THE EFFECT OF CAFFEINE INGESTION ON TENNIS SKILL

PERFORMANCE AND HYDRATION STATUS

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THE EFFECTS OF CAFFEINE INGESTION ON TENNIS SKILL PERFORMANCE AND HYDRATION STATUS

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THESIS ABSTRACT

THE EFFECTS OF CAFFEINE INGESTION ON TENNIS SKILL PERFORMANCE AND HYDRATION STATUS

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The purpose of this investigation was to determine the effect of pre-match consumption of a caffeinated carbonated soft drink on tennis performance and hydration status before and during simulated tennis match play.

Ten skilled male tennis players ranked between 4.5 and 6.0 on the USTA scale volunteered to participate in this study. On the first visit, participants read and signed an IRB-approved informed consent form and were given dietary recall forms. On the second visit, a treadmill VO_{2max} and a Loughborough Shuttle Fitness Test (SFT) were performed. On the third and fourth visits, participants completed the performance trials, which consisted of 90 minutes of simulated tennis match play against a ball machine, after ingestion of a gel capsule with either 3 $mg \cdot Kg^{-1}$ of body weight (BW) of caffeine or placebo. A 32 oz carbonated soft drink was consumed with both caffeine and placebo. Tennis skill performance was measured at pre-ingestion (PRE), 30 minutes (T30), 60 minutes (T60), and post-trial (PO) and consisted of 15 consecutive ground strokes in all four directions (forehand and backhand; cross-court and up-the-line). Also, SFT was

performed at PRE and PO. Heart Rate (HR) was monitored throughout the protocol and recorded every 15 minutes during simulated tennis match play. Blood samples were collected at PRE, pre-trial (PT), and PO and were analyzed for hematocrit (Hct), hemoglobin (Hb) (consequently used to calculated plasma volume changes), serum glucose, and serum caffeine. Body weight (BW), urine volume, urine specific gravity (USG), thermal sensation, Rate of Perceived Exertion (RPE), and sweat rates were also collected and measured at PRE, PT, and PO.

The results (repeated measures ANOVA, $p \leq 0.05$) failed to show statistical significance for urine volume, USG, thermal sensation, RPE, HR, Hct, and sweat rates. Caffeine ingestion resulted in significant improvements in SFT and tennis skill performance at PO. Also, at PO caffeine ingestion resulted in a significant increase in Hb concentration, which also corresponded to a significant reduction in plasma volume. During the placebo trial, there was a significant increase in serum glucose at PO.

In conclusion, ingestion of 3 mg/Kg BW of caffeine improves tennis skill performance in the later stages of match play. However, caffeine ingestion does not have a negative effect on hydration status before and during simulated tennis match play.

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CHAPTER I. INTRODUCTION

Tennis is a sport characterized by intermittent bouts of high intensity exercise followed by longer rest periods over an extended period of time [1]. Kovacs et al. demonstrated that the average point in professional tennis lasts approximately 5 seconds and the average rest period between points lasts approximately 15 seconds, resulting in a work to rest ratio of 1:3 [2]. The authors also demonstrated that 90% of the points played in professional tennis lasted less than 10 seconds. Other researchers have also measured rally length at the collegiate level and junior level competition and found rally length to range between 9 and 13 seconds [3-5]. These results show that regardless of skill level, rally length is fairly consistent in tennis match play. Powers and Howley suggested that for events lasting up to 10 seconds, 90% of the energy may be supplied anaerobically by the immediate energy systems [6]. Therefore, based on the time analysis literature, the energy supplied in tennis playing may be predominantly from the immediate energy systems.

In contrast, some researchers classified tennis as aerobic based on match time, maximal oxygen consumption (VO_{2max}), oxygen consumption during tennis play, and heart rate (HR) [1, 3, 5, 7, 8]. Several studies have shown that elite tennis players have an elevated VO_{2max} when compared to non-tennis players with values ranging from 56 to 65.9 $ml.kg^{-1}.min^{-1}$ [1, 3, 9]. When comparing total distance covered by running during

match play and total distance covered by walking during recovery, Seliger found that 88% of the energy metabolism comes from aerobic sources and 12% from anaerobic sources [8]. Seliger also measured VO_2 during tennis play using indirect calorimetry and found O_2 consumption during play ranged from 24 to 28 $ml.kg^{-1}.min^{-1}$, representing approximately 50% of VO_{2max} [8]. However, subjects played for only 10 minutes, so it may not be possible to apply the results to an entire tennis match.

Mean HR for males 20 to 45 years of age during tennis playing ranges from 132 to 156 $beats.min^{-1}$, which corresponds to between 55% and 80% of HR_{max} [1, 3, 4, 7, 10, 11]. During recovery, researchers have found both higher HR [3] and lower HR [5] when compared to HR during play. Elliott et al. suggested that lower HR during play may be due to the brief work period which may be completed before HR has sufficient time to adjust to the required intensity and therefore may play "catch up" during recovery [3]. Christmass et al. also stated that even though exercise intensity may vary during play, HR remains relatively constant due to the short duration of play [5]. Therefore, HR may not be the best method to estimate exercise intensity during tennis play due to the short length of play. For these reasons, there is considerable debate over which is the predominant energy system during tennis match play. Kovacs summarized tennis as being "anaerobic predominant activity requiring high levels of aerobic conditioning to avoid fatigue and aid in recovery" [12].

Tennis players are required to maintain great levels of concentration throughout the match. The average tennis match lasts about 90 minutes, although it may last as long as 5 hours [12]. Thus, the ability to sustain concentration over long periods of time may be vital to tennis performance. Tennis players are also challenged to make decisions that

require fast reaction time. For example, the average tennis serve is approximately 209 kilometer/hour (km/h), although there have been serves recorded as fast as 230 km/h [13]. At these speeds, tennis players are allowed 0.408 seconds to react, move, and make contact with the tennis ball (Strecker unpublished data). Therefore, the ability to respond rapidly to the moving tennis ball is of great importance during performance. However, success in tennis may not be predicted by basic physiological parameters [14], which leads one to conclude that there is a need for the creation of more applied testing protocols that allow prediction of tennis performance.

Vergauwen demonstrated that it is possible to "closely resemble" a tennis match using a ball machine [15]. These authors also developed a testing procedure to measure stroke performance in tennis players. It consisted of forehands and backhands returned from balls projected by a ball machine to target areas. Stroke quality was determined from simultaneous measurements of ball velocity and precision of ball placement. During data collection the authors used an expensive and complicated system of cameras and digitization, which may not be accessible to athletes, coaches, and tennis aficionados. In addition, they excluded all the shots that were hit out, into the net, and to the wrong spot on the tennis court, which raises the question of how accurate some of their results may be in an applied setting. Thus, in the present research protocol, modifications were made to the testing procedures described by Vergauwen's methodology [15].

In our modified protocol, the tennis court was divided into 12 boxes of similar size 6.75 feet wide by 9 feet long (see figure 1) and scoring followed Vergauwen's definition of neutral, defensive, and offensive shots [15]. Neutral shots were considered as balls that landed close to the middle of the tennis court (positions 2 and 4), defensive

shots were considered as balls that landed inside the service line (positions 1 and 3), and offensive shots were considered as balls that landed close to the singles line (positions 5 and 6). These modifications not only allowed extraction of similar information, but also differentiation of changes in accuracy, single shot placement, and recognition of the total number of errors as well as where those errors were performed.

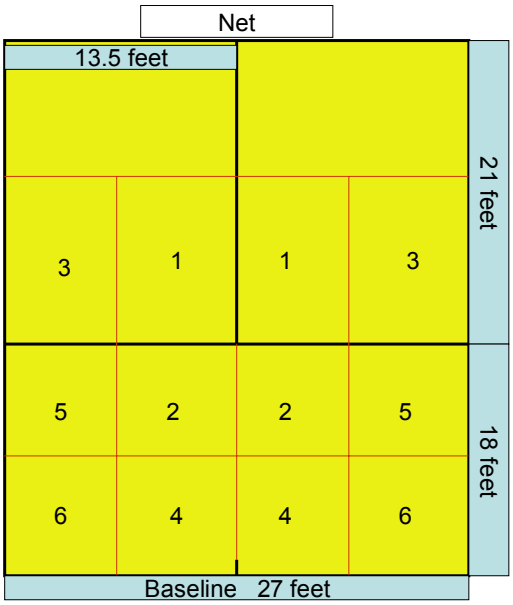

Figure 1. Skill Test Score Assignment. Court dimensions as well as target areas with respective scores are also shown.

Hydration status can influence performance, especially in a hot and humid environment. Fluid replacement helps maintain thermoregulation, reducing the risk of heat injury and/or illness, cardiovascular function, muscle functioning, and fluid volume status [16]. According to the American College of Sports Medicine and The National Athletic Trainers' Association several factors stimulate fluid intake during exercise such as palatability, drink temperature, electrolyte content (i.e. sodium and potassium), and

availability [16, 17]. It has also been suggested by both organizations that athletes should ingest approximately 500 ml of fluids 1-2 hours prior to performance to ensure euhydration as well as to allow the urinary system enough time to clear out excess fluids [16, 17]. It is common for athletes to consume a meal prior to performance (e.g. < 2 hours) and during these meals athletes may also consume carbonated caffeinated soft drinks (e.g. Mountain Dew). Anecdotally, ingestion of such soft drinks during the meal preceding competition has been suggested to be detrimental to performance because it contains caffeine and caffeine has been implicated as having a diuretic effect leading to hypohydration. However, research has found conflicting results. Some researchers have found that during rest, caffeine increases urine production, but they found no difference during exercise [18]. Armstrong et al. found no difference during rest after 11 days of caffeine ingestion[19]. Healthy males (n=59) consumed 3 $mg \cdot Kg^{-1}$ of body weight (BW) of caffeine daily for 6 days (equilibration phase). Then, for the next 5 days (treatment phase) the subjects were divided into 3 groups: 0 (placebo), 3, and 6 $mg \cdot Kg^{-1}$ BW. The authors found that body mass, urine osmolality, urine specific gravity, urine color, 24-h urine volume, 24-h Na^+ and K^+ excretion, 24-h creatinine, blood urea nitrogen, serum Na^+ and K^+, serum osmolality, hematocrit, and total plasma protein were unaffected and within normal clinical ranges. They concluded that in healthy, active males there is no evidence of detrimental caffeine-induced fluid-electrolyte imbalance.

On the other hand, it has also been suggested that caffeine may improve performance if ingested at least 1 hour prior to performance [20-22]. Bell et al. showed that ergogenic effects may remain even 6 hours after ingestion [23]. Twenty one (13 caffeine users and 8 nonusers) subjects perform 6 randomized exercise rides to

exhaustion at 80% of VO_{2max} after ingestion of either placebo or 5 $mg \cdot Kg^{-1}$ of caffeine. Exercise to exhaustion was performed either at 1, 3, or 6 hours after placebo or caffeine ingestion. The authors found significant improvements in performance for users and non-users at 1 and 3 hours after caffeine ingestion and after 6 hours for the non-user group only. This study showed that the ergogenic effects of caffeine may last for hours after its ingestion and may be more long lasting for non-users.

There does not appear to be a dose-related effect for caffeine's ergogenic effect and improvements in performance seem to be similar with doses ranging between 3 and 9 $mg \cdot Kg^{-1}$ [24]. These doses have also been shown to fall below what is considered doping by the National Collegiate Athletic Association (NCAA) and the International Olympic Committee (IOC) [24]. Most of the studies showing the ergogenic effect of caffeine have focused on running and cycling, which are continuous and prolonged in nature and do not require skills to the extent found in tennis. Thus, the present research focused on two questions: Does caffeine improve tennis skill performance? Does caffeine ingestion cause a diuretic effect prior to and/or during tennis performance?

There appears to have been only two studies testing the effects of caffeine on tennis playing success and accuracy [25, 26]. In both, subjects performed 240 minutes of singles match play. Tennis players were asked to perform a ball-machine hitting accuracy test and a tennis-sprint test. The results did not show an ergogenic effect in playing success for men, but it did for women. However, the location of the areas on the accuracy test accounted for only a small part of the tennis court since area #1 was 150 cm^2 and area #2 was 300 cm^2. Besides, the protocol did not relate shots to defensive, offensive, and neutral tennis shots. Therefore, the purpose of the present investigation was to determine

the effect of pre-match consumption of a caffeinated carbonated soft drink on tennis performance and hydration status before and during simulated tennis match play.

Two hypotheses:

1) H_o: A caffeine dose of 3 $mg \cdot Kg^{-1}$ will not improve tennis performance skills and mental acuity.

H_a: A caffeine dose of 3 $mg \cdot Kg^{-1}$ will improve tennis performance skills and mental acuity.

2) H_o: A caffeine dose of 3 $mg \cdot Kg^{-1}$ will not induce a significantly greater degree of dehydration.

H_a: A caffeine dose of 3 $mg \cdot Kg^{-1}$ will induce a significantly greater degree of dehydration.

CHAPTER II. REVIEW OF LITERATURE

Tennis

Performance Characteristics

Tennis is characterized by short bouts of submaximal intensity with longer periods of recovery. The average tennis point lasts eight seconds and the average rest period between points is 15 seconds, with the entire match lasting, on average 90 minutes with the possibility of matches lasting up to 5 hours [27]. The intermittent nature of the sport, combined with the unpredictable length of a match, influences the physiological demands of tennis playing. There has been considerable debate over which energy system supplies the majority of the energy required during tennis performance.

Chandler found in 1988 that the work/rest ratio in professional male tennis players was approximately 1:3 during match play and approximately 1:5 when total time was counted [28]. Kovacs et al. found similar results in 2003 in professional male tennis players with the work/rest ratio being 1:3 during match play and 1:5 when total time was counted [2]. When comparing the results, Kovacs found that even though the work/rest ratios remained similar, the amount of rest players utilized between points was reduced in professional play from 1988 to 2003. This was due to the fact that the rally length was reduced between studies as well. The authors concluded that due to reduction in rally length, the rest required by athletes was also reduced from 1987 to 2003. In a similar

study, the work/rest ratio was measured in male college players and the results showed a 1:4 and 1:6 values during match play and when total time was counted, respectively [29]. The authors concluded that regardless of skill level, work-to-rest ratio remains similar in tennis match play. However, other researchers have found different results. Elliott examined rally length and rest length during one hour of tennis play and found that the work to rest ratio was 1:1.8 [3]. Similarly, Christmass also measured work to rest ratio and found that during 90 minutes of tennis play subjects had a work to rest ratio of 1:1.7 [5]. Therefore, there appears to exist some discrepancy between studies and differences in protocol may explain those differences.

In 1988 Chandler analyzed the U.S. Open final and found that the average rally length was 12 seconds [28]. In 2003, Kovacs et al. replicated the same study and found that rally length average had decreased to 8 seconds [2]. Theses two matches in particular are of extreme importance because they were played by the numbers 1 and 2 on the Association of Tennis Professionals (ATP) rankings on both occasions. Thus, it is possible to argue that the level of players were very similar. In a similar study done on division I college male tennis players, Kovacs et al. found that rally length was similar to professional level matches [29]. Other researchers have also measured rally length during tennis match play and results ranged from 9 to 13 seconds [3-5]. These results show that regardless of skill level, rally length is fairly consistent during match play. Powers and Howley in their textbook suggest that 90% of the energy required for events lasting up to 10 seconds may be supplied by anaerobic alactic energy sources [6]. Therefore, through time analysis it is possible to conclude that the majority of the energy supplied during tennis is the immediate energy system.

Based on tennis match time and average HR during performance, some researchers have suggested that tennis resembles continuous, aerobic exercise [3, 5, 30]. Mean HR for males 20 to 45 years of age during tennis playing ranges from 132 to 156 beats.min^{-1}, which corresponds to approximately 55% to 80% of HR_{max} [1, 3, 4, 7, 10, 11]. According to Morgans et al. the average HR intensity during singles match play is high enough to meet the intensity criteria established by the American College of Sports Medicine for developing and maintaining cardiorespiratory fitness [31].

Researchers have found higher HR [3] and lower HR [5] during recovery when compared to HR during play. Elliott et al. suggested that lower HR during play may be due to the brief work period which may be completed before HR had sufficient time to adjust to the required intensity and therefore may play "catch up" during recovery [3]. Christmass et al. stated that even though exercise intensity may vary during play, HR remains relatively constant during performance due to the short duration of play [5]. Bergeron et al. in agreement explained that HR does not immediately reflect variations in exercise intensity during intermittent exercise [1]. Therefore, HR may not be the best method to estimate exercise intensity during tennis play.

VO_{2max} has been defined as the maximal capacity to transport and utilize oxygen during exercise [6]. Studies have shown that top club and state level tennis players have an elevated VO_{2max} when compared to inactive people [32, 33], but lower than aerobically trained athletes [34]. VO_{2max} among elite tennis players ranges from 56 to 69 ml·kg^{-1}·min^{-1} [9, 35]. Konig et al. suggested that attainment of a VO_{2max} above 55 ml.Kg^{-1}.min^{-1} for females and 65 ml·Kg^{-1}·min^{-1} for males is not desirable because higher values would be achieved by focusing on endurance training, which induces transformation from

fast twitch glycolytic (IIb) fibers to fast twitch oxidative-glycolytic (IIa) fibers reducing strength, power, speed, and explosiveness; characteristics that have been suggested as requirement for successful tennis performance [36, 37]. Therefore, although high aerobic capacity is advantageous during tennis play to aid recovery between points; due to the characteristics of the game, aerobic training should be accomplished through interval training. Deusch et al. stated “Interval training for the anaerobic system increases the anaerobic capacity of muscles and results in muscle group development through recruitment of additional muscle units, increases the resting level of anaerobic substrates, increases the capacity for levels of blood lactate during all-out exercise enhancing glycolytic enzyme activity, and increases hypertrophy” [38].

The Shuttle Fitness Test (SFT) is a progressive shuttle run test for the prediction of VO_{2max} [39] in subject groups ranging from school children to athletes performing in sports with frequent stops and starts. The SFT consists of a progressive shuttle run in which subjects have to follow a pre-set pace that is marked by a sound. The 20 meters shuttle run must be completed simultaneously with each sound. VO_{2max} is determined from a chart that equates the VO_2 cost associated with the work rate as determined by stage and level. Although an estimation, the test was found to be reliable in children (r=0.89) and in adults (r=0.95). Its validity is supported by a correlation of 0.71 and a standard error of 5.9 $ml \cdot kg^{-1} \cdot min^{-1}$ or 12% with criterion VO_{2max} methods. The constant change in direction and constant acceleration and deceleration may be more indicative of tennis play. It could be argued that the SFT is more specific and similar to tennis play, thereby being a more appropriate physiological measure.

Heat Stress

The various competitive venues for tennis competition provide thermoregulatory challenges to the athlete. Humans have the ability to survive in a large range of environmental temperatures while maintaining a narrow range of core temperatures (36-40°C) [40]. Environmental temperature alone does not provide an accurate assessment of thermal stress. Temperature provides information only about air temperature not taking into consideration other factors such as humidity and radiant heat. As a result, several heat stress measures have been developed. Two of the more popular are the Heat Stress Index (HIS) and the Wet Bulb Global Temperature (WBGT). The HSI takes into consideration other environmental factors that may influence tolerance to exercising in the heat as well as physiological stressors such as exercise intensity [41]. However, HIS is based on the ratio between the evaporation required (E_{req}) to equate heat production to heat dissipation and the maximal evaporation possible (E_{max}) failing to differentiate exercise-induced heat load, such that heat index is similar regardless of exercise intensity [42]. WBGT is the combined measure of air temperature, convective-evaporative wet bulb cooling (WB), radiant heat absorption by black globe (GT) and dry temperature (DBT). Thus, WBGT provides more substantial information about the environmental conditions compared to other methods, but fails to take into consideration physiological stressors. Beyond the individual's thermal sensation of heat stress, it is imperative for the individual to promote adequate heat transfer to maintain his/her core temperature within the organism survival zone.

At rest in neutral temperatures, heat production is minimal and heat loss is easily matched. However, during exercise, heat production may be elevated as much as 10-15

times [43] because of the elevated metabolic activity generated by the higher rate at which the body utilizes food energy [44]. Because the body is about 20-25% efficient during exercise, 75-80% of the energy utilized is transformed to heat [6]. This increase in heat production during exercise results in an increase in muscle temperature, which in turn elevates core temperature. In order for body core temperature to remain constant, heat loss must match heat production, otherwise hyperthermia could result [44].

There are four different mechanisms by which the body can exchange heat: convection, conduction, evaporation, and radiation [45]. Radiation is the movement of heat via electromagnetic waves (e.g. tennis court). Convection is the movement of heat down its thermal gradient from an object to its surroundings (e.g. air). Conduction is the movement of heat between two objects that are in direct contact with each other (e.g. hand touching the grip). Finally, evaporation is the loss of heat through the phase change of a liquid to a gaseous state (e.g. evaporation of sweat) [45]. Castellani suggested that the mechanism of heat transfer is dependent upon the ambient temperature and water vapor pressure (relative humidity) [45]. Because core temperature in humans is maintained within a small range [40], at resting conditions in mild temperatures the most important mechanisms for heat loss are radiation and convection. As temperature rises, the ability of the body to lose heat through radiation and convection diminishes, relying more and more on evaporation for heat dissipation. The greatest challenge occurs when humidity is elevated, because the air has less “space” for water particles, thus decreasing the ability of water to evaporate and dissipate heat. Heat production during exercise seems to be proportional to the absolute intensity of exercise and not environmental conditions [46]. Thus, as the potential for heat storage increases with more intense

exercise, the venues for heat transfer must also be modified according to the environmental conditions during exercise [42].

