conducted to determine the pattern of significance. Results are reported as mean ± SD. The figures herein display mean ± standard error. Effect sizes were calculated and interpreted as has been previously described.[20] Significance was identified where $P < .05$.

Results

Table 1 illustrates environmental conditions, physiological responses, and comparisons between conditions.

Protocol Effects

The simulated match induced significant ($P < .0001$) increases in core body temperature, heart rate, ratings of perceived exertion, thermal sensation, and creatine kinase and decreases in blood glucose. The velocity of first serves ($P = .011$) and ground strokes ($P < .0001$) and ground-stroke accuracy ($P = .004$) significantly deteriorated over time (see Figures 3 and 4). The racket-arm acceleration phase of the serve slowed significantly (phase 3, $P = .002$) over the duration of the protocol.

Table 1 Environmental Conditions and Physiological Responses During the Simulated Match[a]

	Placebo	Carbohydrate	Caffeine	Cooling
Temperature (°C)	21.0 ± 4.8	21.6 ± 3.9	21.2 ± 4.6	21.0 ± 4.6
Relative humidity (%)	50.9 ± 12.0	50.5 ± 8.2	50.6 ± 11.0	49.7 ± 9.9
T_C resting (°C)	36.9 ± 0.3	36.8 ± 0.2	36.7 ± 0.3	37.1 ± 0.2
T_C exercising (°C)	37.6 ± 0.5	37.7 ± 0.4	37.7 ± 0.4	37.5 ± 0.4
HR resting (beats/min)	67 ± 12	66 ± 12	65 ± 11	64 ± 11
HR exercising (beats/min)	154 ± 14	154 ± 17	156 ± 14	156 ± 16
TS resting/cooling	4.0 ± 0.1	4.1 ± 0.3	4.0 ± 0.2	2.3 ± 0.6
TS exercising	5.5 ± 0.7	5.6 ± 0.9	5.4 ± 0.7	5.1 ± 0.6
RPE	14 ± 1	14 ± 2	14 ± 1	14 ± 1
BM pre (kg)	73.83 ± 12.45	73.74 ± 12.60	74.14 ± 12.45	74.26 ± 12.40
BM post (kg)	73.51 ± 12.36	73.60 ± 12.23	73.64 ± 12.07	74.10 ± 12.14
BM difference (kg)	0.33 ± 0.57	0.14 ± 0.58	0.50 ± 0.54	0.16 ± 0.58
BM change (%)	0.4 ± 0.8	0.1 ± 0.8	0.6 ± 0.7	0.2 ± 0.7
TFL (mL)	2818 ± 1089	2673 ± 920	3014 ± 1005	2687 ± 895
Urine specific gravity	1.022 ± 0.004	1.024 ± 0.004	1.022 ± 0.005	1.022 ± 0.006
BGL (mmol/L)	5.5 ± 1.5	5.9 ± 1.0	5.3 ± 0.7	5.1 ± 0.7
BLa (mmol/L)	1.3 ± 0.5	1.4 ± 0.4	1.3 ± 0.4	1.2 ± 0.4
CK prematch (μL)	220.6 ± 135.5	213.1 ± 147.8	214.1 ± 121.5	188.0 ± 100.0
CK postmatch (μL)	314.5 ± 120.3	301.4 ± 152.2	347.2 ± 174.4	310.8 ± 131.3
CK difference (μL)	94.0 ± 121.4	88.3 ± 78.8	133.1 ± 110.6	122.8 ± 64.1
PRL prematch (μL)	254.8 ± 90.9	211.0 ± 79.7	243.6 ± 56.5	208.7 ± 99.3
PRL postmatch (μL)	258.2 ± 108.8	266.8 ± 118.3	313.1 ± 189.4	373.5 ± 399.6
PRL difference (μL)	3.4 ± 98.0	55.8 ± 130.0	69.9 ± 180.6	164.7 ± 347.5

Abbreviations: BM, body mass; TFL, total fluid loss; CK, creatine kinase; PRL, prolactin.

[a]Values presented are mean ± SD. Values for ambient temperature, relative humidity, core temperature (T_C), heart hate (HR), thermal sensation (TS), ratings of perceived exertion (RPE), blood lactate (BLa) and blood glucose (BGL) represent averages over the duration in which they were recorded.

