# EFFECT OF CAFFEINE ON SIMULATED INTERMITTENT HIGH-INTENSITY SPORT PERFORMANCE

by

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I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or material which to a substantial extent has been excepted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.

Signed……………………………………………

Gene Stuart (Thesis candidate)

Date………………

# ACKNOWLEDGEMENTS

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# PREFACE

## Background

After returning home from the University of Otago where I completed a Bachelor of Physical Education with Honours, I began teaching sport science and developing the strength and condition of Auckland representative rugby players. At this time there where a number of issues with regard to ideal types of ergogenic aids that could enhance the performance of an intermittent high-intensity team sport like rugby. It was well known that the supplementation of caffeine could enhance endurance type exercise performance but it was less clear whether it could provide any benefit to short-term strength and power performance. Therefore it was uncertain whether the ingestion of caffeine could provide any ergogenic benefit in sports requiring intermittent high-intensity periods over the duration of a game.

During my time at Otago a friend had compiled a comprehensive time-motion analysis of rugby super 12 games to characterise the physical demands of the game. A simulation was developed that measured the specific physical and skill performance tasks of a rugby game over a brief amount of time. With slight timing adjustments made to the simulation the test could be extended to allow performance to be measured over a real-game time. I therefore felt inspired to determine the effect of caffeine on an intermittent high-intensity sport like rugby. The New Zealand Rugby Football Union considered this project worthy of funding.

The main focus of my project was to investigate the effects of caffeine on performance. A new transdermal fluid sampling technique became available that could non- invasively sample blood plasma so that caffeine and adrenaline responses

to an acute dose of caffeine could be measured. These physiological measures could provide information to investigate the underlying mechanisms that might be responsible for any change in performance. All fluid samples were taken by Dr Christian Cook and his assistants and later assayed for at HortReserach labs.

## Organization of the Thesis

My thesis is presented as a series of chapters, the first of which is a meta-analytical review of caffeine and exercise performance presented in the journal format for Sports Medicine. This meta-analytical review is the first quantitative review that has summarized the effect of caffeine on exercise performance and provides magnitudes of effects and associated coefficients of variation. I conclude the review with recommendations on future directions for caffeine research.

It is evident from my literature review that there is still considerable uncertainty in a number of factors relating to the study of caffeine on exercise performance. Furthermore, there is no literature that has examined the effect of caffeine on a team-sport performance that requires intermittent high-intensity bouts of exercise over a real game time.

The second chapter is the report of the controlled trial. The main focus of my project was to measure the effect of caffeine on a simulated intermittent high-intensity sport performance like rugby. The paper has been presented in the format as submitted to the journal Medicine and Science in Sports and Exercise. This research has provided information on the usefulness of caffeine in a game typical of team sport performance

that requires combination of physical and skill demands, and some indications of underlying physiological mechanisms.

Chapter Three consists of an overview where I summarise the findings of my research and deal with some practical applications of the findings. I also discuss some of the strengths and limitations of the controlled trial and conclude with some direction for future research.

Included in the Appendices are the subject information sheets, and consent forms, caffeine food list, and diet history chart. In addition, more detailed descriptions, diagrams and pictures of performance tests and procedures are included. Also included are figures of sprint performance not shown in Chapter 2. A copy of the abstract submitted to the New Zealand Sports Medicine and Science Conference is included in the Appendices. The final form of this manuscript as accepted for publication in the journal Medicine and Science in Sports and Exercise is also appended.