The most important external mechanism of heat gain during tennis play in hot and humid environments seems to be radiation. As the sun heats the atmosphere, the radiant heat released by the sun warms the air and the objects outside. As the temperature of the environment or objects surpasses 37°C (average body core temperature in humans), heat waves transfer the heat to the body. The majority of the professional tour (ATP tour) tournaments and all college tennis matches are played on hard court (asphalt-based surface). Thus, the surface of the tennis court is the major source of heat gain during tennis play along with the sun. Kovacs suggested that the tennis court may be the main source of heat gain on hot days due to the ground thermal radiation and the solar radiation reflected by the court surface [47]. As mentioned before, if core temperature and thermoregulation are to be maintained, then heat loss must match heat gain. The most critical mechanism of heat loss during tennis match play in a hot and humid environment is evaporation of sweat. On average, 578 calories per liter of sweat evaporated are released as heat. Sweat losses in athletes have been reported and range between 1 and 2 liters per hour [16, 17]. Therefore, during exercise, athletes may lose great amounts of body water due to sweating in order to maintain a steady core temperature.

Body Water Balance

The human body, on average, contains 42 liters of water, corresponding to approximately 50-70% of total body weight [45]. The water in the body is divided into an intracellular compartment, which contains 28 liters (67%) and an extracellular compartment which contains 14 liters (33%). The extracellular compartment is

subdivided into interstitial fluid (10.5 liters) and plasma (3.5 liters). Castellani stated that water is freely exchanged between these three compartments and the direction of water movement is mainly determined by hydrostatic and osmotic pressures [45]. Water balance is achieved by a balance between water intake (fluid and food ingestion, metabolic) and water output (urine, respiration, and sweat) [45]. A negative water balance (increased water output compared to water intake) may lead to an overall water deficit or dehydration. McArdle et al. defined dehydration as "body water loss from a hyperhydrated to euhydrated state or euhydrated to hypohydrated state" [40]. Although there are several reasons why the human body dehydrates, this review will focus only on the exercise-induced changes from the euhydrated to the hypohydrated state. Nielsen proposed that exercise leads to a gradual dehydration because of increased sweating [48]. Sawka et al., in agreement with the previous study, suggested that unless rehydration is forced, marked dehydration will occur during exercise in the heat, since it is difficult to match the volume of fluid consumed to the volume of sweat produced [49].

Sweat Rates

Powers and Howley suggested that one of the most important functions of the cardiovascular system is heat transport, since blood has a high capacity to store heat [6]. Sweat is a filtrate of blood formed by the secretory portion of the sweat gland, and although sweat is hypotonic to plasma, its concentration is dependent upon the sweat rate [50]. When sweating does occur, the free exchange of water among all fluid compartments ensures that sweat is derived from all compartments, although the primary source of water is from the extracellular space [51]. The immediate source of water for sweat is the interstitial fluid, but due to the sweat's hypotonicity, there is a simultaneous

movement of fluid from plasma to the interstitial space [52], leading to a reduction in plasma volume and an increase in osmolarity in the extracellular fluid compartment shifting the osmotic pressure gradient toward movement of water from the intracellular compartment to the blood [48].

During exercise, increased sweating imposes challenges to the body to maintain water balance. As exercise intensity increases there is a linear increase in heat production leading to an increase in core temperature [49]. In order to maintain a steady core temperature, the body has to dissipate some of the heat produced by increased metabolism due to exercise. In a hot and humid environment, the body relies almost exclusively upon evaporation for heat dissipation accounting for approximately 80% of total heat loss [50]. High sweat rates reduce blood volume (hypovolemia), limiting the amount of blood available to supply the needs of the skin preventing heat dissipation [50]. To minimize the risk for thermal injuries, it has been suggested that water losses due to sweating during exercise be replaced at a rate equal to the sweat rate [17]. McArdle stated that fluid replacement should focus on maintaining plasma volume, so circulation and sweating progresses at optimal levels [40]. Less than optimal levels (hypohydration) have profound effects on reducing stroke volume and muscle blood flow, thus limiting oxygen delivery to exercising muscles [53]. Reduced stroke volume also results in a decrease in skin blood flow, causing a decrease in sweat rates resulting in impaired thermoregulation [50].

There are several factors that influence sweat production, such as exercise intensity, environmental temperature and humidity, and heat acclimatization [49]. Sweat production has been measured in tennis players. Bergeron et al. reported that tennis

players may sweat up to 2.5 L of water each hour of exercise [30]. In another study, Bergeron et al. measured sweat rates on 20 tennis players (12 males and 8 females) on 3 consecutive days of match play in a hot and humid environment [54]. They found that the average sweat rates were 2.7 $L.hr^{-1}$ and 1.7 $L.hr^{-1}$ for males and females, respectively. However, the authors also found that total fluid intake and changes in body weight percentage were similar for males and females despite larger sweat rates for the male tennis players [54]. Thus, high sweat rates in tennis players lead to hypovolemia and may cause changes in plasma volume.

Plasma Volume

During exercise in a hot and humid environment, core temperature increases resulting in an increase in blood temperature, which stimulates the hypothalamus [50]. As a result, there is an increase in cutaneous blood flow and increased sweating [6, 48]. During prolonged exercise, sweating causes blood volume to be reduced, which is mainly due to a decrease in plasma volume [52]. High sweat rates resulting in hypovolemia cause a shift in body fluids from the interstitial fluid space into the vascular compartment [55, 56]. By measuring changes in plasma volume, it is possible to estimate fluid loss due to sweating. Dill and Costill were the first to measure changes in plasma volume by measuring hemoglobin and hematocrit [57]. Their protocol measured changes in hemoglobin and hematocrit concentrations between pre-exercise and post-exercise by considering pre-exercise values to be 100% [57].

Plasma accounts for approximately 58% of total blood volume and is mainly composed of water, although plasma also contains ions, proteins, and hormones [6]. Plasma volume begins to decrease after approximately 3-5% loss of body weight [45].

Greenleaf found that the upper limit of plasma volume loss due to exercise was approximately 20% of the resting plasma volume [58]. During exercise, reduction in plasma volume through sweating, causes a reduction in total blood volume, which becomes hyperosmolalic [59]. As a result of hypovolemia, stroke volume is reduced and HR is increased in order to maintain cardiac output, a term referred to as cardiovascular drift [52]. Sawka et al. suggested that in an attempt to maintain cardiac output, plasma volume can be partially defended despite progressive dehydration due to water release from glycogen breakdown, metabolic water formation, and water redistribution from inactive skeletal muscle [59]. This would suggest that decreases in plasma volume from dehydration may be blunted during exercise.

Increased sweating combined with failure to match fluid intake to sweat rate results in body weight loss. Some authors have measured body weight losses in tennis players during match play [60, 61]. However, in neither study was plasma volume measured. In contrast, Bergeron et al. measured plasma volume changes after consecutive match play [54]. The results showed that plasma volume slightly increased throughout the day. The authors attributed these results to a possible increase in plasma tonicity, which would result in an increase in osmotic pressure, causing fluid to shift from the intracellular into the extracellular compartment, preventing a decrease in blood volume [54]. Therefore, at this time it is not possible to make any conclusions as to changes in plasma volume during tennis play.

Hydration

Hydration status may be one the most important factors during exercise, since body water loss (plasma volume decrease) can result in a decrement in performance. It has been reported that reductions in blood volume by as little as 1% of total body weight result in reductions in performance [16]. Fluid replacement prevents body fluid deficit, which in turn prevents reductions in blood volume, helping maintain performance and thermoregulation [59]. The American College of Sports Medicine, in its position stand, stated that the most serious effect of dehydration resulting from the failure to replace fluids during exercise is the impaired ability for heat dissipation [17]. Ma et al. [52] presented several reasons why individuals may not properly hydrate during exercise. First, thirst may not provide a good index of body water needs. Second, gastrointestinal intolerance limits fluid consumption since high intensity exercise inhibits gastric emptying and intestinal absorption rates. Third, the rules of the sport may dictate availability and access to fluids [52]. However, when fluid is available and the rules of the game encourage drinking, there are several factors that influence fluid intake during exercise, including fluid volume, drink characteristics (palatability/temperature) and digestive system characteristics.

Volume/Frequency

It appears that there is some debate on the optimal amount (volume) required during exercise performance to maintain blood volume and thermoregulatory capacity. The American College of Sports Medicine (ACSM) and The National Athletic Training Association (NATA) in their position stands recommended the ingestion of 500 ml of fluids 1-2 hours prior to exercise [16, 17]. However, the ACSM position stand suggests

that during exercise fluid should be consumed at a rate sufficient to replace all water lost through sweating or the maximal amount tolerated [17]. NATA, on the other hand, suggested that athletes should drink between 200 and 400 ml every 15-20 minutes of exercise. Shirreffs et al. also suggested that due to obligatory urine losses after exercise to eliminate metabolic waste, respiration, and transcutaneous water loss, the volume of fluid ingested after exercise must be greater than the volume of sweat lost if effective rehydration is to be achieved [51].

There are two main factors that influence the volume of fluid consumed that is absorbed by the human body: 1) gastric emptying; 2) intestinal absorption. The stomach functions as a reservoir that regulates the rate at which ingested material enters the small intestine [62]. Leiper et al. suggested that gastric emptying rate is faster for liquids than for solid foods and also faster for low-energy content foods than for more energy dense contents [62]. The author concluded then that nutrients and water supplied as drinks are more rapidly absorbed. The most important factor regulating gastric emptying is the volume of fluid in the stomach [52], since gastric emptying is not a linear process [63], but fluid composition also plays a role [62]. Exercise does not seem to delay gastric emptying if exercise is below 70% of VO_{2max} [64]. Costill et al. had 15 males consume 200, 400, 600, and 800 ml of fluid with 139, 278, 556, and 834 mM of glucose at a temperature of 5, 15, 25, and 35°C. The authors found that gastric emptying increased proportionally to the volume of fluid consumed up to 600 ml. They also found that gastric emptying was impaired by increased temperature (35°C) and glucose concentration [64]. The authors concluded that carbohydrate and water needs should vary depending on the exercise conditions. Another possible conclusion is that athletes should maintain the

highest volume tolerable in the stomach so that gastric emptying is elevated throughout the exercise session. After fluid moves from the stomach into the intestine, intestinal absorption will dictate the amount of fluid that is absorbed and available for the circulation.

The small intestine is divided into 3 parts: duodenum, jejunum, and ileum [62]. The duodenum is the first part and it receives the biliary and pancreatic secretions facilitating the absorption of fats and digestion of proteins. The jejunum is the second part and it is where most of the absorption of fluids occurs. The ileum is the last part and its main function is to provide reserve absorptive capacity [62]. The major barrier for transport across the intestinal mucosa is the phospholipids bilayer so water soluble solutes require transport carriers [62]. Thus, water absorption from the intestine is considered to be a passive consequence of solute absorption [62]. Intestinal absorption is determined primarily by the composition of the fluid (energy density) and the osmolarity [52].

The challenge for maintaining hydration during tennis is matching the amount of fluid required to maintain euhydration with the available opportunities to consume fluids during a tennis match (change-overs). The characteristics of the sport make prediction of these opportunities for fluid consumption an even bigger challenge since there is no time restrictions on the length of points, games, and matches. Fortunately, tennis players do have the opportunity to ingest fluids after every two games, which according to Bergeron et al. is approximately 15 minutes [54]. The allowed resting time between the change-over in tennis is 90 seconds, which may be more than enough time to replenish fluid lost due to sweating as long as the athlete is aware of the importance of hydration and has

enough fluid available during the change-overs. Kovacs proposed that tennis players should be on an individualized drinking schedule during matches and practices to maximize hydration based on individual sweat rates [47]. The author also stated that if individualization is not practical, then tennis players should ingest 400 ml every 15 minutes (1.6 L/hr) or more even though gastric emptying rarely exceeds 1.2 L/hr [47]. Thus, unless individualized, it is not possible to make practical conclusions about how much fluid tennis players should ingest during practice and competition.

However, these recommendations have been challenged by some authors. Coyle stated that from a performance perspective, sometimes it may be acceptable to drink less than needed to maintain body weight, since it may take approximately 40-60 minutes for the fluid ingested to provide physiological benefits [53]. The author's reasoning was that off-setting body weight loss by fluid ingestion does not offset cellular dehydration, since fluids that are not distributed throughout the body and remain in the gastrointestinal tract will be of no benefit in terms of reducing cardiovascular or thermal strain during exercise [53]. Thus, athletes should maintain high levels of fluid consumption to match fluid loss due to sweating during the exercise session up until the last 30-40 minutes in which time fluid intake could be reduced to a lower volume than sweating rate to minimize gut fluid volume, which could help lower oxygen cost of movement at the end of exercise. Further support is provided by the research of Montain et al. [65]. In this investigation participants exercised for 140 minutes on a cycle ergometer at 62% of their VO_{2max} on 4 different occasions. Participants were provided with a single bolus of approximately 1.2 liters of fluids, which were consumed after 5, 40, or 80 minutes into the exercise session. On the fourth trial, participants consumed similar amounts, but in smaller aliquots

throughout the exercise session. The results showed that hemoglobin, hematocrit, serum osmolality, and blood volume were similar after 140 minutes of cycling in all 4 trials. The authors concluded that changing the timing of fluid consumption changed the pattern of decline in blood volume, but it did not alter the magnitude of hypovolemia after 140 minutes of exercise [65]. Thus, it seems that as long as the total fluid volume consumed is similar during exercise, the timing of consumption does not result in better hydration at the end of the exercise session.

Palatability

Palatability is determined by a number of physical aspects including temperature, taste, mouth feel, and flavor [52]. Research has shown that when fluid ingestion is “ad libitum”, the taste of the drink influences the amount of fluids consumed prior to, during, and after exercise [16, 17]. Wilmore et al. had a total of 15 participants perform three 90-minute runs on a treadmill during which they were assigned one of the three beverages: water, 6% carbohydrate plus electrolyte sports drink, and 8% carbohydrate plus electrolyte sports drink plus B vitamins [66]. Participants consumed significantly more fluid during recovery on the carbohydrate electrolyte sports drink trials compared to water. However, there was no difference during exercise between carbohydrate drinks [66]. Sodium content also has been shown to influence palatability and absorption and thus, to affect the amount of fluids ingested by athletes increasing the amount of fluids retained in the vascular compartment [67]. Burke et al. had ten active tennis players perform three simulated tennis matches while receiving one of three treatments: no fluids, water, and carbohydrate polymer drink [68]. The results showed that during the carbohydrate trial, subjects drank 736 ml of fluid compared to 505 ml during the water

trial [68]. Therefore, drink composition and palatability play a role in fluid volume consumed during tennis playing.

Fluid Temperature

The National Athletic Trainer's Association recommended fluid to be cooled to approximately 10-15°C (50-59°F). However, the American College of Sports Medicine recommended fluid temperature to be 15-22°C (59-72°F). Boulze et al. examined the effects of fluid temperature on total volume of fluid consumed [69]. In experiment 1, subjects drank water *ad libitum* for 15 seconds after exercise and the total amount of water drank was measured. Water temperatures were 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50°C. In experiment 2, subjects were asked to mix water from a cold tank (5°C) with water from a warm tank (temperature not specified). Participants were asked to taste, but not swallow until they obtain their preferred temperature. The authors found that in experiment 1, the temperature that elicited the greatest amount of fluid consumed was 15°C. Surprisingly, in experiment 2, the preferred temperature of the beverage was also 15°C [69]. In agreement, Szlyk et al. compared the influence of fluid temperature on the amount of fluid ingested during treadmill exercise [70]. The authors found that cool water (15°C) was ingested 37% more than warm water (40°C). Therefore, it is clear that fluids should be cooled to approximately 15°C to enhance palatability and help with maintaining cooler core temperature.

Performance

There are several criteria that can be used for performance analysis in tennis. During tennis play, there are three main mechanisms by which a point may be won. First, ball velocity; by hitting the tennis ball with great velocity such that the opponent does not

have enough time to move and touch the tennis ball (i.e. winner shot). Second, accuracy; by executing a shot that lands at specific locations in the tennis court, tennis players may be able to maintain the tennis ball far enough away from their opponents such that they are either unable to touch the tennis ball (winner shot) or are unbalanced causing the opponent to make a forced error. Finally, unforced error, which is the execution of an error that he or she should not have executed. Different playing styles will focus on different mechanisms to win points.

Ball Velocity

Well developed tennis technique and skills may be the most important parameters for talent recognition. Kraemer et al. performed several tests with female junior tennis players and found that joint laxity and only a few strength measurements were correlated to ball velocity [71]. The strength measurements were military press, knee extension and flexion, and shoulder internal and external rotation. All other parameters had low or no correlation to ball velocity. Thus, the authors concluded that tennis playing skills play a major role in the production of peak ball velocities [71]. Perry et al. confirmed the results that players (males and females) with greatest isokinetic strength show the highest ball velocities, but flexibility measures were not correlated to ball velocity [9]. They also showed that players with the greatest ball velocities had the hardest time with ball placement and accuracy. The authors proposed reducing ball velocity during practice to improve ball placement [9]. Although a logical suggestion, such recommendation is unrealistic, due to the game's evolution emphasizing power, which is translated into increased ball velocity.

Hitting Accuracy

According to Webster's New World Dictionary, the definition of accuracy is as follows: the state of being accurate, precision. In tennis, accuracy means being able to hit the tennis ball to one specific target on the tennis court. Most, if not all, studies have tested hitting accuracy using a ball machine for standardization of ball speed and placement [9, 11, 15, 72, 73] and having the subjects hit the tennis balls to a specific area of the court. Although protocols have varied, the results show that tennis players are extremely accurate, being able to consistently place tennis balls into areas as small as 1.5 m^2 [11, 72]. Davey et al. had 18 tennis players (9 males and 9 females) perform two skill tests on two different occasions [11]. Participants performed two 20-ball drills alternating forehand and backhand (10 to each side) hit to a pre-determined area (1.5 m^2). Results showed no difference between tests for forehand and backhand for cross court and down-the-line [11]. Davey et al. also tested the effect of fatigue on hitting accuracy [11]. The same subjects performed a simulated tennis play to exhaustion. The test consisted of 4 minutes of tennis playing alternating forehands and backhands into two 1.5 m^2 pre-determined areas separated by 40 seconds of seated recovery. Balls were fed randomly at a frequency of 30 balls per minute. The authors found that fatigue decreased accuracy at exhaustion and at 75% of the total time to exhaustion [11].

Since fatigue seems to decrease hitting accuracy, it is feasible to suspect that interventions that blunt the effect of fatigue may also improve and/or maintain hitting accuracy during prolonged tennis play. A few researchers have tried to answer this question. Vergauwen et al. tested the effect of carbohydrate and caffeine (5 mg/Kg BW) ingestion on hitting accuracy [74]. They found that carbohydrate supplementation

reduced the fatigue-induced increase in error rate [74], but caffeine had no additional effect in stroke quality as measured by hitting accuracy. In contrast, Ferrauti et al. in two similar studies showed that caffeine ingestion improved hitting accuracy in men, but not in women [25]. The authors also showed that carbohydrate ingestion had no definite positive effect on hitting accuracy [26]. The authors had no explanation as to why caffeine enhanced performance for women and not for men. Perhaps results may be attributed the target areas marked on the tennis court, which may have been too small since they included only a small portion of the tennis court. Thus, more research is needed in this area. Also, perhaps including the majority of the tennis court may be required for differences in hitting accuracy to be found during tennis play.

Metabolism

Bergeron et al. suggested that tennis includes intermittent exercise bouts of varying intensities and numerous recovery periods over a long duration, and due to these characteristics, analyzing tennis responses in a lab and to duplicate responses seen on the tennis court may be difficult [1].

Glucose

Coggan et al. suggested that the beneficial effects of carbohydrate ingestion during prolonged performance is related to the maintenance of blood glucose levels and a high rate of carbohydrate oxidation at a time when muscle glycogen stores are low [75]. The American College of Sports Medicine recommends carbohydrate ingestion in events lasting longer than one hour [17]. Vergauwen et al. showed improvement in tennis stroke performance during simulated tennis play after carbohydrate supplementation [74]. Thus, one might conclude that carbohydrate ingestion would be an effective performance

strategy for tennis. However, there are conflicting results on this matter. Others have reported that carbohydrate ingestion does not improve tennis performance during match play [26, 76].