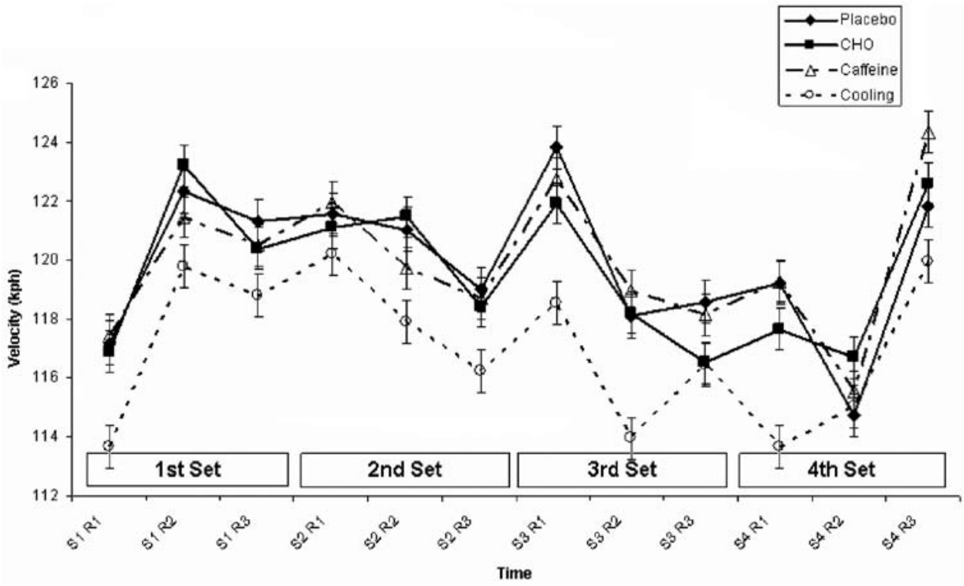

Figure 3 — Ground-stroke velocity over the duration of the simulated match. Values presented are mean ± standard error.

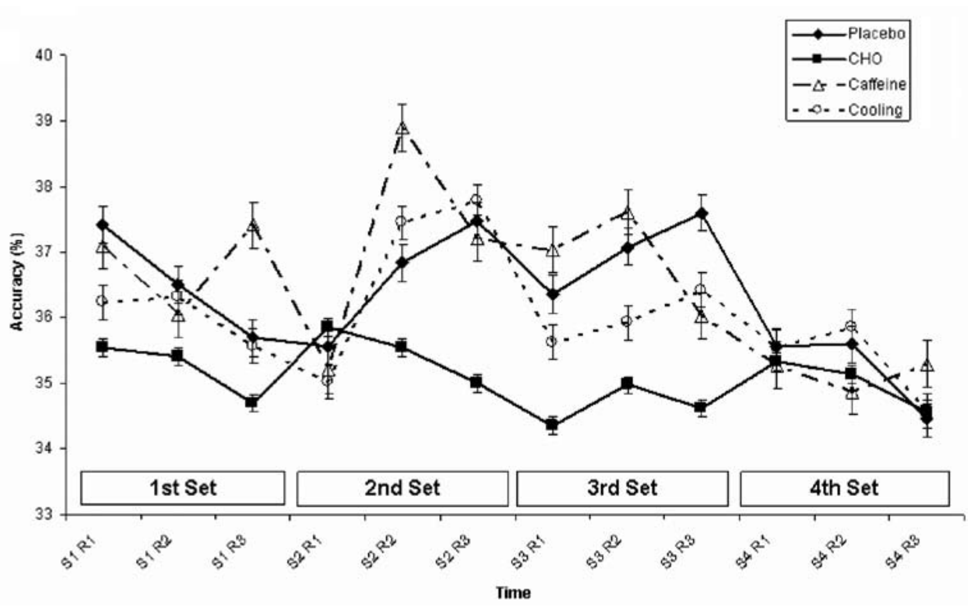

Figure 4 — Ground-stroke accuracy over the duration of the simulated match. Values presented are mean ± standard error.