**Chapter 1**

# Effect of Caffeine on Exercise Performance: A meta-analysis

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**Abstract**

Caffeine is now an unrestricted ergogenic aid for competitive athletes. Previous reviews of caffeine's effects on exercise performance have been limited to qualitative analysis. The purpose of this paper was therefore to quantitatively meta-analyze the effects of caffeine on exercise performance. We identified 90 estimates of performance effects of caffeine in 32 peer-reviewed studies. All estimates were converted to mean power in an equivalent time trial then subjected to a mixed-model meta-analysis. The fixed effects were gender, training status (elite athlete, non-elite athlete, non-athlete), dietary caffeine status (habitual consumer, non-consumer), caffeine abstention period, caffeine dose (mg/kg body mass), type of caffeine (pure or in coffee), delay between ingestion and performance test, duration of test, and presence or absence of fatiguing exercise before the test. The random effects accounted for within- and between-study variance. We found that caffeine enhanced mean power by 2.8% (90% confidence limits ± 1.1%) in male non-elite athletes who are habitual caffeine consumers abstaining from caffeine for 2 d before consuming 6 mg/kg of caffeine capsules 1 h before performing a 30-min time trial without intervening fatiguing exercise. The effects for other athletes and conditions were: females, 3.1% (± 2.7%); elite athletes, 2.9% (± 1.4%); non-athletes, 1.3% (± 1.2%); habitual non-consumers, 4.0% (± 1.4%); 7 d of abstention, 3.4% (± 2.6%); 0.3 mg/kg of caffeine, 1.6% (± 5.3%); caffeinated coffee, 1.0% (± 1.6%); 2-h delay before exercise, 2.9% (± 1.2%); 6-s exercise test, 1.6% (± 1.7%); prior fatiguing exercise, 3.0% (± 1.6%). Each of these effects of caffeine varied typically between studies by ± 1.4% (the between-study random effect; 90% confidence limits ± 0.9 to ± 3.5%). We conclude that caffeine has a greater effect on performance with athletes, with habitual non-consumers of dietary caffeine, when administered as pure caffeine, and

in endurance exercise, but there is considerable uncertainty about the magnitude of the effects on individuals. More research is needed to reduce this uncertainty and to determine the performance effects of caffeine with females, following longer periods of dietary abstention, in low doses, and for brief exercise. There has also been no research on effects of caffeine on the repetitive fatiguing exercise typical of team sports.

## 1    Introduction

The use of caffeine as an ergogenic aid by athletes has been popular over the years owing to the relative inexpensiveness, availability and reports of its ergogenic benefit. Given the volume of research and the variability in the findings there have been a number of qualitative or narrative reviews summarizing the effects of caffeine ingestion on exercise performance (Clarkson, 1993; Dodd, Herb, & Powers, 1993; Graham, 2001; Graham, Rush, & Van Soeren, 1994; Nehlig & Derby, 1994; Spriet, 1995; Tarnopolsky, 1994). These studies identified a number of factors relating to subjects and experimental design that were likely to relate to the variability in outcomes between studies: gender, training status, dietary caffeine status, caffeine abstention period, caffeine dose, type of caffeine, delay between ingestion and performance test, and duration of performance test. Variation in these factors between studies has made it difficult for previous reviewers to reach quantitative conclusions about the effects of caffeine on exercise performance.

Meta-analysis is especially useful for summarizing and analyzing prior research when uncertainty arises from differences in subject characteristics and study design. Meta-analysis also helps identify factors needing further research. The purpose of this

review was therefore to conduct a meta-analysis to allow effective quantitative comparison of caffeine related studies.

## 2   Methods

### 2.1 Study Selection

Literature searches of computer databases were performed for the period up to and including August 2004 (PubMed 1966-2004, Sport Discuss 1949-2004, EMBASE 1980-2004). The reference lists of major review articles and all original-research articles identified by the search were examined for other potentially eligible studies. The computer-based search strategy included common text words and medical subject headings related to caffeine, including caffeine, performance, power output, sprint, strength, endurance. Studies were included only if they were published in English.

### 2.2 Meta-analysis

The main outcome from a traditional meta-analysis is a weighted mean of estimates of the statistic of interest in various studies, where the weighting factor is the inverse of the square of the sampling standard error of the statistic. The procedure can be considered as a sophisticated way to weight estimates by the sample size that produced them, although the procedure also accounts for differences in error of measurement estimates. We performed a mixed-model meta-analysis to account properly for heterogeneity between the estimates provided by the estimate(s) from each study (that is, true variation between estimates, which is variation not due simply to sampling error). Mixed-model meta-analysis provides estimates of sources of true variation as standard deviations, which convey to the reader the typical variation in the true value of the statistic from estimate to estimate (when controlling for the fixed

effects; that is, when all fixed effects have the same values for the estimates). Traditional meta-analysis deals with heterogeneity by testing for it, then deleting "outlier" studies if necessary until the test statistic is no longer statistically significant. Traditional and mixed-model approaches to meta-analysis also permit estimation of the effects of differences in subject characteristics and study design between estimates and studies. In mixed modeling these effects are called "fixed"–hence the term mixed model, which refers to a mixture of fixed and random effects.

The meta-analyses were performed with the mixed modeling procedure (Proc Mixed) in the Statistical Analysis System (Version 8.2, SAS Institute, Cary, NC). The code for the Proc Mixed step was adapted from Yang (2003).