Copley was the first researcher to measure blood glucose responses during tennis playing [77]. Twenty proficient tennis players competed in singles match competition. Pre and post-match mixed venous blood samples were drawn and the author found no difference in blood glucose [77], which may explain the lack of improvement in tennis performance. Mitchell suggested that tennis may not place a heavy enough metabolic demand on the system to make carbohydrate supplementation necessary [76]. Bergeron et al. tested 10 male tennis players during 85 minutes of match play [1]. They found no difference in blood glucose over the duration of the match play, compared to pre-match values. However, when compared to post-warm up values, blood glucose was significantly elevated and remained elevated throughout the protocol [1]. These results showed that there was an initial decrease in blood glucose (after warm up) followed by a rapid increase, which peaked within 30 minutes. In contrast, Ferrauti et al. [26] tested 16 male tennis players during 240 minutes of singles match play with a 30-minute break after 150 minutes of tennis playing. They found that blood glucose decreased during the first 15 minutes, and remained lower compared to pre-match values despite a small increase during play. Mitchell et al. had participants play tennis for 3 hours with 5-minute breaks at 60 and 120 minutes [76]. They found that blood glucose reached peak values at 60 minutes and remained elevated throughout protocol despite significant reductions from 60 to 120 minutes of match play.

Differences in methodology, playing time, ingestion or not of carbohydrates and caffeine, environmental temperature; all may have played a role on the variability of results. Therefore, it is not possible at the moment to make any assumptions about blood glucose responses during singles tennis match play. More research is needed in this area.

Caffeine

Caffeine has been part of our daily life for many centuries. Caffeine occurs naturally in more than 60 plants and is the most consumed drug in the world [78]. Although considered a drug, it is legal and readily available in drinks and foods (e.g. coffee, soft-drinks, chocolate) as well as over-the-counter drugs (e.g. cold medicine, weight loss products) [24]. Chemically, caffeine is a trimethylxanthine that is demethylized in the liver into three dimethylxanthines: paraxanthine, theophylline, and teobromine. In humans, the major product is paraxanthine [24]. Caffeine freely passes the blood-brain barrier and enters quickly into the brain after absorption, which helps explain the relatively rapid onset of its psychological effects [79]. Behaviorally, it is believed that caffeine increases mental alertness, causes a faster and clearer flow of thoughts, reduces fatigue sensation, and delays the need for sleep [78]. Peak caffeine plasma levels are attained within 30 to 60 minutes in a dose-independent manner and caffeine equilibrates almost completely to total body water [80]. The half-life of caffeine is of the order of 2-4 hours and only 4% of total ingested caffeine is excreted unchanged [81, 82]. However, it is still unclear as to the mechanisms in which caffeine acts on the human body.

Mechanism of Action

There have been several speculative explanations as to why caffeine seems to enhance performance. The pharmacological response to any agent is dependent on three

factors *in vivo*: potency, efficacy, and pharmacokinetics [81]. Pharmacokinetics can be further subdivided into rates of uptake, barriers to diffusion, metabolism to inactive or active metabolites, and rates of clearance [81]. Caffeine's metabolism is inhibited by alcohol consumption (acutely), but it is accelerated by tobacco use [79]. Mechanistic testing of caffeine is difficult because caffeine affects many tissues in the body including the central nervous system, cardiovascular system, and adipose tissue [82] causing direct and indirect changes in metabolic and hormonal levels. At physiological concentrations, the most widely accepted theory for caffeine's ergogenic effect is its ability to antagonize adenosine by binding to adenosine receptors [24, 79, 81-86]. However, Graham also suggested that caffeine must act directly on the muscle tissue, since it has been extremely difficult to demonstrate that muscles have adenosine receptors [82]. McArdle et al. [87] suggested four possible pathways by which caffeine can facilitate neuromuscular activity: lowering of the threshold for motor unit recruitment, altering excitation-contraction coupling, facilitating transmission, and increasing ion transport within muscle itself. Three main categories of mechanisms are presented in this review: molecular, metabolic, and physiological.

Molecular

Caffeine is believed to influence several systems in the human body including excitation-contraction coupling, potassium (K^+) channels, calcium (Ca^+) channels, phosphodiesterase, and adenosine receptors.

Excitation-Contraction Coupling (EC)

The EC process in the human body involves several stages between the action potential and the binding of Ca^{++} to troponin, which leads to the development of tension.

It also includes calcium reuptake by the sarcoplasmic reticulum (SR). Tarnopolsky suggested that caffeine may affect any of these major stages, but the question is "Does it occur at caffeine concentrations *in vivo*?" [86]. The only evidence that seems to offer some explanation comes from studies examining Ca^{++} release, and K^{+} release during muscle contraction. Thus, calcium channels and potassium channels will be discussed.

Calcium Channels

There is a consensus among authors that caffeine concentrations ranging from 1-10 mM cause an increase in calcium release from storage pools in the sarcoplasmic reticulum [24, 84-86]. This would cause a lowering of the excitability threshold and would prolong the duration of the active period of muscle contraction. There seems also to be a consensus that this increase in Ca^{++} mobilization is caused by a direct effect of caffeine on the sarcoplasmic reticulum (ryanodine receptor) [88], enhancing Ca^{++} release. However, Daly suggested that concentrations of 250 μM are the threshold for caffeine effects on Ca^{++} mobilization and that such concentrations are unlikely to be seen *in vivo*, since caffeine would become toxic prior to this at lower doses [81]. Therefore, even though Ca^{++} release seems to be influenced by caffeine, it does not seem to be of any benefit at doses found *in vivo.*

Potassium Channels

Potassium ions are lost from the muscle into the blood during muscle contraction. This causes plasma potassium levels to increase, which could result in a decrease in the resting membrane potential and a blockage of depolarization [86]. Caffeine has been shown to attenuate exercise-induced increases in plasma potassium concentration [89], which could help maintain a lower plasma potassium concentration and a higher

intracellular potassium concentration as well as a normal membrane potential in contracting muscles. Lindinger et al. attributed this phenomenon to an increase in Na^+-K^+ pump activity of non-contracting muscles, since Na^+-K^+ pumps in working muscles may already be operating near maximum during moderate exercise [89]. However, only one study looked at the effect of caffeine on K^+ channels [89], so conclusions should be drawn with caution.

Phosphodiesterase

There are two systems where phosphodieterase inhibition may be influenced by caffeine: cardiovascular system (relaxation of smooth muscle) and respiratory system (relaxation of brochioles); the latter has been successfully exploited for treatment of asthma [90]. Caffeine is a weak phosphodiesterase inhibitor, thus its action requires high plasma concentrations that may be well above those seen *in vivo* [81] and such plasma caffeine levels would result in positive drug testing [81]. In addition, phosphodiesterase inhibitors are behavioral depressants and caffeine is considered a behavioral stimulant [91]. Thus, caffeine's ability to inhibit phosphodiesterase may play a minor, if any, role on exercise performance enhancement.

Adenosine Receptors

There have been a few reviews on the effects of caffeine on adenosine receptors [79, 83]. Briefly, adenosine is a purine hormone that acts on different receptors, causing an increase or decrease in cellular concentrations of cyclic AMP (cAMP) [79]. At present, there are four adenosine receptors that have been identified: A_1, A_{2a}, A_{2b}, and A_3 [83]. However, it appears that caffeine has little, if any, effect on A_{2b} and A_3 receptors [83]. Activation of A_1 receptors inhibit lipolysis, activate potassium channels, slow atrial-

ventricular nodal conduction, and inhibit basal and evoked neuronal firing. On the other hand, activation of A_{2a} receptors causes cerebral and peripheral vasodilation, inhibits inflammation, and stimulates dopamine release in the striatum [92]. Benowitz et al. stated that "Adenosine acts presynaptically inhibiting the release of acetylcholine, norepinephrine, dopamine, and serotonin; adenosine reduces spontaneous firing of neurons in many areas of the brain, and produces sedation" [79]. Adenosine stimulation of K^+ channels increases the rate of reversal of action potentials. Through hyperpolarization, adenosine causes a reduction in excitability as well as inhibition of Ca^{++} channels [81], which would result in less motor unit activation and/or less force production per motor unit.

It has been shown that caffeine is a non-selective, weak adenosine receptor antagonist. At pharmacologically active doses of 5-10 μM, which are similar to doses found in moderate caffeine consumption [93], caffeine will partially block the functions of adenosine. Sattin et al. first discovered that theophylline reduced accumulation of cAMP, instead of increasing levels, suggesting that theophylline could block stimulation of cAMP formation by endogenous adenosine [94]. Harland suggested that chronic ingestion of caffeine may stimulate the synthesis of adenosine receptors, which could explain the increased tolerance over time to increased doses of caffeine [78]. This effect seems to be due to blockade of a down-regulation induced by the endogenous agonist [83]. However, there seems to be some controversy [95]. At present, antagonism of adenosine seems to be the only molecular mechanism of possible importance because of the low caffeine doses required for action.

Metabolic

Fat Oxidation/Glycogen Sparing

It has been suggested that caffeine enhances performance due to an elevation in fat oxidation [20]. However, there is significant debate and controversy in the literature surrounding the validity of this theory. The metabolic model predicts that caffeine causes an increase in plasma FFA resulting in an increase in fat metabolism. As a result, there is a decrease in muscle glycogen utilization causing a "sparing effect". Evidence of such an effect is seen by a reduction in RER and an increase in plasma FFA during exercise [85] by participants utilizing caffeine. However, Graham's review of this topic reveals a serious lack of support for this postulate [24].

Spriet [85] also presented several areas of concern with the glycogen sparing theory. First, the predictions of muscle fat oxidation from venous FFA changes are tenuous because FFA turnover is high and the lack of changes in venous FFA may not rule out an increase in FFA turnover. Second, subject variability makes it difficult to find statistical significance, but even small changes may be physiologically important. Third, the estimation of whole-body fat oxidation from RER measurement may be of concern because the increases in fat oxidation and the decreases in carbohydrate oxidation may be below the sensitivity of RER measurement. Fourth, the assumption that a lower RER should exist at all times during exercise for an effect to exist. In agreement, Spriet et al. showed that increases in fatty acid metabolism due to caffeine ingestion during endurance performance are short, occurring only in the first 15 minutes of exercise [96], which could explain why RER is not different throughout the entire exercise session.

There have been studies showing an increase in FFA due to caffeine ingestion [21, 97-99]. Tarnopolsky et al. had six trained subjects run 90 minutes at 70% of VO_{2max} after ingestion of either caffeine (6 $mg \cdot kg^{-1}$) or placebo. They found a significantly higher plasma FFA concentration throughout the protocol after caffeine ingestion as compared to placebo [99]. Similarly, Trice et al. found higher plasma FFA concentration after caffeine ingestion during intermittent cycling [97]. On the other hand, there are several studies that failed to show an increase in plasma FFA after caffeine ingestion [23, 100-102]. Bell examined the effect of caffeine ingestion on FFA metabolism. In the first study, the subjects ingested 5 $mg \cdot kg^{-1}$ of either caffeine or placebo 1, 3, and 6 hours prior to cycling to exhaustion at 80% of VO_{2max}. The authors found no difference among trials or between caffeine and placebo for plasma FFA [23]. In the second study [100], the authors had a similar exercise protocol, but subjects exercised twice on the same day. There were a total of four testing days during which participants received one of the following: A) caffeine in the morning and afternoon; B) placebo in the morning and afternoon; C) caffeine in the morning and placebo in the afternoon; D) placebo in the morning and caffeine in the afternoon. The authors found no differences between caffeine and placebo on plasma FFA prior to and during exercise in any of the trials [100]. It should be noted that all of these studies cited above found an improvement in performance due to caffeine ingestion. Graham [24] speculated that if caffeine does indeed enhance lipolysis, the elevation of free fatty acids (FFA) results in an increase in hepatic uptake of FFAs with the excess forming ketone bodies, which are cleared by several tissues. This could then result in similar values of plasma FFA despite an increase

in lipolysis. For this reason, Graham also suggested that researchers need to find another explanation for the ergogenic effects of caffeine.

Research evaluating blood glucose and lactate, have also contributed to the controversy, since it is assumed that changes in FFA utilization are proportionally followed by changes in carbohydrate utilization. Several studies have shown that caffeine causes an increase in blood glucose [103-105]. However, some studies have shown no difference [22, 106, 107]. In addition, it seems that during short intense exercise blood lactate is elevated after caffeine consumption [108, 109]. Collomp et al. tested the effect of ingestion of 5 $mg \cdot Kg^{-1}$ BW caffeine on Wingate Test performance [108]. The authors found that both end of exercise lactate and maximal blood lactate concentrations were significantly elevated despite no performance benefit [108]. Graham stated that increases in blood lactate are somewhat surprising considering the supposed impact of caffeine on muscle glycogen utilization [93]. The author also stated that an increase in lactate has been observed more often than an increase in FFA and a decrease in RER suggesting that lactate production may be greater than pyruvate because pyruvate oxidation is suppressed by enhanced fat oxidation. However, the author also states that measurements of acetyl-CoA and citrate do not support such mechanism [24].

Tarnopolsky stated, in 1994, that in every human study that measured muscle glycogen utilization directly during exercise following caffeine ingestion showed a "sparing" effect [86]. However, at the time, there were only three studies that had directly measured muscle glycogen utilization [103-105]. Since that report, two other studies have been conducted [110, 111]. The results showed no difference in glycogen utilization after caffeine ingestion. In the same review, Tarnopolsky also stated that only one study

examined the effect of caffeine on intramuscular triglycerides (IMTG) [103]. The author explained that it is assumed that about 50% of FFA utilized during exercise comes from plasma and the remaining from IMTG [86]. Essig et al. showed an increase in exercise IMTG utilization of 18% with a corresponding increase in plasma FFA concentration [86], supporting the sparing theory. Due to contradictory evidence, it is impossible to make any conclusions at this time as to whether caffeine results in a glycogen sparing effect or not. It seems clear, however, that sparing of glycogen may not be the major mechanism for caffeine's ergogenic effect, since exercise lasting less than 60 minutes is enhanced by caffeine ingestion and in such a short time it is unlikely that muscle glycogen is the limiting factor in performance.

Physiological

Central Nervous System

Caffeine is a well-known stimulant of the central nervous system, increasing motoneuron recruitment and frequency of potentials [84], resulting in increased arousal, vigilance, and reduction of the sensation of fatigue and motor reaction time [112]. Caffeine affects the vagal centers in the medulla, the cortex, and the spinal cord. In athletics, reduction in perception of fatigue may be the most important effect caused by caffeine. Sinclair suggested that this effect would translate into an athlete feeling less tired thereby increasing performance [92]. Tarnopolsky reasoned that reduction in perception of fatigue at a given intensity could arise from a reduction in inputs to the central nervous system or an increase in the threshold for detection [86].

Cardiovascular System

It is believed that caffeine consumption increases HR and blood pressure (BP). The caffeine dose in two cups of coffee (250 mg) results in increased blood pressure and an initial reduction in HR followed by an increase in HR above baseline during rest [113], primarily caused by peripheral vasoconstriction [79]. Sawyer proposed that the actions of caffeine may be dictated by a balance between the direct effect of caffeine in all parts of the circulatory system and the antagonizing effect of caffeine's stimulation on compensatory vagal centers in the medulla [114]. For example, caffeine tends to increase BP due to stimulation of the myocardium, but it tends to decrease BP due to an increase in peripheral blood vessel dilation [114].

Most studies testing the effects of caffeine on HR during exercise found no difference between caffeine and placebo [97, 100, 115]. Costill et al. were the first to examine the effect of caffeine ingestion on endurance performance [20]. Participants exercised until exhaustion on a cycle ergometer at 80% of VO_{2max} after ingestion of either caffeine or decaffeinated coffee. The authors found that there was no difference between treatments on HR at any point during exercise [20]. In agreement, Trice et al. reported the effect of caffeine ingestion on intermittent high-intensity exercise [97]. Subjects exercised intermittently, alternating 1 minute of cycling at 90% of maximal workload accomplished during maximal testing and 1 minute of resting. Results showed that HR was not different between treatments. Thus, it seems that caffeine may influence HR and BP during passive recovery, but not during exercise.

Daly et al. suggested that caffeine stimulates the cardiovascular system, which is accompanied by an increase in coronary blood flow, and that adenosine depresses the

cardiovascular system while increasing coronary blood flow [81]. Thus, it appears that the cardiovascular effects of caffeine are not due to a blockade of adenosine receptors. The exact mechanism by which caffeine stimulates cardiac function remains unclear.

Renal System

It has been suggested that caffeine affects renal function by increasing diuresis through increases in renal blood flow and stimulation of renin release [116]. Benowitz suggested that caffeine increases renal excretion of sodium and water by increasing glomerular filtration and inhibiting tubular reabsorption [79]. Armstrong suggested that when low doses of caffeine (114-249 mg of caffeine) were consumed, urine volume changes ranged from -8 to +14% and when the doses were greater than 250 mg, urine volume output increased from 4-35%. This diuretic effect caused by caffeine has been linked to inhibition of adenosine receptors [81]. However, Armstrong also stated that all the studies measured urine output for less than 6 hours [117]. A recent study showed that 11 days of caffeine consumption at various doses had no effect on sodium, potassium and water excretion in healthy, active males [19]. Perhaps a higher dose is necessary for these effects to be seen or the possibility remains that caffeine does not result in a long-term increase in urine volume excretion.

Ergogenic Aid

Even though caffeine has been part of daily life for centuries, it was not until 1978 that caffeine received attention as an ergogenic aid for endurance sports [20]. Wilcox published in 1990 the first review of literature examining the possible ergogenic effects of caffeine ingestion prior to exercise [118]. The author concluded that there was insufficient evidence to support caffeine as an ergogenic aid. Wilcox also stated that

caffeine did not seem to jeopardize performance either [118]. Since then there have been several reviews on the effects of caffeine on endurance and performance [24, 78, 82, 84-86, 92, 93, 117, 119]. Exercise mode can be qualified in several different ways, but in this review, exercise will be divided into continuous, high intensity/incremental, and intermittent. The effects of caffeine on RPE, thermal sensation, reaction time will also be discussed.

Exercise Mode

Continuous

Tarnopolsky suggested a number of factors that are necessary requisites to make generalizations of the results pertaining to the ergogenic effect of caffeine on exercise performance [86]. First, the population needs to be athletic and extrapolations should be made under sport-specific conditions (i.e. running vs cycling). In addition, the testing variables must be a true measure of performance (i.e. open-ended test to exhaustion, test for a given time with maximal effort, or a field test). Second, sample size must be large enough, randomized, counterbalanced and double-blind. Graham also suggested that caution should be used when referring to performance to describe an increase in endurance [93], since for coaches and athletes performance would describe movement velocity, that is, how fast one can move a given distance and not how long an athlete can run until reaching exhaustion. Upon extensive examination of the pertinent literature, there is no doubt that caffeine improves endurance when ingested prior to exercise [82, 84-86, 92, 93, 117, 119].

Most of the studies done on the effect of caffeine ingestion on exercise performance have been performed on either cycling or running. Researchers have either

measured maintenance of a set work load (time to exhaustion) or time to completion of a set work output (time trial). There are only two studies conducted testing the effects of caffeine ingestion during competition [120, 121]. Berglund et al. had well-trained cross-country skiers perform four races (two at 2900 meters of altitude and two at 300 meters of altitude) after ingestion of 6 $mg \cdot kg^{-1}$ BW of either caffeine or placebo [120]. The authors found that caffeine improved performance regardless of the altitude. Similarly, Bridge et al. had trained male distance runners perform three 8 km races after ingestion of 3 $mg \cdot kg^{-1}$ of caffeine or placebo after a control trial [121]. They found that caffeine significantly improved performance by 23.8 seconds, which corresponded to 1.2%. Although there are a few studies conducted testing the effects of caffeine during endurance competition, the existing evidence suggests that caffeine improves performance in an applied setting. Thus, caffeine seems to not only improve exercise endurance, but also performance during competition.

High Intensity/Incremental

Incremental exercise tests to exhaustion usually last a few minutes and end with the subject's volitional exhaustion. Because caffeine seems to reduce the perception of effort [23], it is feasible that caffeine could increase time to exhaustion. A closer analysis of the literature imposes two challenges: discrepancy on the definition of high intensity exercise and disagreement as to whether caffeine does or does not enhance high intensity/incremental exercise. Armstrong defined high intensity exercise as 8-22 minutes to exhaustion [117], but Paluska defined it as 1-10 minutes to exhaustion [119]. For this review, high intensity exercise will be defined as exercise in which fatigue results from accumulation (e.g. lactic acid) rather than depletion (e.g. muscle glycogen). Some studies

report that caffeine enhances performance [85, 119], whereas others do not [82, 86, 117]. Graham argued that discrepancy in results may be due to the fact that a 10% improvement may not be statistically significant, but may be highly significant in competition [93].

When performance is measured by time to completion of a certain distance during high intensity exercise, caffeine seems to enhance performance regardless of the mode of exercise. Collomp et al. tested the effects of caffeine ingestion (250 mg) on swimming sprint performance in trained and untrained swimmers [109]. Participants performed two 100 m sprints separated by 20 minutes of passive recovery on two separate occasions. The results showed that caffeine ingestion significantly improved sprint performance in trained subjects and prevented a drop in performance on the second sprint, but not in the untrained group [109].