Condition Effects

Carbohydrate Supplementation. In the CHO supplementation trial, over the duration of the protocol blood glucose concentration was significantly ($P < .0001$) higher than in all other conditions (CHO, 5.9 ± 1.0 mmol/L; PLA, 5.5 ± 1.5 mmol/L; CAF, 5.3 ± 0.7 mmol/L; cooling, 5.1 ± 0.7 mmol/L). Supplementation mitigated the trends toward hypoglycemia observed in all conditions (significant effect of time, $P < .0001$) but did not prevent a decline in, or enhance, any performance measure.

Caffeine Supplementation. No significant physiological responses were induced, but there was a trend for reduced rating of perceived exertion toward the later stages of the protocol. Effect sizes of moderate magnitude reflect the divergence between the CAF and PLA conditions (see Figure 5). A significant condition effect was revealed for serve velocity ($P = .016$). Participants served significantly faster in the caffeine trial (164 ± 14 km/h) than in the CHO condition (160 ± 11 km/h, $P = .008$, ES = 0.33) over the duration of the simulated match but not compared with PLA (161 ± 15 km/h, $P = .215$, ES = 0.19) and cooling (161 ± 15 km/h, $P = .259$, ES = 0.19) conditions. Further examination of a significant ($P = .014$) condition-by-time interaction revealed that players served significantly faster in the fourth set under the CAF condition (165 ± 15 km/h) than in PLA (159 ± 15 km/h, $P = .008$) and CHO (158 ± 13 km/h, $P = .001$) conditions but not the cooling condition (162 ± 14 km/h, $P = .213$). The temporal analysis of the serve revealed trends for caffeine to facilitate racket-arm acceleration phases (phase 2, $P = .052$). A significant interaction of condition and time ($P < .0001$) was also revealed for phase 3, but post hoc analysis did not identify the point of divergence. Figures 6 and 7 illustrate the time profile of serve velocity and phase 2 of the serve temporal analysis (from ball release to maximum height of the ball toss), respectively.

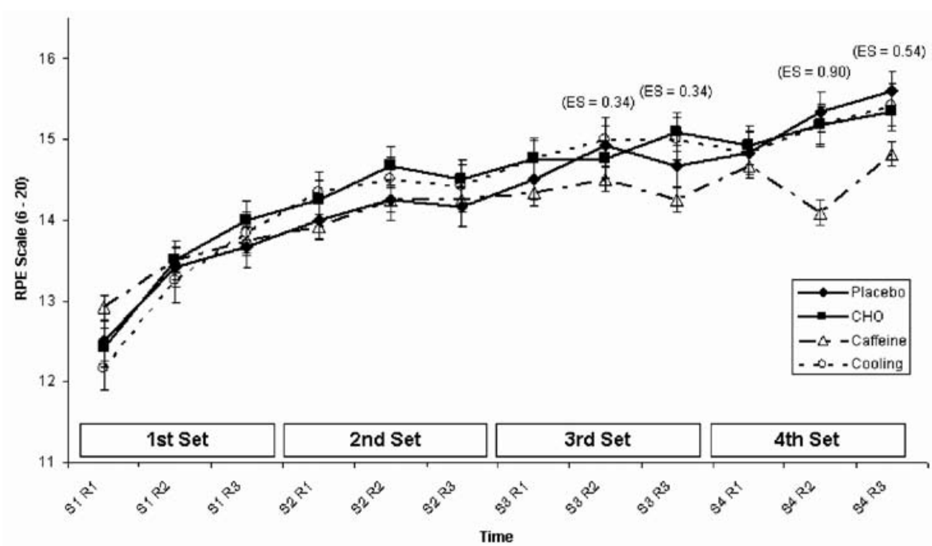

Figure 5 — Ratings of perceived exertion (RPE) over the duration of the simulated match. Values presented are mean ± standard error. Effect sizes are comparisons of means for caffeine and placebo trials only.