The reported measures of exercise performance were converted into percent changes in mean power in an equivalent time trial of the same duration as the performance test. To perform the conversions we used the methods of Hopkins et al. (2001). The converted values of mean power and relevant data from each study that contributed to the meta-analysis are presented in Appendix 2 [appended at the end of this chapter, not at the end of the thesis; the numbered references in the Table are included in this chapter and in the final reference list at the end of the thesis].

The weighting factor for the meta-analysis was derived from the $p$ value provided by the authors and the degrees of freedom. Where the $p$ value was given as "$p<0.0x$", we attempted to derive the exact $p$ value from any test statistics that were also provided. Otherwise we used the value 0.0x. We were able to estimate $p$ values for almost all non-significant ("$p>0.05$") estimates using errors of measurement from similar measures from the same study or other studies by the same authors. For several studies we used estimates of the standard error of measurement from similar measures in the review of Hopkins et al. (2001). The fixed-effect model consisted of

the following terms: gender (coded as proportion of males, ranging from 0 for all females to 1 for all males), training status (three levels: elite athlete, non-elite athlete, non-athlete), type of caffeine (simplified to pure caffeine and caffeine administered as coffee or added to decaffeinated coffee), the logarithm of the dose of caffeine in mg per kg of body mass, the square of the log of the dose (to account for any first-order curvature over the dose range), the proportion of habitual caffeine users in the study (0 for all non-users through 1 for all users), the interaction of the proportion of users with the number of days of withdrawal from caffeine-containing foods and drinks before the study, the time in hours between ingestion of caffeine and the start of the exercise test, the presence of absence of a bout of fatiguing exercise between administration of caffeine and the exercise test, the logarithm of the duration of the exercise test in minutes, and the square of the log of the duration (to account for any first-order curvature over the range of durations). With so many main effects we did not attempt to model any interactions between the main effects. The random effects were within- and between-study variances.

Individual values for the residuals and random effects were displayed graphically for identification of possible outliers ($t$ values ~3 or more). The funnel plots showed little evidence of publication bias (asymmetry with more positive effects for studies with smaller weighting factors).

To express uncertainty in the effects we used 90% confidence limits (90%CL), because the true value of the effect is "very unlikely" (5% chance) to be greater than the mean + 90%CL and very unlikely to be less than the mean - 90%CL (Hopkins, 2002). To interpret the outcomes and confidence limits we assumed that the smallest worthwhile change in mean power is ~0.5% (Hopkins, Hawley, & Burke, 1999).

2.3 Descriptive Statistics of Studies and Estimates

We performed the meta-analysis on 90 estimates of performance from 32 studies of 990 subjects (834 males, 93 females, 73 gender not stated). The details of these studies are provided in Appendix 2. Estimates were subgrouped as follows: 34 for elite athletes, 20 for non-elite athletes, and 36 for non-athletes; 85 for caffeine and 5 for coffee; 76 without and 14 with intervening fatiguing exercise between administration of caffeine and start of the exercise test. Other descriptive statistics for the meta-analyzed estimates are shown in Table I. Only a few studies were omitted from the meta-analysis; the studies and their findings are listed in Appendix 1 [appended at the end of this chapter, not at the end of the thesis].

Table I. Descriptive statistics of subjects and protocols for the 90 meta-analyzed estimates in the 32 studies of the effect of caffeine on exercise performance.

| | No. of estimates | | | | | |
| | Info. stated | Info. not stated | Mean | SD | Min | Max |
|---|---|---|---|---|---|---|
| Proportion of males | 84 | 6 | 0.89 | 0.24 | 0 | 1 |
| Proportion of caffeine users | 62 | 28 | 0.52 | 0.48 | 0 | 1 |
| Time withdrawn from caffeine (d) | 89 | 1 | 2.6 | 2.2 | 0 | 7 |
| Dose of caffeine (mg/kg) | 90 | 0 | 5.8 | 1.9 | 2.1 | 13 |
| Duration of exercise test (min) | 90 | 0 | 21 | 28 | 0.01 | 120 |
| Ingestion-exercise delay (h) | 90 | 0 | 1.3 | 0.9 | 0.5 | 6 |

## 3   Effects of Caffeine on Performance

The meta-analyzed effects are summarized in Tables II and III. Table II shows the effect of caffeine on performance for "reference" subjects and conditions, which are generally typical of the studies: male non-elite athletes who are habitual caffeine users abstaining from caffeine for 2 d before performing a 30-min time trial 1 h after consuming 6 mg/kg of caffeine capsules without intervening fatiguing exercise. For

these subjects and conditions caffeine enhances mean power by 2.8% (90% confidence limits ±1.1%). Effects for other subjects and conditions are also shown in Table II, whereas Table III shows the difference in the effect between different subjects and conditions.