Caffeine does not seem to enhance anaerobic maximal performance [82, 117, 118]. Indeed, there have been several studies that tested the effect of caffeine on Wingate performance. Collomp et al. had participants perform one Wingate test after ingestion of 5 $mg \cdot kg^{-1}$ BW of caffeine or placebo [108]. The authors found no differences in anaerobic power (the peak power performed during any five second period), anaerobic capacity (the total work performed during the entire 30 second period), and power decrement (the difference between peak power and the lowest power calculated for each five second period) between treatments. Greer et. al. tested the effects of caffeine on repeated Wingate tests [122]. Participants ingested 6 $mg \cdot kg^{-1}$ BW one hour before performing four Wingate tests separated by four minutes of passive rest. The authors also found no

difference in anaerobic power, anaerobic capacity, power decrement, and total power output accomplished throughout all four tests.

On the other hand, during graded exercise, there is some controversy regarding the ergogenic effects of caffeine. When VO_{2max} is measured, caffeine does not seem to enhance oxygen utilization [115, 123]. However, when time to exhaustion or total work accomplished is measured, some studies show an improvement [106, 124] while others do not [115]. For example, Flinn et al. showed that time to exhaustion and work output were significantly affected by 10 $mg \cdot kg^{-1}$ BW of caffeine during VO_{2peak} test on a cycle ergometer [106], while Powers et al. showed no difference in time to exhaustion during VO_{2peak} test with a dose of 5 $mg \cdot kg^{-1}$ BW [115]. The difference in doses used may explain the discrepancy in the results. Besides, 10 $mg \cdot kg^{-1}$ BW may be too high and result in positive drug testing. Therefore, it is difficult to make any conclusions regarding the effects of caffeine ingestion on graded maximal exercise, as more research is needed in this area.

Finally, one study showed an ergogenic effect at supramaximal intensity. Doherty showed that a dose of 5 $mg \cdot kg^{-1}$ BW enhanced running at 125% VO_{2max} by significantly increasing maximal accumulated oxygen deficit (MAOD) and also time to exhaustion [125]. However, more research may be necessary for conclusions to be drawn.

Intermittent

There has not been much interest in the effects of caffeine on intermittent types of exercise. In addition, some of the research examining the effects of caffeine on intermittent exercise may not be applicable to any major sport (i.e. basketball, football, tennis, soccer) because of methodology. For example, Greer et al. had nine males

perform four Wingates with four minutes rest between bouts. They found that caffeine had no effect in peak power, average power, and rate of power loss on Wingate tests 1 and 2, and that caffeine had a negative effect on peak power on Wingate tests 3 and 4. However, this protocol does not simulate any major sport, thus its applicability may be questionable.

When submaximal intensity was tested, caffeine had positive effects on intermittent performance [97, 100, 111, 124, 126]. Stuart et al. tested the effect of caffeine on simulated rugby playing. They tested 11 male high level amateur rugby players on a series of skills and physical performance [126]. Caffeine showed an ergogenic effect in almost all measurements, but the most notable was a 10% improvement in pass accuracy under simulated game conditions. The authors attributed caffeine's effects to its ability to influence the central nervous system to reduce fatigue [126]. This appears to be the first study to examine the effects of caffeine on skill performance, more precisely accuracy.

Two studies performed on the cycle ergometer may have implications for the sport of tennis [97, 124]. Trice et al. investigated the influence of caffeine ingestion on intermittent cycling [97]. The author had eight trained rugby players perform three 30 minute intermittent cycling protocols, where participants pedaled at 85-90% VO_{2max} maintaining 70 rpm. Participants alternated 1 minute pedaling and 1 minute rest, with 5 minutes rest between each 30 minute block until completion of all three blocks or to exhaustion, which was defined as the inability to maintain 70 rpm for 15 seconds consecutively. The results showed that ingestion of 5 $mg \cdot kg^{-1}$ BW increased time to exhaustion by 16 minutes (29%) compared to placebo. Total time to exhaustion was 77.5

± 5.3 min for caffeine and 61.3 ± 2.2 min for placebo. The average tennis match lasts 90 minutes [12]. Even though work time was longer than work times found in tennis, which has been found to average 5 seconds [2], the intermittent nature of the study and the total time to exhaustion may allow comparisons to be made with tennis playing.

Another study showed that 250 mg of caffeine improved power output in intermittent cycling [124]. Anselme et al. had 14 subjects (10 males and four females) perform 6 second maximal sprints with increasing load and a 5 minute rest between sprints. The load was increased after each sprint by 2, 1, or 0.5 kg to obtain the measurement that would be as precise as possible until maximal anaerobic power was attained. The authors found that caffeine caused an increase in maximal power output, but had no effect on workload. Results were attributed to an increase in pedaling frequency [124]. Although total time to exhaustion was not reported, it is possible to compare time under stress with tennis playing, since each sprint was 6 seconds long and the average tennis point lasts 8 seconds. Because both of these studies showed an ergogenic effect after caffeine ingestion, it is plausible to believe that tennis performance may be influenced by caffeine ingestion due to the similarity of the characteristics of the testing protocols to tennis playing.

Rating of Perceived Exertion

Tarnopolsky suggested that fatigue is a multifactorial process that is influenced by numerous variables, which makes quantification of fatigue difficult [86]. Subjective quantification of fatigue may be possible through Borg's Rating of Perceived Exertion (RPE) [127]. RPE is measured on a scale created to subjectively quantify exercise intensity associated to participants' HR. The scale ranges from 6 to 20 to mimic the range

of heart rate, which would be approximately 60 at rest and 200 at maximal exercise. It has been shown that Borg's RPE scale is reliable and valid for subjectively quantifying exercise intensity [127]. The subject is shown a board during the exercise session at which time he or she will assign a number to how hard he or she perceives the exercise session to be [127].

There is some debate as to whether caffeine has any effect on reductions of the rating of perceived exertion (RPE) during exercise. It has been suggested that such effects would translate into athletes feeling less tired, enabling an increased performance [92]. There is evidence that moderate doses of caffeine reduce perception of stress during exercise, resulting in lower RPE [20, 23, 128-131]. However, there is some evidence that caffeine may not have any effect on subjects' perceptions of how hard they are working [97, 99, 102, 120, 121, 132-135]. Doherty et al. performed a meta-analysis on the effect of caffeine on RPE that included 21 studies [125]. They found that caffeine was responsible for a 6% reduction in RPE compared to placebo. The authors also stated that RPE could explain nearly one-third of the variation in improvements in performance [125]. Closer analysis of the data presents several challenges to the interpretation of the influence of caffeine on RPE.

First, many studies have a small sample size, so even if there is a difference, it is difficult to find statistical significance. For example, Trice et al. found that ingestion of 5 $mg \cdot kg^{-1}$ BW of caffeine during intermittent cycling resulted in a full point difference in RPE between caffeine and placebo [97], but because sample size was only eight, they did not find statistical significance. On the other hand, Bell et al. found a significant

difference in RPE with a smaller difference between caffeine and placebo [23], since their sample size was 21.

Second, the method utilized to record RPE during exercise may have an influence as well. Some studies [23, 120, 129], have used Borg's Rating of Perceived Exertion chart which ranges from 6 to 20 [127]. In contrast, others have used charts with five numbers [135], which may not have enough sensitivity to detect changes in subjective ratings during exercise. Finally, other studies have employed 20-number charts, which may inflate sensitivity due to wider range of values [133]. Therefore, it is important to standardize methodology before comparisons are made.

Third, because RPE is subjective, a participant's experience and understanding of RPE charts makes comparison between studies difficult. For example, Erickson found that during 90 minutes of cycling at 90% of VO_{2max}, caffeine caused a significant reduction in RPE at the beginning of exercise when subjects were rested, but not at later times, and only when the caffeine was ingested in combination with fructose [132]. Also, Giles et al. found that during 120 minutes of treadmill running at 65% VO_{2max}, caffeine significantly reduced RPE when ingested with placebo, but not with glucose [130]. Interestingly, though, the results also showed that glucose ingested with placebo resulted in significant elevations of RPE at 15 minutes (group average 13.7), but decreased at 30 minutes (13.0) and 45 minutes (12.0), and remained lower than at 15 minutes for the remainder of the testing protocol. It is difficult to believe that as time elapsed, the exercise session became easier and participants perceived the exercise session as less and less stressful.

Finally, exercise protocol may also have some influence on RPE results. During exercise sessions that are performance related (i.e. time trials, simulated races, time to accomplish a set work output), RPE seems to be altered in the form of either a direct reduction in RPE or a similar RPE to accomplish greater work output or faster time. Cole et al. performed an interesting study in which the author had 10 healthy males complete six 30-minute exercise bouts on a cycle ergometer [129]. Participants were required to cycle at 80 rpm, maintaining what they perceived to be a RPE rating of 9 for the first 10 minutes, 12 for the next 10 minutes, and 15 for the final 10 minutes on the original Borg scale. Accumulated work output accomplished after each 10 minute section was recorded and used for analysis. The authors found that mean total work output during the caffeine trial was significantly higher than placebo, even though the perceived effort was the same [129]. In agreement with the previous study, Berglund et al. found that ingestion of caffeine 1 hour prior to a cross-country ski race improved completion time without any effect on RPE [120]. The author suggested that athletes were able to choose a faster speed to match perceived effort.

On the other hand, when the trial is endurance related (a set time of exercise or testing is to be to exhaustion), caffeine does not seem to influence RPE. Titlow failed to show any difference in RPE between caffeine and placebo during 60 minutes of treadmill exercise at 60% VO_{2max} [102]. In agreement, Casal et al. also failed to show any difference in RPE during 45 minutes of treadmill running at 75% of VO_{2max} between caffeine and placebo [128]. Doherty suggested that the effort sensed and the fatigue experienced at the end of such exercises are the same [125]. The author also mentioned that exercise will be terminated at physiological limits (maximal oxygen consumption or

maximal heart rate) and these parameters are not affected by caffeine [125]. Thus, there is no reason to expect RPE to be influenced by caffeine in such protocols.

In conclusion, caffeine does seem to improve performance due to a reduction in perceived effort, even though it may not appear in the form of significant reduction in RPE ratings.

Thermal Sensation

Even though there is debate on caffeine's potential diuretic effect and ability to cause dehydration, if such factors are true, then one may wonder what effect caffeine would have on thermoregulation and thermal stress during exercise. Three studies have been published looking at the effects of caffeine on thermoregulation [136-138]. All three studies showed a tendency for an elevated rectal temperature, but all three failed to find statistical significance. However, McLean et al. found significant differences in skin temperature for men and eumenorrheic women following caffeine ingestion [136]. The authors had participants cycle for 90 minutes at 65% of VO_{2max}. However, thermal stress was achieved by clothing additions and not elevated temperature (temperature was kept constant at 21°C). In fact, the average ambient temperature in these three studies was 24.6 °C and humidity 45%. Surprisingly, though, no studies measured participant's thermal sensation during exercise. Thermal sensation is a subjective way to measure the perception of heat stress. Therefore, it is impossible to draw any conclusions about the effects of caffeine in the subjective perception of thermal stress due to lack of scientific measurements, raising the need for investigation.

Reaction Time

Reaction time is defined as the time interval between the presentation of a stimulus and the initiation of movement. There are three main types of reaction time: 1) simple reaction time, where there is one stimulus and one response; 2) choice reaction time, where there are at least 2 possible stimuli and at least 2 possible responses, and 3) discrimination reaction time, where there are several stimuli, but only one would require a response [139]. Variables that influence reaction time include stimulus intensity, the amount of information in the stimulus, the number of choices that have to be made, and the modality [140]. It has also been suggested that the average reaction time to a visual stimulus is 180 msec, auditory stimulus is 160 msec, and tactile stimulus is 140 msec [140].

It is believed that caffeine may enhance reaction time. However, the general agreement is that of an inverted U-shaped curve for caffeine's effect on reaction time performance, with doses greater than 500 mg causing a decrease in performance due to an increase in anxiety and tension [141]. Rutledge suggested that the inverted U-shape is due to an increase in sensory motor irritability on one end and an increase in skeletal muscle excitability on the other end [142]. In fact, there are several studies supporting this theory [143-146]. Lieberman et al. tested the effects of several different doses of caffeine ingestion (32, 64, 128, and 256 mg) in a four-choice reaction time test [146]. Subjects were presented with a series of visual stimuli on a computer monitor and asked to strike one of four adjacent keys on a microcomputer keyboard. The authors found that even low doses (32 mg of caffeine) resulted in a reduced reaction time compared to placebo [146]. Similarly, Jacobson et al. tested the effects of either 300 mg or 600 mg of

caffeine on simple reaction time [143]. They found that at 300 mg, reaction time was significantly improved, but no changed occurred with 600 mg. Thus, it seems that daily doses of caffeine can improve reaction time.

Ingestion Timing

Most of the studies performed on caffeine had the subjects ingest caffeine 1 hour prior to exercise performance. The main reason behind this timing is that it takes between 45 and 60 minutes for peak caffeine levels to be seen in the blood [80, 113]. Sinclair suggested in his review that athletes should ingest caffeine 3 hours prior to exercise instead of 1 hour to allow peak plasma FFA to be reached [92]. However, there is some debate as to whether peak plasma FFA is responsible for the caffeine's ergogenic effects (see preceding section on Fat Oxidation/Glycogen Sparing), thus there may be no need to wait such a long period of time.

Bell et al. [23] showed that 5 $mg \cdot kg^{-1}$ BW of caffeine ingested up to 6 hours prior to performance showed an ergogenic effect in naïve caffeine users. However, habituated caffeine users showed ergogenic effects only after 1 and 3 hours [23]. Bell et al. also tested the effect of 5 $mg \cdot kg^{-1}$ BW of caffeine ingested one hour prior to exhaustive exercise in the morning and re-dosed with 2.5 $mg \cdot kg^{-1}$ BW one hour prior to exhaustive exercise in the afternoon [100]. They found that caffeine significantly improved time to exhaustion compared to placebo, but there was no difference between a single dose and repeated doses on time to exhaustion. The results also showed that a single caffeine dose in the morning was sufficient to maintain caffeine's ergogenic effects in the afternoon exercise bout, even in habituated caffeine consumers [100]. This suggests that peak plasma concentration may not be required for caffeine's ergogenic effects.

Other authors have tested the effects of multiple doses of caffeine on exercise performance. Cox et al. tested a single dose of caffeine of 6 $mg \cdot kg^{-1}$ BW versus 6 x 1 $mg \cdot kg^{-1}$ BW taken every 20 minutes during exercise [147]. The authors found that both treatments improved performance compared to placebo, but there was no difference between treatments. Similarly, Conway et al. tested one single dose of caffeine of 6 $mg \cdot kg^{-1}$ BW vs. 2 x 3 $mg \cdot kg^{-1}$ BW, with the second dose taken half way into the exercise session [148]. Although they did not find statistical significance due to a small sample size, there was a trend for reduced time to completion of a set work output compared to placebo. Thus, timing of ingestion may not be a major issue, but more research should be conducted with varied ingestion timing. It is worthy to note that Conway found that post-exercise urine caffeine concentration was substantially lower when dose was divided [148]. The authors suggested that this effect might present a loophole to athletes and add to difficulty to accurately determine an athlete's caffeine intake. However, doses ranging between 3 $mg \cdot kg^{-1}$ BW and to 9 $mg \cdot kg^{-1}$ BW produce urine caffeine concentrations well below IOC and NCAA doping levels. Also, caffeine's ergogenic effect does not seem to be dose related (see section below), and redosing does not seem necessary for performance improvements, thus, there may not be any benefit in taking higher doses divided into 2 or more boluses.

Dosage

Graham suggested that the ergogenic effects of caffeine ingestion do not seem to be dose related [24], and that caffeine doses ranging from 3 $mg \cdot kg^{-1}$ BW to 9 $mg \cdot kg^{-1}$ BW showed performance improvements. One study, however, showed ergogenic effects with a dose below 3 $mg \cdot kg^{-1}$ BW [104]. Kovacs et al. had subjects ingest either 150 mg (2.1

$mg \cdot kg^{-1}$), 225 mg (3.2 $mg \cdot kg^{-1}$), or 320 mg (4.5 $mg \cdot kg^{-1}$) of caffeine prior to cycling. They found that all caffeine trials resulted in a significant improvement in performance, but the doses of 225 mg and 320 mg caused significantly more improvement than the 150 mg [104]. These results suggest that a lower dose of caffeine (2.1 mg/kg of BW) may improve performance, but such a dose is not as effective as a higher dose such as 3 mg/kg of BW.

There have been a few studies examining the effect of different doses of caffeine ingestion on performance [101, 123, 147]. Graham et. al. compared three different doses: 3, 6, and 9 $mg \cdot kg^{-1}$ BW on time to exhaustion in subjects running at 85% VO_{2max} [101]. They found that 3 and 6 $mg \cdot kg^{-1}$ BW improved time to exhaustion compared to placebo, but there was no difference between treatments. However, the highest dose of 9 $mg \cdot kg^{-1}$ BW did not show any ergogenic effect. The authors attributed the inconsistency to an increase in side effects [101]. Similarly, Spriet suggested that doses ranging from 3 to 6 $mg \cdot kg^{-1}$ BW are safer because they produce less side effects [85]. On the other hand, Pasman et al. compared doses that ranged from 5 to 13 $mg \cdot kg^{-1}$ BW. They found that all caffeine treatments resulted in an improvement in performance, but there was no difference between treatments [149]. Thus, the ergogenic effect of caffeine ingestion on endurance exercise does not seem to be dose related.

One study tested the effect of different doses of caffeine on graded exercise performance. Dodd et al. compared 3 and 5 $mg \cdot kg^{-1}$ BW caffeine dosages on graded exercise [123], also examining the effect of caffeine habituation. They found that VO_{2max} was significantly increased for naïve participants, but not for habituated caffeine consumers when compared to placebo. However, there was no difference between doses

[123]. This is the only study examining different doses and caffeine consumption characteristics on graded exercise. Thus, at this time it is impossible to make any inferences about the effects of different doses on maximal graded exercise.

Safe caffeine consumption in athletics is defined as doses that produce urine caffeine concentrations below what is considered doping by the IOC (12 $\mu g \cdot ml^{-1}$) and the NCAA (15$\mu g \cdot ml^{-1}$) [24]. Wilcox suggested that normal caffeine consumption (2-4 cups of coffee) is not likely to result in urinary levels above the threshold for doping [118]. It also has been suggested that caffeine doses must be above 897 mg (8 cups of coffee) to reach doping levels [84]. Spriet stated that if an athlete has a urinary caffeine concentration above 12 $\mu g \cdot ml^{-1}$, then the athlete is deliberately taking caffeine in an attempt to improve performance [85]. However, it has also been shown that urine caffeine levels are highly variable. Robertson et. al. showed that interindividual differences in peak levels ranged from 4.2 to 26 $\mu g \cdot ml^{-1}$ after ingestion of 250 mg, which corresponded to a sixfold variation [113]. Therefore, the reliability of such measures seems questionable. Besides, caffeine measurements are performed on the unmetabolized caffeine excreted in the urine, which corresponds to only three percent of the total caffeine ingested [148]. Thus, it not only requires a very high dose of caffeine to be ingested for urine concentrations to surpass the IOC threshold, but also measurements are performed over a very small amount of the unmetabolized caffeine, which may not provide accurate information about the caffeine ingestion habits of the subjects.

Hydration

It has been believed for years that caffeine causes dehydration due to its diuretic effect, increasing urine production and excretion, which could lead to fluid and

electrolyte losses and decreases in plasma volume [24]. However, recent research has not supported this theory. Some authors have concluded that caffeine is a diuretic at rest after acute ingestion only [86, 92]. Robertson et al. tested the effects of caffeine ingestion (250 mg) on urine production during 5 hours of passive recovery [113]. The authors showed a 29% increase in urine production, which reached statistical significance. Similarly, Wemple et al. showed a significant increase in urine excretion after caffeine ingestion during 3 hours of passive recovery [18], but the difference disappeared during exercise. However, Armstrong et al. tested the effect of chronic caffeine consumption on a variety of hydration parameters [19]. The authors found that body mass, urine osmolality, urine specific gravity, urine color, and 24-h urine volume were unaffected by different doses of caffeine ingestion.

There are a few other recent studies demonstrating that caffeine does not seem to affect hydration during exercise [24, 85, 117, 119]. Graham et al. had participants run to exhaustion at 85% VO_{2max} after ingestion of 4.45 $mg \cdot kg^{-1}$ BW of caffeine [150]. The participants performed 5 trials: placebo, decaffeinated coffee, decaffeinated coffee with caffeine, regular coffee, and water with caffeine. The investigators found that even though urine production was significantly lower after exercise than before, there was no difference between treatments [150]. Conway et al. tested the effects of a single dose versus divided doses on urine production [148]. They found that there was no difference in urine production between treatments. It has been suggested that caffeine's diuretic effect may be blunted by an increase in catecholamine release reducing renal blood flow and enhancing renal solute reabsorption and water conservation due to osmotic pressure [151].