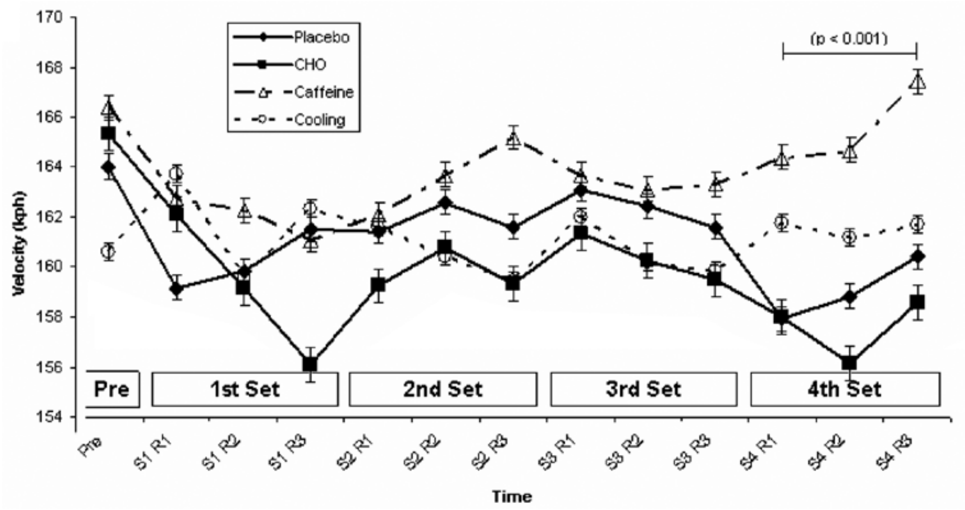

Figure 6 — First-serve velocity over the duration of the simulated match. Values presented are mean ± standard error.

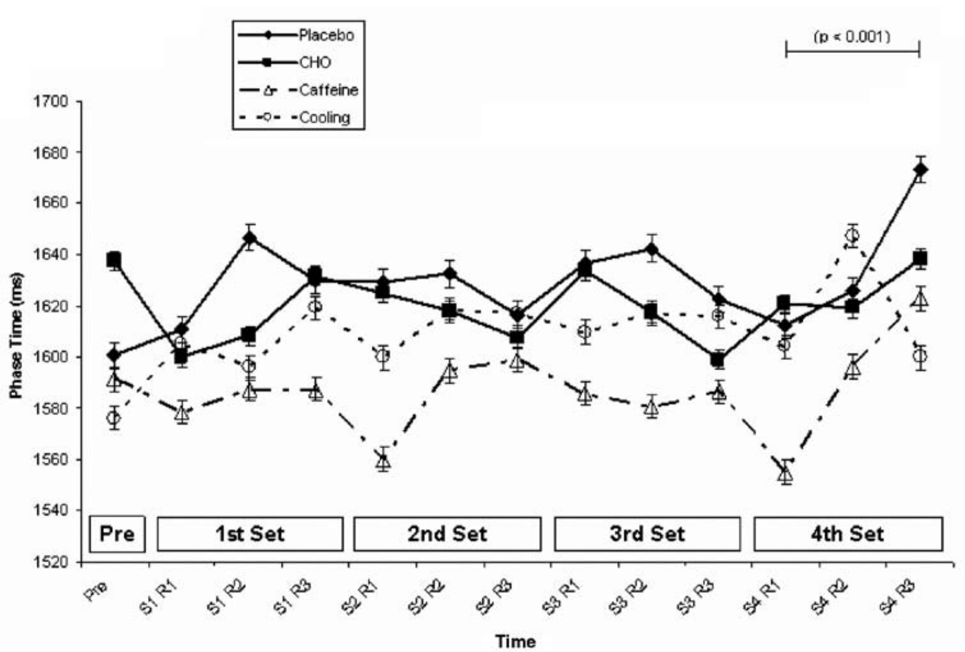

Figure 7 — Temporal analysis of the service action (phase 2, ball release to maximum height of the ball toss) over the duration of the simulated match. Values presented are mean ± standard error.

Precooling and Intermittent Cooling. Precooling initially increased core body temperature (P = .005) and reduced thermal sensation (P < .0001) at rest. Combined precooling and intermittent cooling did not significantly reduce core body temperature (P = .230) or thermal sensation (P = .172) over the duration of the simulated match. Enhanced prematch thermoregulation did not benefit performance. There was a trend (nonsignificant, P = .263) for slower ground-stroke velocity in the cooling trial (cooling, 117 ± 7 km/h; PLA, 120 ± 8 km/h, ES = 0.38; CHO,120 ± 7 km/h, ES = 0.37; CAF, 120 ± 8 km/h, ES = 0.47).

Perceptual Skill

There were no significant effects of time or intervention (P > .05) on tennis-specific perceptual skill for either occlusion condition.

Discussion

The purpose of this investigation was to identify the ergogenic potential of caffeine, carbohydrates, and cooling strategies to enhance tennis performance. First, it was imperative that performance impairment be observed during prolonged simulated match conditions. Previous investigators attempted to reproduce in situ performance deterioration in an experimental setting.[1,2] Physiological responses to the current field-based protocol indicated that the intensity was equivalent to tournament tennis, and the prevailing implications were gradual reductions in key performance outcomes (serve velocity and ground-stroke velocity and accuracy). Likewise, serve kinematics displayed temporal lengthening, potentially causing a reduction in serve efficiency. This observation provides unique insight into the mechanics of stroke-quality deterioration during match play. As with other investigations that have shown deterioration of throwing-related mechanics with fatigue and performance decrement, it is unclear whether inherent kinetic and kinematic changes manifest as a fatigue response or an attempt to decrease the potential for injury.[4,5]

Serving and throwing actions are highly ballistic and explosive, exposing the shoulder joint and muscles to extreme loads and forces. It is suggested that any disruption to the functional integrity of stroke biomechanics (timing and coordination of body segments) would reduce performance and increase injury vulnerability.[5] This investigation revealed that serve velocity gradually slowed with extended play; in concert a temporal lengthening of the acceleration phase of the service motion was observed. It is suggested that longer phase time is linked to slower angular momentum and thus reduced racket-head velocity at impact. Further investigation of this relationship using more detailed biomechanical analyses is recommended to confirm these findings.

Mechanisms of Performance Deterioration

Dehydration, hypoglycemia, and hyperthermia are the typically proposed physiological mechanisms of performance deterioration, but in this instance performance impairment appeared to manifest almost as a product of time rather than a substantial disruption to homeostasis. The performance profile suggests that a central governor might control power output. Specifically, players might subconsciously reduce stroke power as fatigue evolves in an effort to prevent injury.[21] This suggests that central fatigue might play a pivotal role, but markers of central fatigue (prolactin) did not support this conclusion. Struder et al,[22] however, observed an increased ratio of tryptophan to branched-chain amino acids during prolonged tennis (no change in prolactin), suggesting that other markers of central fatigue might be more accurate indicators of the origins of performance deterioration. In the absence of typical physiological perturbations, the proliferation of creatine kinase, an indicator of muscle damage,[23] might implicate muscle trauma associated with the eccentric loading placed on the shoulder muscles during high-intensity hitting actions as another potential mechanism.

Efficacy of Experimental Strategies

Carbohydrate Supplementation. The commercially available carbohydrate drink enhanced blood glucose concentration, which mitigated trends toward the development of hypoglycemia. In contrast to some previous investigations carbohydrate supplementation failed to enhance serve or ground-stroke proficiency.[14,24] Likewise, there were no significant benefits to serve kinematics or perceptual skill. It is possible that the benefit of adequate blood glucose and muscle glycogen concentrations to prolonged skill-based performance is not consistent with that commonly reported in other endurance sports.[25] The findings of this investigation are common to other skill-based sports[26] and encourage further research before carbohydrates can be recommended for their performance-enhancement capacity, in addition to maintenance of sufficient substrate availability.

Caffeine Supplementation. Supplementation with a modest amount of caffeine increased serve velocity, specifically during the final stages of the simulated match. A potential explanation for the increased serve velocity can be found in trends that indicated caffeine also had a facilitative role on serve kinematics, specifically the increased speed of the throwing-action phase of the serve (phase 2). In addition, a trend for reduced perceived exertion was evident toward the latter stages of the experimental protocol, when fatigue and associated performance deficits were most likely to occur. The suggested mechanisms underlying these findings are caffeine's central and molecular stimulatory properties.[9]

Previous investigations examining the use of caffeine by tennis players returned equivocal results, which are likely attributable to the lack of sensitivity of selected performance measures (games won and lost during matches and stroke-accuracy assessments).[14,15,27] Neither Struder et al[15] nor Ferrauti et al[27] measured velocity of serves or ground strokes, and hence a speed–accuracy trade-off could not be discounted. Because no improvements in stroke accuracy were observed in this or previous investigations, it could be suggested that caffeine has a greater capacity to sustain movement power than movement accuracy. Further work is required to confirm what appears to be a fatigue-resistant capability afforded by caffeine.