A few studies have measured the effect of caffeine ingestion on plasma volume changes, sweat rates, and body weight changes during rest and exercise [18, 104, 137]. However, they all failed to find statistical significance in these parameters. Gordon et al. showed that consumption of 5 $mg \cdot kg^{-1}$ BW of caffeine had no effect on sweat rates, plasma volume changes, and body weight changes after 2 hours of running (intensity not specified) [137]. Armstrong further suggested that water and fluid-electrolyte replacement beverages have similar diuretic potential if ingested in excess [117]. The author in his review concluded that: a) daily caffeine intake below 300 mg induces diuresis similar to water; b) water retention with caffeinated beverages was similar to water, with the highest values being 84% for caffeine compared to 81% for water c) consumption of 250-379 mg of caffeine during rehydration may paradoxically result in smaller Na^+ and K^+ losses than water [117]. Therefore, there is no reason to believe that caffeine has any negative effects on hydration that would result in a decrement in performance.

CHAPTER III. METHODS

The purpose of this investigation was to determine the effect of pre-match consumption of a caffeinated carbonated soft drink on tennis performance and hydration status before and during simulated tennis match play.

Subjects

Ten male tennis players between the ages of 19-35 participated in this study. All participants met the criteria required for participation in this study, which was: 1) United States Tennis Association (USTA) rank between 4.5 and 7.0; 2) Playing frequency of at least 60 minutes twice a week; 3) Healthy and injury free as assessed by the Physical Activity and Readiness Questionnaire (PAR-Q); 4) Signed University Human Subjects approved informed consent; 5) Daily caffeine intake below 400 $mg \cdot day^{-1}$. It has been suggested that caffeine habituation is not a factor if daily ingestion does not exceed 400 mg [93]. Dietary recall provided an estimate of actual caffeine intake based on a 3-day log notation.

Design

This investigation used a crossover, double-blind design in which participants received either caffeine or placebo (cooking flour) in a gel capsule 90 minutes prior to simulated tennis match play. To complete all testing procedures, the participants were required to visit the lab on four different occasions. On the first visit

subjects received and signed the University Human Subjects approved informed consent, and answered a medical screening (PAR-Q) questionnaire. Participants who met the study requirements were given the diet recall forms and invited back for the remainder of the study. Figure 2 shows the overall research design. Three-day dietary recall forms were used to monitor daily caffeine intake. For analysis, a computer based program (Food Processor: Nutrition and Fitness Software Version 9.8, Esha Research, Salem, OR) was used to determine daily caffeine intake and diet patterns.

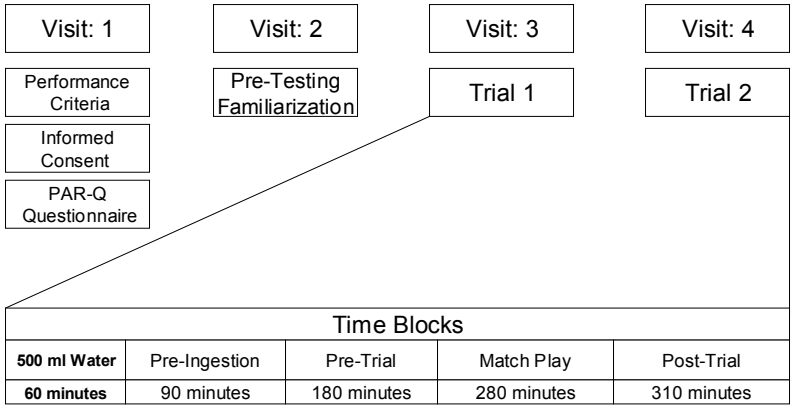

Figure 2. Project Design. Also shown are daily activities of all 4 testing days.

On the second visit to the lab body composition was determined. Treadmill VO_{2max} and the Shuttle Fitness Test also were performed. Body composition was assessed using a skinfold caliper (Lange Skinfold Caliper). Three sites were measured: chest, suprailliac, and thigh. Skinfold measurements were performed in duplicate and

when the difference in skin thickness was greater than 2.0 mm a third measurement was performed. The two closest measurements were then averaged and used for calculation using the three site formula according to the Siri Equation [152]. Skinfolds measurements were performed by trained personnel. VO_{2max} was measured using an incremental speed and grade treadmill test. Participants ran at three different speeds for 5, 3, and 3 minutes at which time the treadmill was elevated 2% every minute until volitional fatigue. For O_2 and CO_2 gas analysis, expired air was collected and analyzed using a Parvo Gas Analysis System (Salt Lake City, UT). VO_{2max} was verified by achievement of at least three of the following criteria: volitional exhaustion, RER value above 1.10, plateau on VO_2 with increased work rate, and HR no less than 10 beats per minute below estimated HR_{max} (220-age). The Shuttle Fitness Test (SFT) (Multistage Fitness Test, Loubourough University and Sports Coach, England) was also performed to estimate VO_{2max} and to assess decrements in endurance performance after simulated tennis match play. The interval between tests was approximately 30 minutes. SFT consisted of a progressive shuttle run in which subjects had to follow a pre-set pace that was marked by a sound along a 20 meter track. Participants were required to run back and forth, while covering the 20 meters between sounds, until they could no longer keep up with the set pace. The interval between sounds decreased after each minute causing the running speed to increase. The test was terminated when participants missed the line (touched the line after the sound) twice in a row. VO_{2max} was determined from the SFT chart that equates the VO_2 cost associated with the work rate as determined by stage and level.

On the same day, participants were familiarized with the tennis skill test and visual and auditory reaction time testing procedures. Subjects were then instructed to

avoid caffeinated products and alcohol 24 hours before each trial and to avoid strenuous physical activity 48 hours prior to each trial. They were also asked to maintain similar diets 24 hours before each trial. At this time they were also given two 500 ml water bottles and were instructed to consume one bottle 60 minutes prior to reporting to the lab before each trial, as recommended by the American College of Sports Medicine (ACSM) [17].

On visits three and four, the performance trials were conducted. In each trial, participants performed a 90-minute session of simulated tennis match play in response to a ball machine that alternated shots along the baseline (Lobster Tournament Series 401, Toluca Lake, CA) on an outdoor court (WBGT $\geq$ 28°C). Environmental temperatures were matched between trials (WBGT ± 2°C). A ball machine was used for standardization of ball speed and absolute work output so every player would play the same amount of balls in a point, same number of points in a game, and same number of games throughout the protocol. During each trial, participants were provided with 946ml (32 oz) non-caffeinated carbonated soft drink (7 Up, Pepsi-Cola Company) 90 minutes prior to simulated tennis match playing with either 3 $mg \cdot kg^{-1}$ BW of caffeine or placebo in a gel capsule. Participants were also provided with 1200 ml (40.6 oz) of water during the trial in 300 ml increments every 30 minutes. Total fluid consumption during each trial was 2846 ml (approximately 96 oz) over the 5 hour performance test. Physiological measurements and test parameters for this investigation were made at the times specified on the timeline diagram shown in figure 3.

Procedure

On trial days participants arrived at the lab 60 minutes after ingestion of 500 ml of water. Participants were then instructed to provide a pre-ingestion (PRE) urine sample and nude body weight (BW). Nude body weight was measured using a digital scale (GSE Scale Systems, Model 550) set in kilograms (Kg). Urine volume and specific gravity were measured for assessment of hydration status. Urine Specific Gravity (USG) was measured using a urine spectophotometer (American Optical Corporation, Keene, NH). Participants were cleared for initiation of the trial if USG was <1.030 [44]. Figure 3 shows the timeline for the performance trial. At this time participants were also provided with the telemetric HR monitor, which was placed snuggly at the chest line (Xiphoid Process). Next, subjects were asked to sit for 15 minutes prior to the PRE venous blood sample collection.

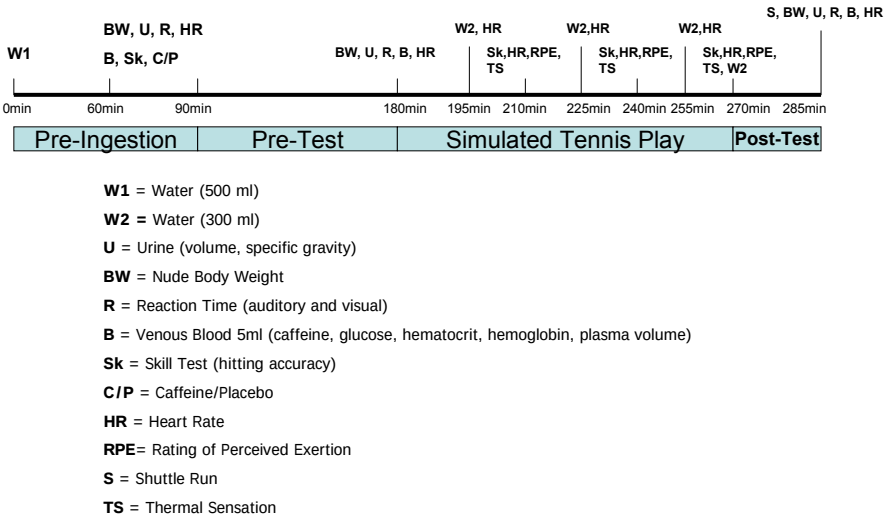

Figure 3. Time line. Protocol was divided into 4 section: Pre-Ingestion (PRE), Pre-Test (PT), Simulated Match Play (SMP), and Post-Test (PO).

During these 15 minutes, PRE auditory and visual reaction time tests were performed. The sequence of these events remained the same throughout the protocol pre-ingestion (PRE), pre-trial (PT), post-trial (PO) and on both trials. Once the first blood sample was collected, participants walked towards the tennis courts (total distance covered was approximately 300 m) where they performed a 5 minute warm up with a hitting partner. Warm up consisted of only ground strokes. Once warmed up, participants performed the PRE skill test on the tennis court. At the completion of the tennis skill test, the subjects received the non-caffeinated carbonated soft drink (7 UP) and a gel capsule containing either 3 $mg \cdot kg^{-1}$ BW of caffeine (USP Anhydrous, Penta Manufacturing) or placebo (baking flour). Participants were instructed to drink the 7 UP and to ingest the capsule. Once the fluid and capsule were ingested, participants walked back to the lab

where they passively recovered for 90 minutes in a neutral environment (20±2°C and 30±2 % humidity).

At completion of the 90 minutes of passive recovery, participants provided PT urine sample, nude BW, auditory and visual reaction time tests and blood sample. After the second blood sample was collected, subjects walked to the tennis courts where they performed a 5-minute warm up including serves to simulate a pre-match warm up followed by 90 minutes of simulated tennis match play using a ball machine. Wilson US Open tennis balls (Wilson Sporting Goods Corporation, Chicago, IL) were used throughout all trials. Simulated tennis match play was comprised of both serving and receiving games. Each game consisted of 10 points and each point consisted of 5 strokes. During serving games participants performed one serve and 4 ground strokes (balls hit at the baseline). During receiving games, participants received 5 ground strokes (the first ground stroke was considered the service return). Between each point subjects were allowed at least 15 seconds, but not more than 25 seconds. Time was called at 15 seconds, at which time players proceeded to the baseline to start the following point. A total of 120 points and 12 games were played. After 10 points participants were allowed a 30 second break to mimic the end of a game, and at the end of two games participants were allowed a 90 second break, which represented the change of sides. During the 90 second break subjects were allowed to passively recover. During the breaks at 15 minutes, 45 minutes, and 75 minutes 300 ml of water were provided. Following the breaks at 30 minutes, 60 minutes, and 90 minutes the tennis skill test was performed. At completion of the simulated tennis match, subjects received an additional 300 ml of water and a 5 minute break. Following the break, subjects were required to perform the PO

SFT. At completion of the SFT, participants walked back to the lab where they provided a PO urine sample, BW, and performed PO auditory and visual reaction time tests and provided a PO venous blood sample.

Measurements

Heart rate (HR) was telemetrically monitored throughout the protocol using a Polar Heart Rate Monitor and recorded for data analysis at PRE (rest), PT at 30 minutes (PT30), 60 minutes (PT60), and 90 minutes (PT90), every 15 minutes during simulated tennis playing (T15, T30, T45, T60, T75, T90), during the PO SFT (PO), and 15 minutes after PO SFT (PO15). HR was also monitored during the VO_{2max} test for determination of HR_{max} and the PT SFT.

Tennis skill performance was performed using a modified Leuven Tennis Performance Test. Different regions of the tennis court were assigned different values, which are consistent with Vergauwen's definition of neutral, defensive, and offensive shots [15]. As previously discussed, Figure 1 (p. 4) shows the tennis court layout. The skill test consisted of 15 consecutive ground strokes in all 4 directions (forehand (FH) cross court (CC), up-the-line (UTL), backhand (BH) cross court, and down-the-line). The ball machine was directed to one of the two corners of the tennis court where the baseline and singles line intersect. Participants were instructed to recover to a pre-determined position on the baseline, which was placed approximately 70 cm from the center mark, after each shot. The interval between shots was approximately 3 seconds. The order of the strokes (FH or BH) and direction (CC or UTL) was randomized between tests and trials. Participants were allowed at least 45 seconds, but not more than 60 seconds rest between each direction. The spot where each ball landed was recorded and the total

amount of points in each direction, total number of unforced errors (shots missed that should not have been missed), and shot index (total number of balls that landed on spots 5 and 6 minus unforced errors) were used for data analysis. Tennis Skill Tests were performed PRE and at T30, T60 minutes and PO.

Visual and auditory reaction times were tested using an Automatic Performance Analyzer (Dekan Timing Devices, West Chicago, IL). Subjects were instructed to release the trigger button upon hearing a sound or seeing a light stimulus. Reaction time to the stimulus was recorded (milliseconds) for all 15 attempts. The first five trials were considered practice trials and the remaining 10 trials were recorded and averaged for subsequent analysis according to Jacobson et al [143]. The delay before the signal was randomized in all attempts and in both trials such that it was impossible for the subjects to anticipate when the signal would be turned on. Sound reaction time was always performed prior to visual reaction time.

Venous blood samples (10 ml) were collected from the antecubital vein of the forearm after 15 minutes of sitting. Blood samples were collected at PRE, PT and PO and used for hematocrit and hemoglobin measurements, which were further used for plasma volume change determination according to Dill and Costill [57]. Hematocrit and hemoglobin were performed in triplicate. Hematocrit was determined using 20 µL capillary tubes, which were centrifuged for 5 minutes. Hemoglobin measurements were performed using a colormetric hemoglobin assay (Waco Chemical USA Incorporation, Richmond, VA). The remaining blood was allowed to clot for 30 minutes, at which time it was centrifuged for 10 minutes for serum separation. Serum was then frozen for later analysis of glucose and caffeine. Serum glucose was determined using an enzymatic

protocol (Raichem Glucose Color Reagent, San Diego, CA) and serum caffeine was determined using HPLC.

Environmental conditions were recorded during simulated tennis playing using Wet Bulb Global Temperature (WBGT) (Quest Technologies, QUESTemp 34), which was placed on the side of the tennis court being used for the trial. The WBGT temperature range for the trials was set between 28°C and 35°C. Thermal sensation (TS) and Rating of Perceived Exertion (RPE) (Borg Scale) were recorded during T30, T60, and T90. Subjects were also asked to qualitatively and quantitatively score how closely the protocol mimicked a tennis match at the end of each trial.

Statistical Analysis

Two (treatment; caffeine, placebo) by three (time; PRE, PT, PO) analysis of Variance (2x3 ANOVA) with repeated measures was used for statistical analysis and where statistical significance was found Bonferroni's Post Hoc was performed. When only two means were compared, t-tests were performed. Statistical significance was set at p-value ≤ 0.05.

CHAPTER IV. RESULTS

The purpose of this investigation was to determine the effect of pre-match consumption of a caffeinated carbonated soft drink on tennis performance and hydration status before and during simulated tennis match play. Ten highly skilled tennis players qualified for this project. Participants' characteristics are shown in table 1.

Table 1: Participants Physical Characteristics

Characteristics	Mean±SD	Range
Age (years)	24±6	19-35
Weight (Kg)	75.0±8.6	60.5-85.5
Height (m)	1.80±0.06	1.70-1.90
BMI (Kg/m^2)	23.2±1.5	19.8-25.0
Body Fat (%)	12.9±2.9	7.1-16.8
VO_{2max} (ml/Kg/min)	55.0±4.7	45.9-61.8

In order to avoid perceptual cues to influence data, a double-blind format was used during data collection. Success on hiding which treatment each participant received was measured by asking each participant at the end of each trial the following two questions: "Which treatment do you think you received?" and "How sure are you?" There

were a total of 20 trials and out of these 20 trials, 8 times participants were not sure at all about which treatment they had received. On the remaining 12 times in which the participants claimed they knew which treatment they had received, 6 times they were wrong and 6 times they were right. Thus, out of 20 trials, only 6 times did the participants know correctly which treatment they received. This corresponds to 30% of correct answers, confirming success in blinding the treatment since just by guessing they had a 50% chance of choosing the correct answer.

Tennis Performance

At the completion of each trial, all participants were asked the following question: "How close does this protocol resemble a real tennis match?" They were asked to assign a number from 0 (not at all) to 10 (exactly the same). The group's mean of how close the simulated tennis match playing resembled a real match was 8.1. Thus, the protocol was successful in mimicking a tennis match.

Skill Test

Tennis skill performance was analyzed for total score, total number of unforced errors, and shot index. Statistical analysis of the results showed a significant difference ($p < 0.05$) between caffeine and placebo at post-trial on total scores and shot index. There was no difference between treatments on total number of unforced errors at any time. However, there was a significant increase in total number of unforced errors between pre-trial and post-trial on the placebo treatment ($p < 0.05$). Tennis skill performance is illustrated in figures 4A-C.

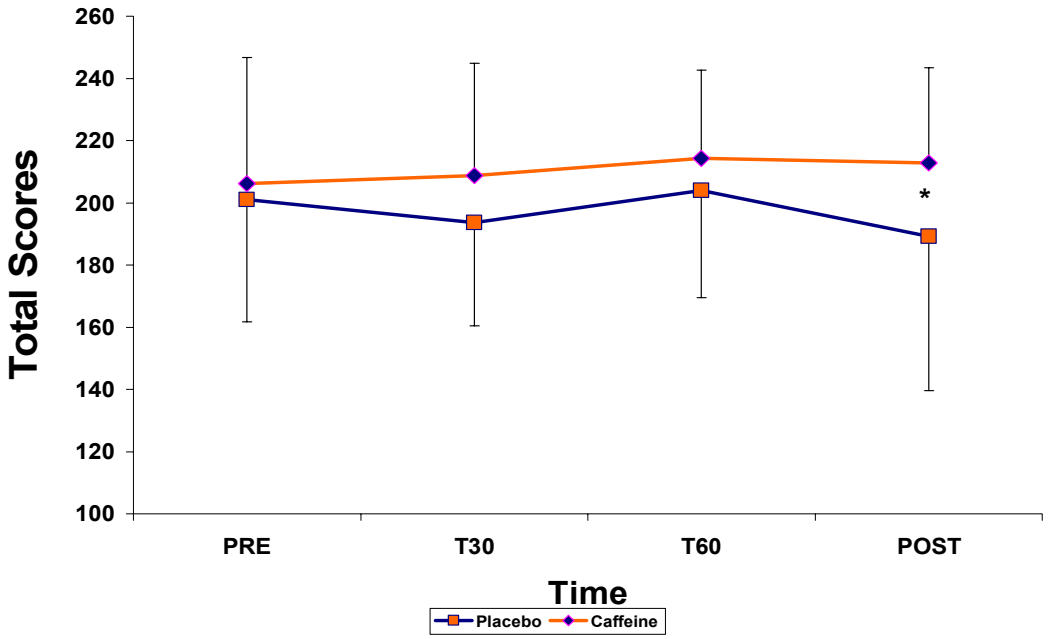

Figure 4A. Tennis Skill Test: Total Scores. Diamonds represent caffeine and squares represent placebo. Star indicates significant difference ($p<0.05$) between caffeine and placebo treatments at PO.