Precooling and Intermittent Cooling. In contrast to the expected findings, no performance benefits were associated with the cooling strategy. Specifically, cooling appeared to elicit a reduction in the initial measures or serves and ground strokes (see Figures 3, 4, 6, and 7). The reduction in power measures is consistent with other investigations of high-intensity exercise after cooling,[28] but ergogenic effects have been observed during later bouts of intermittent exercise.[29] Collectively these findings might be explained by insufficient warm-up before performance assessment. Inhibition of muscle contractile properties, with reduced muscle and body temperature, is the proposed mechanism of the performance reduction and is the basis of the preexercise warm-up.[30] The lack of performance-enhancing effects might also be attributed to the temperate environmental conditions under which the experiment was conducted. Significant thermoregulatory strain was not induced, potentially nullifying previously reported benefits of the precooling strategy (Quod, 2006, unpublished observations). Physical and cognitive performance compromise is a common response to large perturbations in core temperature.[12,13] Significant thermoregulatory strain has been reported in tennis[13]; it is therefore clear that efforts should be made to counteract its manifestation.

Conclusion

Highly trained tennis players performed a prolonged, simulated match under various experimental strategies thought to mitigate the effects of fatigue. It is clear that fatigue, regardless of its manifestation, is an ensuing physiological response to prolonged tennis match play and detrimentally affects performance. There is encouraging evidence that caffeine and carbohydrate supplementation offset potential manifestations of fatigue. Caffeine supplementation also appeared to confer ergogenic properties, an area that demands further investigation. Further research should be conducted in challenging environmental conditions, to elicit a natural increase in participant intensity, before we can confidently understand the effects of various potentially ergogenic modalities. Future investigators should endeavor to assess the processes (perceptual skill and stroke kinematics) that underscore observable performance qualities, such as stroke velocity and accuracy and anticipation. These skills are fundamental to tennis success and warrant inclusion in skill-assessment protocols.

Practical Applications

- The developed protocol is an effective means to measure the effect of fatigue and experimental strategies on tennis skills, but it is recognized that simulated match play does not capture the true essence of competition.
- When examining the effect of fatigue on performance it is important to consider all facets of performance and the various means by which fatigue can manifest.
- Of the 3 strategies tested, only caffeine appears to offer performance-enhancing potential, whereas carbohydrates and cooling offered only physiological advantages.
- Players should test these interventions in training, under the guidance of a sport scientist, before using them in competition.

Acknowledgments

The authors would like to thank the Australian Institute of Sport, Tennis Australia, and the University of Ballarat, who collaboratively funded the project. The authors would also like to thank Pat Rottura from Maximum Sport, who provided the ball machine for the duration of the data-collection phase.