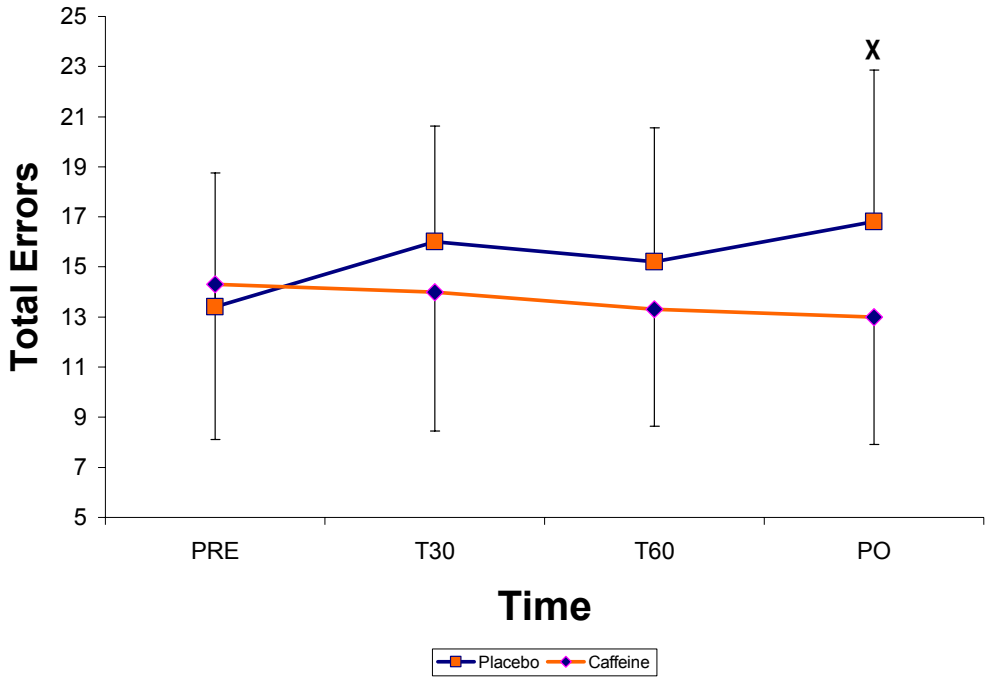

Figure 4B. Tennis Skill Test: Total Unforced Errors. Diamonds represent caffeine and squares represent placebo. Significant increase in unforced errors at PO in the placebo trial only is indicated ($p<0.05$) by "X".

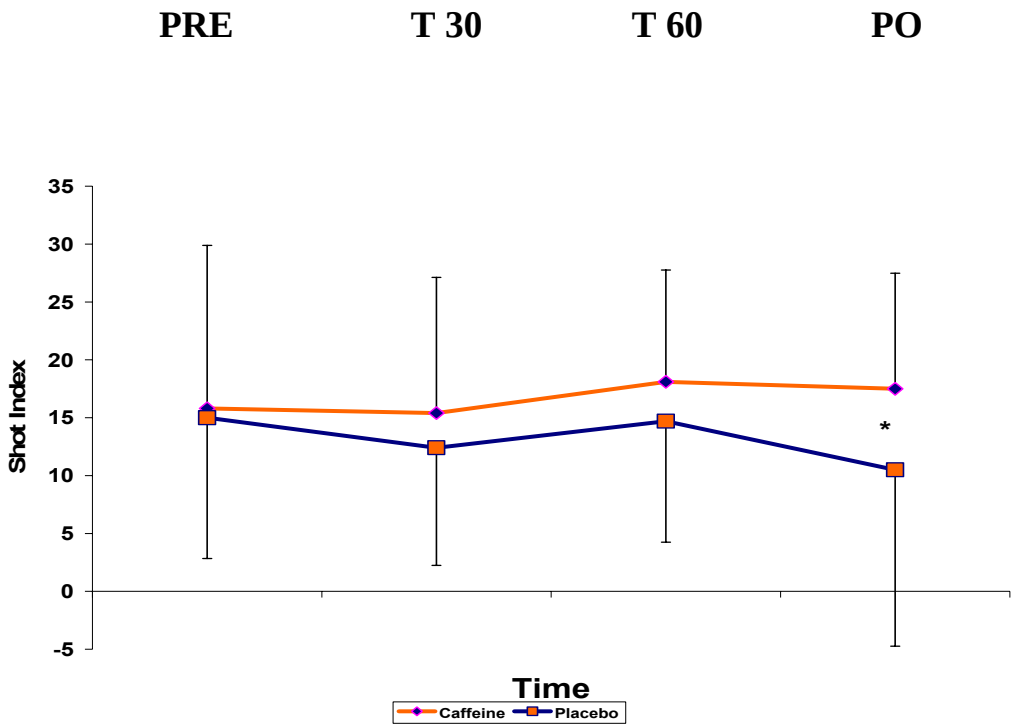

Figure 4C. Tennis Skill Test: Shot Index. Diamonds represent caffeine and squares represent placebo. Star shows significant difference ($p<0.05$) between caffeine and placebo treatments at PO.

Heart Rate

Mean HRs for both trials during simulated tennis match playing were 165 and 164 beats per minute for placebo and caffeine, respectively. The results show that HR was significantly ($p < 0.05$) elevated from rest to exercise and remained elevated throughout the protocol. Although HR was significantly reduced 15 minutes after completion of exercise, it remained significantly elevated compared to resting HR. Statistical analysis showed that there were no differences in HR between caffeine and placebo at any time

during the protocol. The heart rate profile during the performance trials is shown in figure 5.

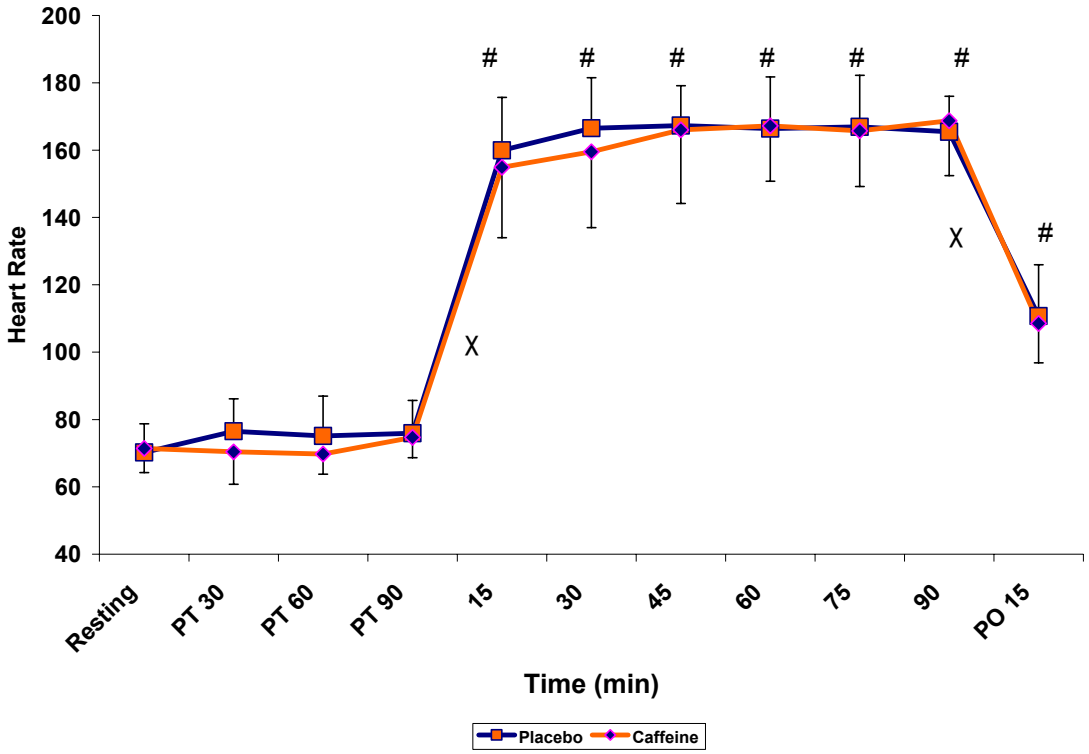

Figure 5. Heart Rate Profile. Dimonds represent caffeine and squares represent placebo. Significant ($p<0.05$) changes in HR between rest and tennis play as well as tennis play and passive recovery are indicated by "X" and # denote significant ($p<0.05$) elevated HR during simulated tennis match play.

Shuttle Fitness Test

Analysis of the data revealed that eight out of 10 participants improved in an average of 1.6 stages after caffeine ingestion compared to placebo. One subject did not reach the minimum stage required for VO_2 assignment. Therefore, only nine subjects were considered for statistical analysis. Subjects performed a total of three SFT, one rested (PRE) and two POs (one after each trial). Group mean stage accomplished was 9.7 $\pm$ 6.6 PRE and 6.6 $\pm$ 2.2 for the placebo trial and 7.5 $\pm$ 2.1 for the caffeine trial

corresponding to 36.5 ± 7.0 $ml \cdot kg^{-1} \cdot min^{-1}$ for placebo and 39.1 ± 7.3 $ml \cdot kg^{-1} \cdot min^{-1}$ for caffeine. Statistical analysis showed a significant decrease between PRE and PO ($p<0.05$) on both treatments. Caffeine ingestion resulted in a full extra stage (approximately 1 minute longer to reach exhaustion) during SFT, this difference was statistically significant ($p \leq 0.007$).

Rating of Perceived Exertion (RPE)

Mean RPE values were: 13.4 ± 1.3, 15.2 ± 1.5, and 16 ± 1.6 for placebo and 13.1 ± 2.2, 15 ± 1.9, 16 ± 1.3 for caffeine at T30, T60, and PO, respectively. Statistical analysis showed a significant increase in RPE throughout the protocol in both treatments. However, there was no difference in RPE between caffeine and placebo across the board. See figure 6.

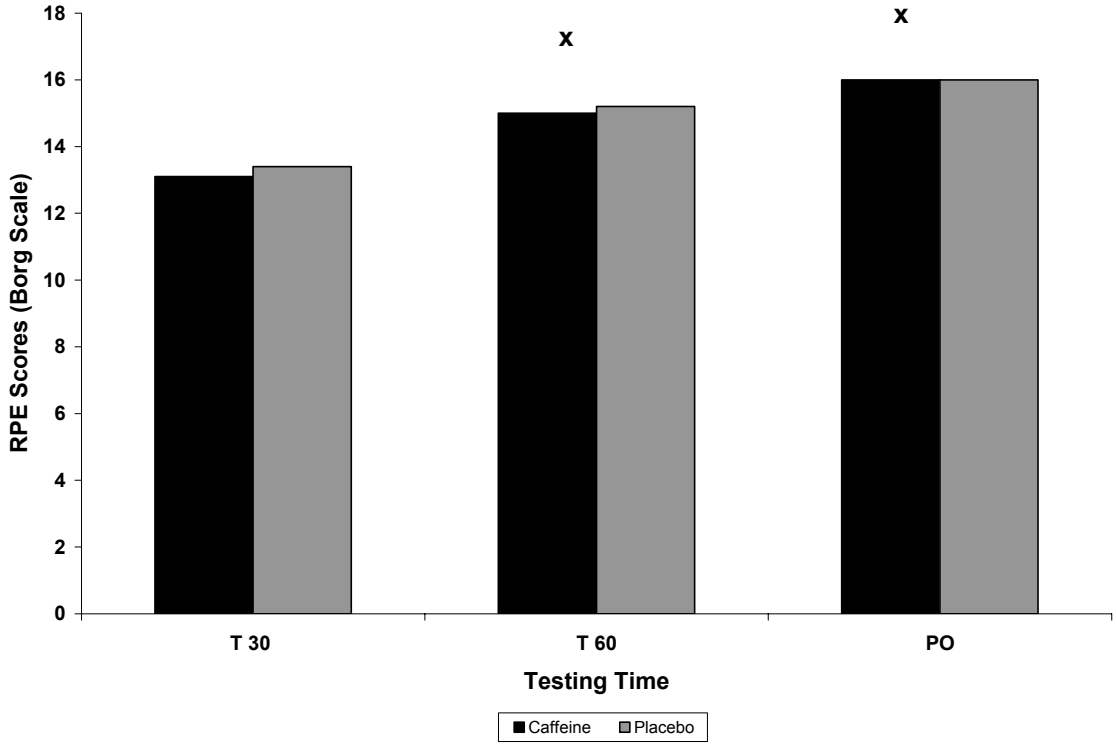

Figure 6. Rating of Perceived Exertion. Gray represents placebo and black represents caffeine. “X’s” denote significant ($p<0.05$) increase in RPE during simulated tennis match play on both trials.

Reaction Time

Analysis of the results showed no difference between treatments at any time during the protocol for Auditory Reaction Time (ART). Also, there was no difference in ART over time in either treatment. See figure 7A.

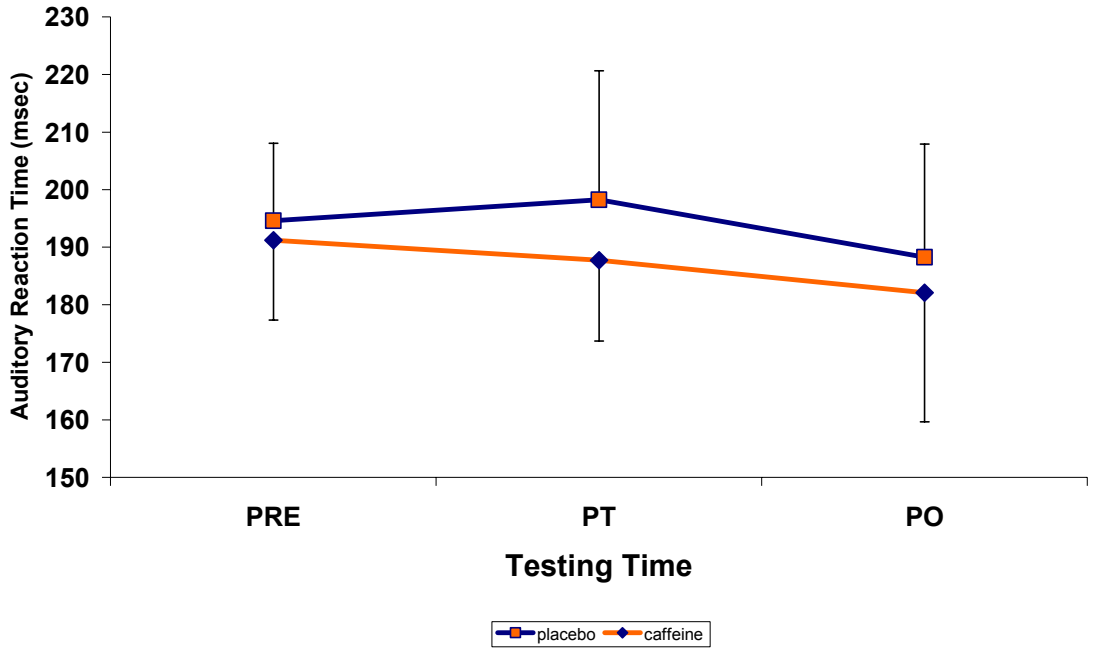

Figure 7A. Auditory Reaction Times. Diamonds represent caffeine and Squares represent placebo. PRE, PT, and PO represent Pre-Ingestion, Pre-Trial, and Post-Trial, respectively.

Analysis of the results showed no difference over time for either treatment for Visual Reaction Time (VRT). There was no statistical difference in VRT between treatments at any time during the protocol. See figure 7B.

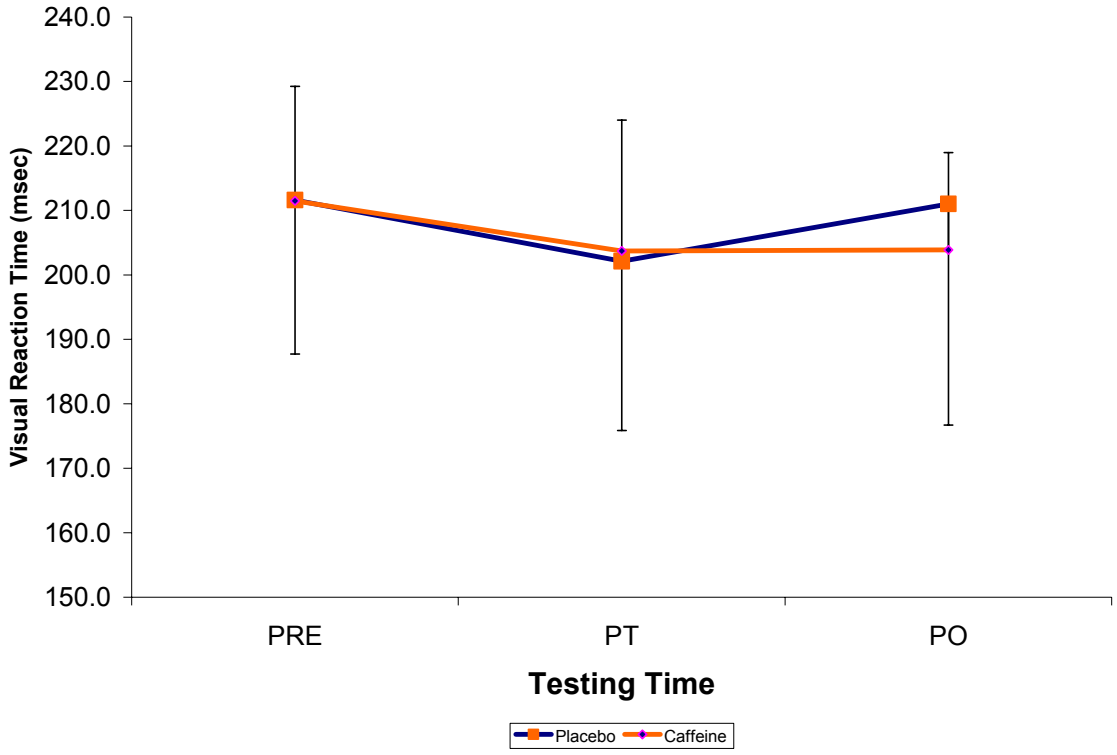

Figure 7B. Visual Reaction Times. Diamonds represent caffeine and Squares represent placebo. PRE, PT, and PO represent Pre-Ingestion, Pre-Trial, and Post-Trial, respectively.

Hydration

Body Weight

There was a significant ($p<0.05$) reduction in BW from PRE to PT as well as from PT to PO on both treatments. Table 2 shows group means for BW. There was no difference in mean BW between caffeine and placebo at any time. In fact, BW was identical between treatments.

Urine Volume and Urine Specific Gravity

Mean group urine volumes and urine specific gravities are shown in table 2. Statistical analysis showed no difference in urine volume between treatments at any

time. In both trials, there was no difference in urine output between PRE and PT. However, there was a significant ($p<0.05$) reduction in urine output from PT to PO during both trials.

There was a tendency for lower USG on the caffeine trial throughout the protocol. However, there was no difference between caffeine and placebo at any time. Also, there was no difference in USG at any time during the protocol.

Table 2: Hydration Parameters

	BW (Kg)	U Vol (ml)	USG (g/ml)	Hct (%)	Hb (g/dl)
Placebo PRE	76.9 ± 8.9	102 ± 79	1.019 ± 0.01	43.9 ± 1.8	15.6 ± 1.3
Placebo PT	76.1 ± 8.8#	158 ± 112	1.019 ± 0.01	44.4 ± 2.4	15.2 ± 1.2
Placebo PO	73.5 ± 7.9#	59 ± 32#	1.018 ± 0.01	46.3 ± 2.4#	15.6 ± 1.7
	BW (Kg)	**U Vol (ml)**	**USG (g/ml)**	**Hct (%)**	**Hb (g/dl)**
Caffeine PRE	76.9 ± 9.0	156 ± 113	1.015 ± 0.01	44.4 ± 1.9	15.2 ± 1.1
Caffeine PT	76.2 ± 8.8#	218 ± 152	1.015 ± 0.01	44.4 ± 2.2	14.7 ± 1.2
Caffeine PO	73.5 ± 8.6#	87 ± 53#	1.015 ± 0.01	46.2 ± 1.8#	16.2 ± 0.9#

Group means ± SD for hydration values and pre-ingestion (PRE), pre-trial (PT), and post-trial (PO). The # sign denotes significant changes over time for body weight (BW), urine volume (UVol), urine specific gravity (USG), hematocrit (Hct), and hemoglobin (Hb).

Plasma Volume

Due to inability to collect a blood sample, only eight subjects were included in the statistical analysis for hematocrit and hemoglobin, and consequently, changes in plasma volume. Table 2 shows group means for hematocrit concentrations. Hematocrit concentrations did not change between PRE and PT on either treatment. However, in both treatments there was a significant increase in hematocrit concentration between PT and PO. In contrast, statistical analysis did not show a significant difference between caffeine and placebo at any time throughout the protocol.

Hemoglobin group means are also shown in table 2. As with hematocrit, hemoglobin concentration did not change between PRE and PT on either treatment. In the placebo trial, hemoglobin concentration did not change between PT and PO. However, during the caffeine trial there was a significant elevation ($p<0.05$) in hemoglobin concentration between PT and PO. Despite differences in response between caffeine and placebo, there was no difference between treatments in hemoglobin concentration throughout the protocol.

During the placebo trial, there was no difference in plasma volume changes throughout the protocol. In contrast, during the caffeine trial, there was a significant reduction ($p<0.05$) in plasma volume during match play. When compared to placebo, caffeine ingestion resulted in a significantly lower plasma volume during match play ($p<0.05$). Changes in plasma volume are shown in figure 8.

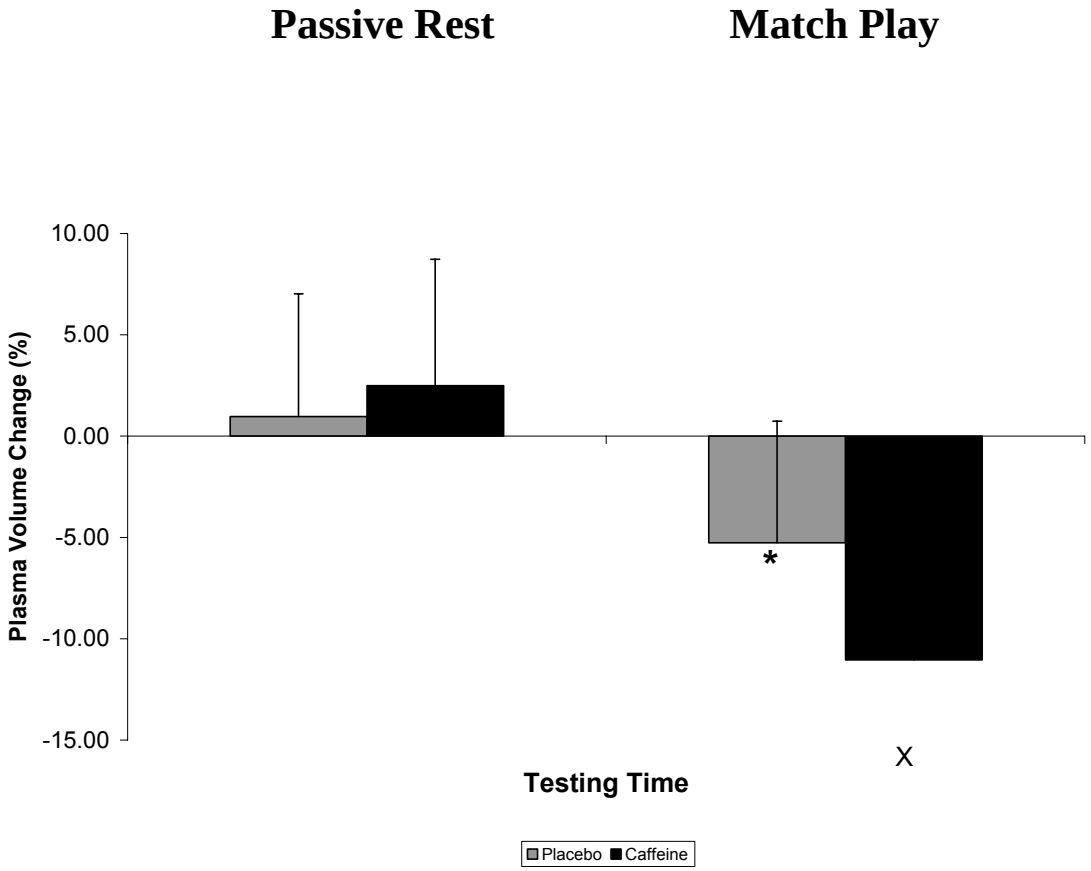

Figure 8. Plasma Volume Changes. Passive rest represents changes between pre-ingestion and pre-trial and match play represents changes between pre-trial and post-trial. Black represents caffeine and gray represents placebo. Star denotes significant ($p<0.05$) difference between treatments and X denotes significant change between passive rest and match play.

Sweat Rates

Mean sweat rates were 1261 $\pm$ 32 $ml \cdot hr^{-1}$ and 1289 $\pm$ 53 $ml \cdot hr^{-1}$ for placebo and caffeine trials, respectively. Statistical analysis revealed no difference in sweat rates between trials.

Thermal Sensation

Mean wet bulb global temperature (WBGT) was 30.1 $\pm$ 1.8°C and 29.1 $\pm$ 1.3°C for the placebo and caffeine trials, respectively. No statistical significance was found

between environmental conditions for the two trials. There was also no difference in thermal sensation throughout trials. Table 3 shows thermal sensations during the protocol.

Table 3: Thermal Sensation

	T 30	T 60	PO (T 90)
Caffeine	5.2 ± 0.9	5.4 ± 0.8	5.6 ± 0.7
Placebo	5.5 ± 0.8	5.7 ± 0.8	5.8 ± 1.1

Metabolism

Serum Caffeine

To ensure that the caffeine restriction and delivery were effective, serum caffeine levels were measured for PRE and PT (placebo and caffeine) and PO for caffeine. The mean serum caffeine level at PRE was 0.096 ± 0.31 $\mu g \cdot ml^{-1}$ and 0.091 ± 0.21 $\mu g \cdot ml^{-1}$ for the placebo and caffeine, respectively. These values indicate negligible amounts of serum caffeine at the beginning of the protocol confirming compliance to the protocol. The difference in serum caffeine concentration at PRE was not statistically significant between trials. Serum caffeine levels were significantly elevated after caffeine ingestion to 3.16 ± 0.29 $\mu g \cdot ml^{-1}$ at PT and remained elevated until the end of the protocol with a serum concentration of 3.06 ± 1.1 $\mu g \cdot ml^{-1}$ at PO. There was a significant difference ($p < 0.05$) in serum caffeine concentration between placebo and caffeine during simulated tennis playing showing that caffeine was successfully delivered to the system. Serum caffeine concentrations are shown in figure 9.

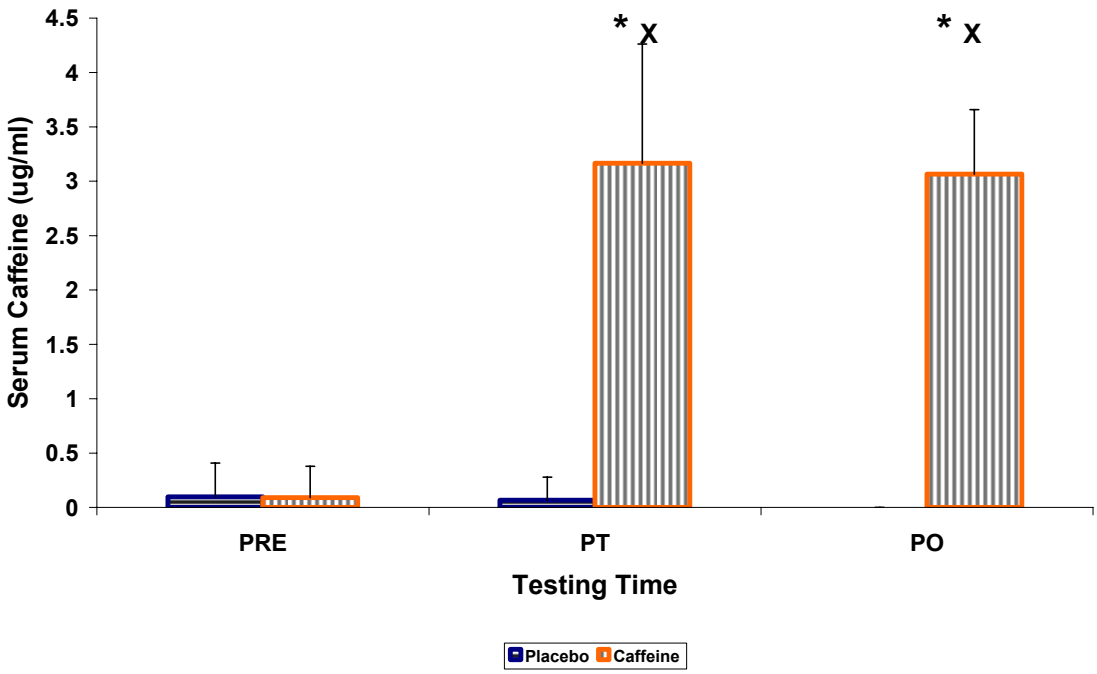

Figure 9. Changes in Serum Caffeine Concentration. Vertical lines represent caffeine and horizontal lines represent placebo. Stars denote significant difference between caffeine and placebo trials and X denotes significant increase in serum caffeine concentration between Pre-Ingestion (PRE) and Pre-Trial (PT) and PRE and Post-Trial (PO) time periods.

Serum Glucose

Figure 10 shows serum glucose responses during both trials. At no time were serum glucose concentrations significantly different between treatments. Also, during the caffeine trial, serum glucose remained unchanged. However, during the placebo trial, there was a significant ($p<0.05$) elevation in serum glucose concentration from PT to PO.

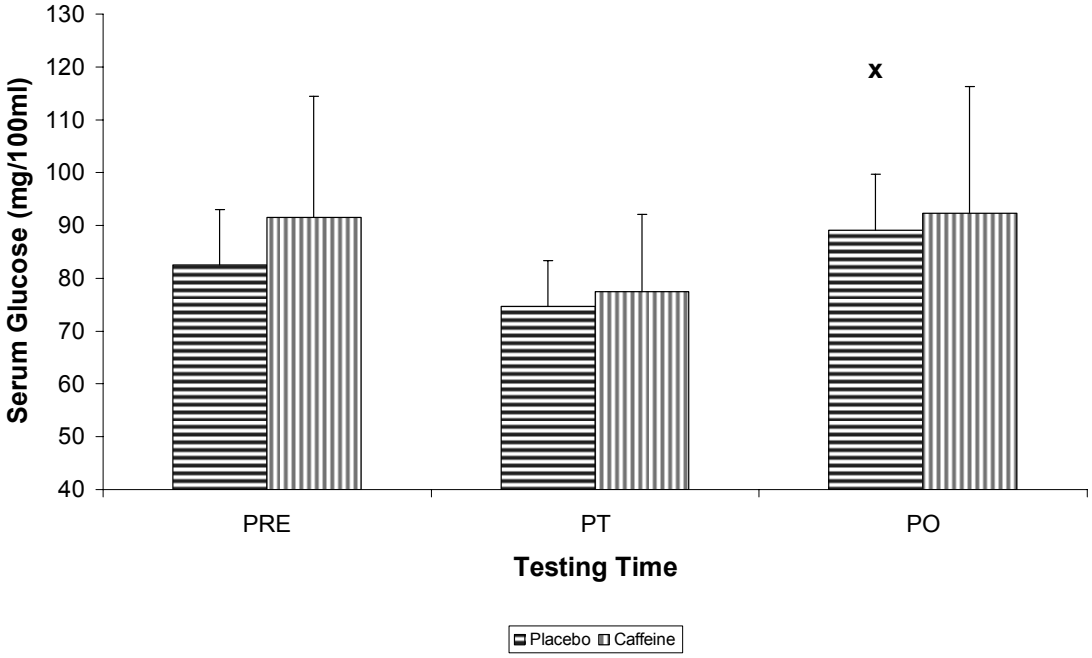

Figure 10. Changes in Serum Glucose Concentration. Vertical lines represent caffeine and horizontal lines represent placebo. "X" denotes significant ($p<0.05$) increase in serum glucose concentration between Pre-Trial (PT) and Post-Trial (PO).

CHAPTER V. DISCUSSION

The purpose of this investigation was to determine the effect of pre-match consumption of a caffeinated carbonated soft drink on tennis performance and hydration status before and during simulated tennis match play. The results of this investigation showed that ingestion of 3 $mg \cdot kg^{-1}$ BW of caffeine did improve tennis skill performance. Simulated tennis play did cause participants to significantly dehydrate based on body weight loss by an average of 2.6 kg throughout the protocol. However, caffeine ingestion did not result in an increase in dehydration as shown by lack of statistical significance between treatments. Caffeine ingestion also helped to stabilize serum glucose during simulated match play.

Performance

Skill Test

This is the first study examining Vergauwen's modified protocol, thus no comparison can be made. However, there are other studies that measured tennis skill performance based on accuracy [11, 15, 25, 26, 72, 74]. It is clear from the published data that tennis players have the ability to control ball placement during tennis play to pre-determined areas in the tennis court. Also, day-to-day variability in accuracy has been shown to be very small in skilled tennis players (Strecker unpublished data).

The present results show that caffeine consumption produced an observable increase in tennis skill performance throughout the protocol, although the increase did not

reach statistical significance. Also, during the placebo trial, there was an observable decrement in the scores however the difference was not statistically significant. When compared to placebo, caffeine ingestion resulted in a significant difference at PO, with the total scores and shot index being significantly higher during the caffeine trial. These results, although conflicting with Ferrauti's [25, 26], suggest that caffeine may enhance tennis skill performance at later stages of tennis match play. A significant increase in total score may be achieved by players either hitting higher valued areas of the court or performing fewer unforced errors. The fact that shot index was significantly higher during the caffeine trial does suggest that athletes committed fewer unforced errors since total scores during the caffeine trial did not change. In addition, during the placebo trial, unforced errors were significantly higher at PO. Therefore, caffeine improved skill performance by reducing the amount of unforced errors during simulated match play. In agreement, previous research has shown fatigue decreases skill tennis performance [11]. Davey et al tested the effect of fatigue on tennis hitting accuracy [11]. The authors found that at 75% of time to exhaustion and at exhaustion, hitting accuracy was significantly reduced. Thus, it seems that fatigue may cause a reduction in hitting accuracy and ingestion of 3 $mg \cdot Kg^{-1}$ BW of caffeine may prevent such reductions.

Two studies have been published evaluating the effect of caffeine consumption on hitting accuracy. Ferrauti et al. [25, 26] found that caffeine ingestion (130 $mg \cdot L^{-1}$ of fluid ingested) did not improve stroke hitting accuracy in men. However, caffeine ingestion did significantly improve hitting accuracy in women. Males consumed 150 ml of fluid at the start and every 15 minutes during match play, while females consumed 100 ml of fluid at the start and every 15 minutes. Total caffeine consumed was 364 mg for men and 260 mg

for women. When relative dose was calculated, the relative doses were approximately 4.5 $mg \cdot Kg^{-1}$ of BW for men and 4 $mg \cdot Kg^{-1}$ BW for women, respectively. The authors speculated that the lower intensity of play and the smaller daily consumption of caffeine for the women may have influenced the results. However, as mentioned before, habituation does not seem to be a factor in the ergogenic capacity of caffeine [93]. Also, no gender differences in response to caffeine consumption have been identified [153]. Therefore, some other explanation must be presented to explain why caffeine improved performance in women, but not in men.

Heart Rate

Mean heart rate (HR) during tennis match play has been estimated to range between 132 and 156 bpm [1, 5, 7, 32, 154]. Although not significant, there was a continued elevation in HR as the present subjects progressed throughout the protocol. Mean HR in this study was 165 and 164 for placebo and caffeine, respectively. Thus, the modified protocol resulted in higher HR, when compared to the literature. Two arguments are possible as explanation for the higher HR during the present protocol. First, progressive increases in heart rate during continuous exercise in the heat with concurrent dehydration have been termed cardiovascular drift [155]. Prolonged exercise leads to gradual dehydration caused by increased sweating. The decrease in blood volume and the decrease in stroke volume leads to a proportional increase in HR in order to maintain cardiac output [156-158]. Second, it has been shown that exercise in a hot and humid environment leads to higher exercising HR despite similar blood volume [159]. Gonzales-Alonzo et al. showed a synergistic effect in cardiovascular function due to both dehydration and hyperthermia [158]. The test conditions for this research were 30.1 and

29.1°C (WBGT) for placebo and caffeine, respectively. Thus, increased heat stress accompanied by dehydration may be responsible for elevated HR during simulated tennis match play.

A second explanation for increased HR may be the length of each point in this protocol, which was approximately 10 seconds. It has been shown that the average point during tennis match play is 8 seconds [27]. However, during match play, points range between 1 and 15 seconds with 90% of the points being shorter than 10 seconds [2, 29]. Elliot et al. showed that during tennis match play, recovery HR was slightly higher than exercising HR due to short work periods that may be completed before the HR had enough time to adjust to the required intensity [3]. Therefore, because the points were constantly slightly longer than the average point, there is an increased time for the HR to adjust to the exercise intensity of the simulated tennis match. As a result, HR may have been slightly higher due to increased time under stress.

The increase in HR during the protocol cannot be related to the ingestion of caffeine. It has been shown that caffeine consumption increases HR while at rest [113], but not during exercise [20, 97, 100]. The results of this investigation showed no statistical difference in HR's between treatments at any time throughout the protocol. This is in agreement with some [20, 97, 100], but not others [113]. As mentioned before, it seems that the effects of caffeine on HR may be blunted by the effects of caffeine on vagal centers in the medulla, such that the increase in HR due to the direct effect of caffeine on the myocardium is antagonized by the effect of caffeine in the brain [114]. If this is true, then it makes sense that HR response during exercise is similar after caffeine

ingestion when compared to placebo. Thus, according to these results, caffeine does not seem to impose extra stress on the heart during simulated tennis match play.

Shuttle Fitness Test

The results of this investigation showed a significant decrease in the total capacity to perform work from PRE to PO. The reduction in performance during the SFT measured as predicted VO_{2max} corresponding to the final stage accomplished was possibly due to either a direct reduction in VO_{2max} due to dehydration [160] or an impaired capacity to perform total work caused by dehydration-induced fatigue [161]. Armstrong reported that dehydration representing as little as 2% of body weight loss reduced VO_{2max} by 10% when measured in a hot environment [160]. Mean WBGT temperature during both trials were 29.1°C and 30.1°C for caffeine and placebo, respectively. Cheuvront et al. reported that dehydration of at least 2% of body weight reduces endurance performance, especially in hot and humid environments [161]. Fallowfield et al. examined the effect of dehydration on endurance performance and found that fluid ingestion enhanced performance by increasing time to exhaustion on treadmill run by approximately 25 minutes compared to no fluid at all [162]. Therefore, the results of this investigation are in agreement with the previous studies, showing that acute dehydration reduced SFT performance after 90 minutes of simulated tennis match play.

In this study, the SFT was chosen in an attempt to better match the intermittent characteristics of tennis to a well established, reliable test [39]. Caffeine has been shown to improve endurance performance either by increasing time to exhaustion [23, 99, 107] or allowing greater work output in a set amount of time [120, 121, 148]. In contrast,

caffeine has failed to improve maximal performance measured as VO_{2max} or VO_{2peak} [109, 115, 122, 123]. The intermittent nature of the SFT makes comparisons to either mode of exercise (prolonged continuous or short maximal) somewhat challenging, due to the constant acceleration and deceleration caused by the changes in direction, which are different from the more traditional continuous method of measuring VO_{2max} or VO_{2peak} on a treadmill or cycle ergometer, respectively.

The results of this investigation showed that participants exercised longer on the SFT during the caffeine trial approximately 1 minute longer (1 full stage: 6.6 on the placebo trials versus 7.5 on the caffeine trial, which corresponds to 36.5 $ml \cdot kg^{-1} \cdot min^{-1}$ for placebo and 39.1 $ml \cdot Kg^{-1} \cdot min^{-1}$) after caffeine ingestion compared to placebo. As mentioned before, eight out of the 10 participants improved performance in an average of 1.6 stages during the caffeine trial compared to placebo. One of the two participants who did not improve performance was excluded for not meeting the minimum stage required for VO_2 assignment. Statistical analysis without this participant revealed significant difference between caffeine and placebo ($p \leq 0.007$). These results would be in agreement with studies showing an improvement in endurance performance [20, 117, 120, 121]. These results would also mean that tennis players were capable of performing more work at the SFT after simulated match play during the caffeine trial compared to the placebo trial.

Rating of Perceived Exertion

Caffeine ingestion had no statistical effect on RPE compared to placebo during this investigation. There was, however, a significant increase in RPE throughout the trials. These results are in conflict with some studies that show a reduction in the RPE

after caffeine ingestion [20, 23]. However, the results are in agreement with studies that do not show any improvements after caffeine ingestion [97, 100, 132]. As mentioned before, one of the main difficulties in the interpretation of the results may be the testing protocol. For example, studies that failed to show a difference in RPE, but showed an improvement in performance may be interpreted incorrectly, since the improved capacity to perform work, may be due to a reduced perceived stress imposed by exercise due to caffeine ingestion. Thus, because participants feel more "energized" they are capable of exercising longer and/or faster with no changes in RPE because the subject may match RPE at different exercise intensities. Berglund et al. examined the effect of caffeine ingestion on cross-country skiing race performance at high and low altitude [120]. The results showed an improvement in performance, even though RPE was not significantly different. The authors suggested that participants were able to choose a faster pace to match RPE [120].

In agreement, Cole et al. demonstrated that caffeine resulted in greater work output at similar rates of perceived exertion [129]. Ten males performed six 30-minute exercise bouts divided in three segments of 10 minutes. In each segment, participants cycled at what they perceived to be 9, 12, or 15 on the Borg Rating of Perceived Exertion scale. The authors found that caffeine ingestion resulted in a significantly greater amount of work accomplished compared to placebo [129]. This is in agreement with the results of this investigation, since there was no difference in RPE during the protocol, but tennis players performed better during the caffeine trial compared to placebo.

Reaction Time

There have been no studies conducted measuring reaction times in tennis players. Also, it has not been determined how reaction time is affected by tennis playing and how caffeine ingestion would affect reaction time in tennis players. However, it has been shown that caffeine improves reaction times during simple [143] and complex reaction time tests [146]. The results of the current investigation are within acceptable ranges for young males [140], which have been reported to be on average 180 ms for visual stimulus and 160 ms for auditory stimulus. In this investigation, although slightly slower, visual reaction time was consistently slower than auditory reaction time, by approximately 30 ms. Visual and auditory average reaction times were approximately 210 ms and 190 ms, respectively. However, the results of this investigation conflict with Jacobson et. al. who showed that ingestion of 300 mg of caffeine improved simple reaction time compared to placebo [143]. The average dose in our study was 231 mg of caffeine. Lieberman et al. showed that doses as small as 32 mg resulted in faster choice reaction times [146]. Therefore, the dose given to the participants in this investigation was within an acceptable range.