References

1. Davey PR, Thorpe RD, Williams C. Fatigue decreases skilled tennis performance. *J Sports Sci*. 2002;20:311-318.
2. Vergauwen L, Spaepen AJ, Lefevre J, Hespel P. Evaluation of stroke performance in tennis. *Med Sci Sports Exerc.* 1998;30(8):1281-1288.
3. Fernandez JF, Fernandez-Garcia B, Mendez-Villanueva A, Terrados N. Exercise intensity in tennis: simulated match play versus training drills. *Med Sci Tennis.* 2005;10:6-7.
4. Royal K, Farrow D, Mujika I, Halson S, Pyne D, Abernethy B. The effects of fatigue on decision making and shooting skill performance in water polo players. *J Sports Sci.* 2006;24(8):807-815.
5. Murray TA, Cook TD, Werner SL, Schlegel TF, Hawkins RJ. The effects of extended play on professional baseball pitchers. *Am J Sports Med.* 2001;29(2):137-142.
6. Pluim BM, Safran M. *From Breakpoint to Advantage*. Solana Beach, CA: Racquet Tech Publishing; 2004.
7. Elliott B. Biomechanics in tennis. *Br J Sports Med.* 2006;40:392-396.
8. Williams AM, Ward P, Knowles JM, Smeeton NJ. Anticipation skill in a real-world task: measurement, training, and transfer in tennis. *J Exp Psychol Appl.* 2002;8(4):259-270.
9. van Duinen H, Lorist MM, Zijdewind I. The effect of caffeine on cognitive task performance and motor fatigue. *Psychopharmacology.* 2005;180:539-547.
10. Davis JM, Bailey SP, Woods JA, Galiano FJ, Hamilton MT, Bartoli WP. Effects of carbohydrate feedings on plasma free tryptophan and branched-chain amino acids during prolonged cycling. *Eur J Appl Physiol.* 1992;65:513-519.
11. Kraning KK II, Gonzalez RR. Physiological consequences of intermittent exercise during compensable and uncompensable heat stress. *J Appl Physiol.* 1991;71(6):2138-2145.
12. Gopinathan PM, Pichan G, Sharma VM. Role of dehydration in heat stress-induced variations in mental performance. *Arch Environ Health.* 1988;43(1):15-17.
13. Therminarias A, Dansou P, Chirpaz M-F, Eterradossi J, Favre-Juvin A. Cramps, heat stroke and abnormal biological responses during a strenuous tennis match. In: Reilly T, Hughes M, Lees A, eds. *Science and Racket Sports*. London, England: E & FN Spon; 1994:28-31.
14. Vergauwen L, Brouns F, Hespel P. Carbohydrate supplementation improves stroke performance in tennis. *Med Sci Sports Exerc.* 1998;30(8):1289-1295.
15. Struder HK, Ferrauti A, Gotzmann A, Weber K, Hollmann W. Effect of carbohydrates and caffeine on plasma amino acids, neuroendocrine responses and performance in tennis. *Nutr Neurosci.* 1999;1:419-426.
16. Magal M, Webster MJ, Sistrunk LE, Whitehead MT, Evans RK, Boyd JC. Comparison of glycerol and water hydration regimens on tennis-related performance. *Med Sci Sports Exerc.* 2003;35(1):150-156.

17. Cotter JD, Sleivert GG, Roberts WS, Febbraio MA. Effect of pre-cooling, with and without thigh cooling, on strain and endurance performance in the heat. *Comp Biochem Physiol.* 2001;128:667-677.
18. Bahamonde RE. Changes in angular momentum during the tennis serve. *J Sports Sci.* 2000;18:579-592.
19. Yatham LN, Steiner M. Neuroendocrine probes of serotonergic function: a critical review. *Life Sci*. 1993;53:447-463.
20. Hopkins WG. A new view of statistics. http://www.sportsci.org. 2002. Accessed September 1, 2006.
21. Noakes TD, St Clair Gibson A, Lambert EV. From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *Br J Sports Med.* 2005;39:120-124.
22. Struder HK, Hollmann W, Duperly J, Weber K. Amino acid metabolism in tennis and its possible influence on the neuroendocrine system. *Br J Sports Med.* 1995;29(1):28-30.
23. Evans WJ, Cannon JG. The metabolic effects of exercise-induced muscle damage. *Exerc Sport Sci Rev.* 1991;19:99-125.
24. Burke ER, Ekblom B. Influence of fluid ingestion and dehydration on precision and endurance performance in tennis. *J Athl Train.* 1982;17:275-277.
25. Coggan AR, Coyle EF. Reversal of fatigue during prolonged exercise by carbohydrate infusion and ingestion. *J Appl Physiol.* 1987;63(6):2388-2395.
26. Abt G, Zhou S, Weatherby R. The effect of a high-carbohydrate diet on the skill performance of midfield soccer players after intermittent treadmill exercise. *J Sci Med Sport.* 1998;1(4):203-212.
27. Ferrauti A, Weber K, Struder HK. Metabolic and ergogenic effects of carbohydrate and caffeine beverages in tennis. *J Sports Med Phys Fitness.* 1997;37:258-266.
28. Mitchell JB, McFarlin BK, Dugas JP. The effect of pre-exercise cooling on high intensity running performance in the heat. *Int J Sports Med.* 2003;24:118-124.
29. Hornery DJ, Papalia S, Mujika I, Hahn AG. Physiological and performance benefits of halftime cooling. *J Sci Med Sport.* 2005;8(1):15-25.
30. Bergh U, Ekblom B. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscle. *Acta Physiol Scand.* 1979;107:33-37.