Cian et al. have examined the effects of dehydration on reaction time [163]. Participants were dehydrated by approximately 2.8% of body weight either by passive recovery or treadmill running. They found that regardless of the method of dehydration or fluid intake, reaction times were unchanged throughout the experimental period [163]. The authors attributed the results to the task's lack of sensitivity to dehydration. Thus, it seems that dehydration does not alter reaction times, at least for visual choice reaction time. Finally, Smith et al. showed that fatigue increased simple reaction time, but caffeine

significantly improved results [164]. Therefore, based on previous studies, it seems that the lack of statistical significance in this study cannot be explained by the caffeine dose ingested, participant's dehydration, or exercise-induced fatigue since even during the placebo trial there was no statistical difference.

Tennis players are required to react and respond to several stimuli at the same time (i.e. the sound of the racket hitting the ball, the image of the opponent striking the ball, and the direction in which the tennis ball travels) during match play. Thus, the results of this investigation may be explained by a lack of applicability of our testing to the population chosen. Due to its complexity, the sport of tennis may be better represented by complex reaction time instead of simple reaction time tests. Separation of the stimuli may have taken participants sensitivity away, which could reflect the lack of significant change in either visual or auditory reaction time. Perhaps more complex testing is required to observe changes due to caffeine ingestion in skilled tennis players. Future research should examine the effect of tennis play on reaction time as well as more complex types of reaction time testing in skilled male tennis players.

Hydration

Pre-exercise hydration was not an issue in the results of this investigation considering similar body weight, hematocrit, hemoglobin, urine specific gravity, and resting heart rate. It is important to mention that The National Athletic Trainer's Association in their position stand suggested that athletes should consume approximately 200 to 400 ml of fluid every 15 minutes [16]. In our protocol, participants consumed a total of 1200 ml of water in 90 minutes of exercise, which corresponds to an average of 200 ml every 15 minutes.

There was significant dehydration during the protocol, considering an average reduction of 2.6 Kg of body weight during simulated tennis match play. Thus, it is reasonable to conclude that for high level male tennis players performing in a hot and humid environment, 200 ml every 15 minutes is not sufficient. Thus, tennis players should consume greater amounts of fluids when performing in a hot and humid environment. In agreement, Kovacs suggested that tennis players should be on an individualized hydration protocol that should maximize fluid intake such that total consumed fluids would match their personal sweat rates. However, the author also stated that due to limitations in the rate of gastric emptying, ingestion of high volumes of fluids may be a challenge [47].

Hematocrit/Hemoglobin

Despite a significant increase in hematocrit concentration from PT to PO, there was no difference between treatments. At the beginning of the simulated tennis match play and at the completion of the protocol, hematocrit values were identical. Hematocrit percentages were 43.9 PRE, 44.4 PT, and 46.3 PO for the placebo trial and 44.4 PRE, 44.4 PT, and 46.2 PO for the caffeine trial. These values are in agreement with previous research [56, 165], which showed an increase in hematocrit concentration during exercise. Based on changes in BW, participants in this investigation clearly did not ingest enough fluids throughout the protocol. Thus, there was an increase in hematocrit concentration (hemoconcentration) after 90 minutes of simulated tennis match play in a hot and humid environment.

Due to inconsistency in the data, hemoglobin data were analyzed for eight subjects. Changes in hemoglobin concentration followed a slightly different pattern

compared to hematocrit. There was a significant increase in hemoglobin concentration after exercise during the caffeine trial only. During the placebo trial, hemoglobin remained unchanged throughout the protocol. Despite differences in the responses during tennis match play, there was no statistical difference between caffeine and placebo in hemoglobin concentration at any time throughout the protocol. Hemoglobin concentrations were within acceptable ranges for the population in this investigation and hemoglobin responses during simulated tennis match play did not seem to be abnormal [56, 159, 166]. Hematocrit and hemoglobin values were used to calculate plasma volume changes according to Dill and Costill [57].

Plasma Volume

The results of the present investigation showed a significant decrease in plasma volume from PT to PO, which suggests that participants had a negative fluid balance during the simulated tennis match play. Also, there was a significant difference in plasma volume changes between the caffeine and placebo trials, with caffeine ingestion resulting in a greater decrease in plasma volume compared to the placebo trials. Although not statistically significant, there was a tendency for a greater increase in plasma volume during the caffeine trial from PRE to PT, with changes being 0.97% and 2.49% for placebo and caffeine, respectively. Caffeine does not seem to have any influence on the sweat glands and on sweat rates during exercise as expressed by the almost identical sweat rates seen during the trials (see section below) despite caffeine's apparent ability to reduce skin blood flow. Daniels et al. showed that caffeine consumption attenuates forearm blood flow and forearm vascular conductance [167]. Thus, changes in sweating do not seem to explain the greater plasma volume changes during simulated tennis match

play after caffeine ingestion. As mentioned previously, hemoglobin concentration was increased significantly during the caffeine trial, although not statistically different from placebo. Thus, significant increases in hemoglobin concentration during the caffeine trial may have contributed, at least in part, to a significant change in plasma volume calculations since changes in hemoglobin concentration will directly influence plasma volume calculations. At present differences in hemoglobin response and therefore, plasma volume, during the caffeine trial cannot be explained since no other variable such as body weight, total urine output, hematocrit, sweat rates, and thermal sensation were affected by caffeine ingestion.

Sweat Rate

As mentioned before, participants had significant reductions in body weight and plasma volume and significant increases in hematocrit and hemoglobin concentration. These changes may have been caused by either an increase in sweating and/or insufficient fluid intake. Although fluid consumption in the present study was consistent with the NATA recommendations [16], there was a significant reduction in body weight. The average sweat rates in this investigation were 1.26 $L.hr^{-1}$ and 1.28 $L.hr^{-1}$ for placebo and caffeine, respectively. Bergeron et al. measured sweat rates in male tennis players during consecutive tennis match play. The authors found that on average males had higher sweat rates with mean sweat rates of 1.7 $L.hr^{-1}$ [54]. Thus, our results showed a lower sweat rate during simulated match play compared to the previous studies. Perhaps differences in methodology may explain the difference in results, since in Bergeron's study tennis players participated in actual tennis matches and in this investigation, match play was simulated. Also, during this protocol participants were euhydrated prior to

initiation of each trial. Each participant was required to ingest 500 ml of water 1 hour before commencement of each trial. However, considering that participants in this investigation rated the simulated match play similar to an actual tennis match, the perceived effort does not seem to be much different. Also, HR in this study was higher than Bergeron's, so intensity of play could not explain the differences in sweat rates either.

The results of this investigation confirmed that fluid intake is a challenge to tennis players. Maximal gastric emptying has been shown to be approximately 800 $ml.hr^{-1}$ [64] and sweat rates during either simulated or actual tennis match play seem to be greater than 1 $L.hr^{-1}$. Fluid replacement that matches fluid lost through sweating may be impossible during tennis play in hot and humid environment. Therefore, the results of this investigation show that insufficient fluid intake was responsible for the significant reduction in body weight and not changes in sweating. By virtue of all the data described above, it does not seem that caffeine ingestion adds any detrimental effect on hydration during simulated tennis match play when compared to placebo.

Metabolism

Serum caffeine

Significant increases in serum caffeine levels seen in this investigation ensured that caffeine was ingested and delivered to the body during the protocol. Also, negligible values during the placebo trial confirm compliance by the participants prior to the placebo trial. It is also interesting that serum caffeine levels did not change from PT to PO. This suggests that serum caffeine stayed elevated for at least 4 hours after ingestion, since after 90 minutes of passive recovery and approximately 120 minutes of testing,

serum caffeine levels were still elevated reaching statistical significance at post-exercise compared to placebo and PRE levels. These results are in agreement with others [23, 100, 104]. Elevated serum caffeine values throughout the protocol may be explained by either: 1) hemoconcentration, so as plasma volume decreases, the concentration of caffeine remains relatively constant despite continuous caffeine metabolism; 2) reduced caffeine metabolism due to blood redistribution during exercise. The rate-determining factor for caffeine clearance seems to be liver metabolism [81]. It has been shown that exercise itself does not seem to influence caffeine pharmacokinetics [136]. However, it has been shown that exercise reduces hepatic blood flow [6]. Thus, a reduced amount of blood is supplied to the liver, which results in a decreased amount of caffeine traveling to the liver leading to a lower total caffeine metabolism. Therefore, it makes sense that serum caffeine would remain elevated during tennis match play.

Serum Glucose

Serum glucose concentrations in this investigation were within normal concentrations found in previous tennis research [1, 4, 33, 77]. Tennis research has found serum glucose to increase [1, 4, 33] or to decrease [25, 77] during tennis match play. The results of our investigation found that there was no difference in serum glucose between placebo and caffeine throughout protocol. Also, during the caffeine trials, serum glucose remained unchanged. However, during the placebo trial, there was a significant increase in serum glucose concentration from PT to PO. These results conflict with the results from Ferrauti et al. [25] who found that caffeine ingestion resulted in a reduction in capillary blood glucose. Differences in methodology may explain discrepancies in the results (i.e. simulated versus live tennis play).

Current results suggest that there was a significant reduction in glucose uptake during the placebo trial. Chesley et al. investigated the effect of caffeine on glycogenolytic flux during intense exercise and found that caffeine resulted in a 10% reduction in muscle glycogen use during 15 minutes of cycling. The authors suggested that enhanced fat oxidation early in exercise may be responsible for the reduction in glycogen utilization [105]. These findings contradict some of our results, since serum glucose uptake seemed to be unchanged during the caffeine trials, but reduced during the placebo trial, which although not measured could represent an increase in an alternative fuel being utilized (e.g. free fatty acids, muscle/liver glycogen). Therefore, caffeine seems to help maintain serum glucose utilization during simulated tennis match play.

In conclusion, the main findings of this project are that ingestion of 3 mg/Kg of BW of caffeine 90 minutes prior to simulated tennis match play significantly improves tennis skill performance by maintaining higher levels of accuracy shown by constant total scores, improving shot index by preventing an increase in unforced errors. Second, although significant dehydration occurred during the protocol due to insufficient fluid consumption, caffeine ingestion 90 minutes prior to simulated tennis match play did not add further detrimental effect on hydration status prior to and during match play. Caffeine did result in a significant increase in hemoglobin concentration during the caffeine trial, but results were not different compared to the placebo trial. This increase in hemoglobin concentration may have further influenced the significant decrease in plasma volume during the caffeine trial compared to the placebo. Third, our modified skill test protocol is a simple, reliable, and an accurate assessment tool to measure tennis skill performance.

Finally, the new simulated tennis match protocol closely mimics a competitive tennis match shown by the proximity of the subjective score (8.1) to a real tennis match.

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APPENDIX

Auburn University

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INFORMED CONSENT
FOR
---The Effects of Caffeine Ingestion on Tennis Performance and Hydration Status---

You are invited to participate in a research study on the influence of caffeine on tennis performance and hydration status. With your participation, we will investigate the effect of caffeine ingestion on tennis skills, metabolism, hydration, and performance. This study is being conducted by Estevam Strecker, BS under the supervision of Dr. David Pascoe, Ph.D.

Participants: You were selected as a possible participant because you are a male between 19 and 35 years of age, ranked between 4.0 and 7.0 on USTA, currently playing 2 times/week for at least an hour, currently exposed to daily caffeine intake in foods and beverages, and you are in good health.

Purpose: The purpose of this investigation is to examine the effects of caffeine ingestion on tennis performance and hydration status. The objectives of this study are: 1) to determine if caffeine causes and increase in dehydration prior and during exercise; 2) to determine if a dose of 3mg/Kg BW of caffeine is sufficient to improve tennis performance. This study aims to expand to our knowledge in the effects of caffeine on hydration and to add to our knowledge on the effect of caffeine on performance during intermittent exercise.

Methodology: If you decide to participate, the protocol consists of 3 sessions (1 familiarization and 2 test sessions). During familiarization session you will be asked to perform a Treadmill VO_{2max} Test and a Shuttle Fitness Test. During this study you will be required to play a 90-minute simulated tennis match after ingestion of 32oz of Sprite with either caffeine or placebo. If you choose to participate in this study you will be given a single dose of either caffeine or placebo that represents 3mg/Kg of Body Weight (BW), which would be equivalent to 1 teaspoon, to be ingested 90 minutes prior to simulated tennis play. The powder will be placed in a gel capsule by Dr Pascoe, which will be prepared after BW has been recorded. The 2 test trials will be separated by at least 24 hours. Upon arrival to the lab, you will also be required to provide a urine sample and nude body weight. During simulated tennis, we will be measuring heart rate (HR), rate of perceived exertion (RPE), and tennis skill (Sk). Each test day will last approximately 5 hours, including 90 minutes of passive rest in which time you will be tested on a mental number task, and sound reaction time. During the protocol we will collect 3 venous blood samples (3-5ml) and collect 3 ear prick blood samples. Venous blood will be collected from a vein on your forearm while you are sitting comfortably in a chair. Ear prick blood samples will be collected while

Participant's initials _____

you are sitting on a bench in the tennis courts using a device to perforate the ear lobe. The total amount of blood used for ear prick is one or two drops of blood.

Risks and Precautions: The risk of injury is minimal, as the tasks that we are asking you to perform are similar to what you perform during a singles tennis match. With exercise and/or hot environmental conditions there is a chance of dehydration, heat illness. The potential for heat related injuries or dehydration will be reduced by the monitoring of hydration status and the provision of fluids throughout the trials. Trials will be canceled if the environmental conditions become extreme based on the WBGT- temperature, radiant heat, and evaporative temperature (WBGT > 34°/95°F). With any exercise there is also a minimal risk of death (0.5 per 10,000 tests), but we believe that this risk is reduced as you have been active playing during the months preceding this project and we will ask you to accurately complete a Par-Q Medical Assessment. This will let us know if there are any medications or medical conditions that might put you at risk during participation. There is also a minimal risk of infection during any blood collection. To reduce the potential of infection, we will have an experienced phlebotomist collecting and handling all blood sampling. We will also use sterile needles and aseptic techniques. In the unlikely event that you sustain an injury from participation in this study, you will be required to assume full financial responsibility you're your own medical care. Participants are responsible for any and all medical cost resulting from injury during the study. Further, you may discontinue participation at any time without penalty.

Benefits: You will have access to all your personal data that has been collected during all trials. All requests for data must be made within the month after participation, which time a report will be provided with your personal data. After this time the data will be decoded to your identity. During participation in this study we will be collecting physiological assessments (VO_{2max}, body composition, lactate, blood glucose, tennis skills scores, mental performance, ratings of perceived effort, and hydration status). We cannot promise you that you will receive any or all of the benefits described.

Confidentiality: Any information obtained in connection with this study and that can be identified with you will remain confidential (or anonymous, depending upon the specific conditions of data collection). Data will be collected using a participant number. Information collected through your participation may be used to fulfill an educational requirement (Thesis Project), published in a professional journal, and/or presented at a professional meeting. If published, no identifiable information will be included. Your decision whether or not to participate will not jeopardize your future relations with Auburn University and the Department of Health and Human Performance. If you decide later to withdraw from the study, you may also withdraw any identifiable information, which has been collected about you in this study. A copy of this form is you to keep for your records.

Participant's initials _____

HUMAN SUBJECTS
OFFICE OF RESEARCH
PROJECT # 05-122 HR 0506
APPROVED 6/13/05 TO 6/12/06

Contact Information: If you have any questions we invite you to ask them now. If you have questions later, please feel free to contact Estevam Strecker (streces@auburn.edu) at 750-1258 or Dr. David Pascoe (pascodd@auburn.edu) at 844-1479. For more information regarding your rights as a research participant you may contact the Auburn University Office of Human Subjects Research or the Institutional Review Board by phone (334)-844-5966 or e-mail at MACROBUTTON HtmlResAnchor hsubjec@auburn.edu or MACROBUTTON HtmlResAnchor IRBChair@auburn.edu.

You will be provided a copy of this form to keep.

YOU ARE MAKING A DECISION WHETHER OR NOT YOU WISH TO PARTICIPATE IN THIS RESEARCH STUDY. YOUR SIGNATURE INDICATES THAT YOU HAVE DECIDED TO PARTICIPATE HAVING READ THE INFORMATION PROVIDED ABOVE.

		06/22/05	
Participant's signature	Date	Investigator obtaining consent	Date
		ESTEVAM STRECKER	
Print Name		Print Name	

HUMAN SUBJECTS
OFFICE OF RESEARCH
PROJECT # 05-122 MR 0506
APPROVED 6-13-05 TO 6-12-06

DIET RECALL

The diet recall is often performed for three days. For college students, usually one day to represent their Monday, Wednesday, Friday schedule, one day for your Tuesday or Thursday schedule, and one day for a typical weekend day.

In performing the diet recall, it is essential that you maintain normal eating habits and write down everything, with the exception of water. This is the only way that you will understand your current eating habits that can be maintained or changed. Itemize your food intake and be specific regarding food description and serving size.

What's a Standard Serving?

Type of Food	Serving Size
Meat, poultry, fish, beans, eggs, and nuts	2 to 3 oz. cooked, which is about the size of: • half a chicken breast without skin • 1 chicken leg and thigh without skin • 2 slices of roast beef • 1 medium loin pork chop • 1 cup of cooked, dry beans • 4 Tbsp. of peanut butter • 1 small hamburger patty • 1/2 cup tuna, canned in water • 2 eggs • 8 to 12 large shrimp
Nonstarchy vegetables, such as carrots, broccoli, and lettuce	• 1/2 cup cooked • 1 cup raw
Starchy vegetables, such as potatoes, beans, and squash	• 1/2 cup corn • 1 small baking potato • 1/2 cup peas, lentils, or beans • 1/3 cup sweet potato or yam • 3/4 cup winter squash
Fruit	• 1 apple, banana, orange, or peach • 3 apricots • 12 sweet cherries • 1½ dried figs • 3 prunes • 1½ cups cubed watermelon • 1/2 cup canned fruit • 3/4 cup fruit juice • 1/8 avocado

Cheese	• 1½-oz. low-fat or nonfat cube • 1/2 cup low-fat or nonfat ricotta cheese • 1 Tbsp. grated low-fat or nonfat cheese
Milk	• 1 cup low-fat or nonfat milk • 1 cup low-fat or nonfat yogurt
Bread	• 1/2 bagel • 2 bread sticks • 1 slice bread • 1 roll • 1/2 English muffin • 1 6-inch tortilla
Cereal	• 1 oz. dry breakfast cereal, or about 1 cup of cereal flakes • 1/2 cup cooked cereal, such as oatmeal
Rice	• 1/2 cup cooked
Pasta	• 1/2 cup cooked
Oil or spread	• 1 tsp. safflower, olive, or canola oil • 1 tsp. margarine, butter, or shortening • 2 tsp. mayonnaise
Salad dressing	• 1 Tbsp. low-fat or nonfat French, Italian, or Thousand Island dressing

Taken from:
http://health.discovery.com/centers/articles/articles.html?chrome=c14&article=LC_135&center=p04

Sample Dietary Recall

Food/Beverage	Serving Size
Breakfast	
Skim Milk	1 ½ cups
Apple	Medium size
Plain Bagel	1
Non-Fat Strawberry Yogurt	1 cup

Name ______________________________ Date: ________________

Gender: M F Height: _____ ft _________ in Weight __________ lbs.

Activity Level: Very Sedentary Sedentary Moderately Active Active Very Active

Food/Beverage	Serving Size

Tennis Research Study PAR Q Medical Questionnaire*

Please read each question carefully and answer honestly. If you do not understand the question, please ask the investigator for clarification. Check the appropriate answer.

No	Yes	
____	____	1. Are you under the age of 19 or over the age 35?
____	____	2. Has your doctor ever said you have heart trouble?
____	____	3. Have you ever had a heart murmur, rheumatic fever or respiratory problems?
____	____	4. Have you ever been told that you have a fast resting heart rate?
____	____	5. Have you ever been told by your doctor or nurse that your blood pressure is too high?
____	____	6. Have you ever been told that your cholesterol is too high?
____	____	7. Have you been told that you have a kidney disorder?
____	____	8. Have you been told that you have diabetes or that your blood sugar is too high?
____	____	9. Have you been told that your electrocardiogram (EKG), 12 lead EKG or stress test is not normal?
____	____	10. Has your doctor ever told you that you have a muscle, bone, or joint problem such as arthritis that has been aggravated by exercise, or might be made worse by exercise?
____	____	11. Have you felt faint, dizzy, or passed out during or after exercise?
____	____	12. Have you ever felt pain, pressure, heaviness, or tightness in the chest, neck, shoulders, or jaws as a result of exercise?
____	____	13. Do you have any reason to believe that your participation in this investigative effort may put your health or well being at risk?
____	____	14. Have you been hospitalized in the past year? If so, why?
____	____	15. Are you taking prescription medicine? If so, what?

*Adapted from British Columbia Department of Health and Michigan Heart Association

Signature of subject _____ Date _____