Table II. Meta-analyzed effects of caffeine on physical performance for the reference condition and departures from the reference condition of male non-elite athletes who are habitual caffeine users abstaining from caffeine for 2 days before performing a 30-min time trial 1 hour after consuming 6 mg/kg of caffeine capsules without intervening fatiguing exercise. Effects shown are percent improvements in mean power output in the time trial, with uncertainty expressed as 90% confidence limits (±90%CL).

| | Effect (%) | ±90%CL (%) |
|---|---|---|
| Effect of gender | | |
|     Females | 3.1 | 2.7 |
|     Males | 2.8 | 1.1 |
| Effect of training status | | |
|     Elite athlete | 2.9 | 1.4 |
|     Non-elite athlete | 2.8 | 1.1 |
|     Non-athlete | 1.3 | 1.2 |
| Effect of user status | | |
|     Non-users | 4.0 | 1.4 |
|     Users, 0 days withdrawn | 2.6 | 1.2 |
|     Users, 2 days withdrawn | 2.8 | 1.1 |
|     Users, 7 days withdrawn | 3.4 | 2.6 |
| Effect of caffeine dose | | |
|     0.3 mg/kg | 1.6 | 5.3 |
|     1 mg/kg | 2.3 | 2.0 |
|     3 mg/kg | 2.7 | 1.2 |
|     6 mg/kg | 2.8 | 1.1 |
|     10 mg/kg | 2.8 | 1.3 |
| Effect of type of caffeine | | |
|     Caffeine capsules | 2.8 | 1.1 |
|     Caffeine in coffee | 1.0 | 1.6 |
| Effect of ingestion-exercise delay | | |
|     0.5 h | 2.4 | 2.4 |
|     1 h | 2.8 | 1.1 |
|     2 h | 2.9 | 1.2 |
|     4 h | 2.7 | 1.4 |
|     6 h | 2.5 | 1.9 |
|     10 h | 2.0 | 3.2 |
| Effect of duration of test | | |
|     0.1 min | 1.6 | 1.7 |
|     1 min | 2.4 | 1.4 |
|     10 min | 2.8 | 1.2 |
|     30 min | 2.8 | 1.1 |
|     100 min | 2.8 | 1.4 |
|     200 min | 2.7 | 1.8 |
| Effect of intervening fatiguing exercise | | |
|     No exercise | 2.8 | 1.1 |
|     Exercise | 3.0 | 1.6 |

Table III. Effects of Table 2 shown as changes in the effect of caffeine for different subjects and conditions. Effects shown are percent changes in mean power output in a time trial, with uncertainty expressed as 90% confidence limits (±90%CL).

|  | Effect (%) | ±90%CL (%) |
|---|---|---|
| Females – males | 0.3 | 2.8 |
| Elite – non-elite | 0.1 | 1.6 |
| Elite – non-athlete | 1.7 | 1.5 |
| Non-elite – non-athlete | 1.5 | 1.4 |
| Withdrawal from caffeine use per day | 0.1 | 0.4 |
| Non-users – users (0 d withdrawal) | 1.4 | 1.2 |
| Non-users – users (2 d withdrawal) | 1.2 | 1.2 |
| Non-users – users (7 d withdrawal) | 0.7 | 2.8 |
| Caffeine dose linear per 10x | 1.1 | 5.2 |
| Caffeine dose quadratic per 10x | -0.6 | 4.2 |
| Caffeine – coffee | 1.8 | 1.6 |
| Ingestion-exercise delay linear per 10x | 0.9 | 4.5 |
| Ingestion-exercise delay quadratic per 10x | -1.7 | 6.3 |
| Exercise duration linear per 10x | 0.6 | 0.6 |
| Exercise duration quadratic per 10x | -0.2 | 0.5 |
| Perform intervening exercise | 0.2 | 1.3 |

# 4 Considerations for Caffeine Use

## 4.1 Gender

The pharmacokinetics of caffeine have been compared in men and women, both at rest and when exercising (Duthel et al., 1991; Graham & McLean, 1999). At rest, elimination of caffeine in relation to body weight appears to be identical in men and women (Duthel et al., 1991). However, during exercise a fivefold decrease in the female and twofold decrease in male eliminations has been observed (Duthel et al., 1991). In spite of these differences our analysis has revealed little difference in the effects of caffeine on females and males, and although there is considerable uncertainty in the effect on females and in the difference between females and males, athletes of both sexes are likely to obtain considerable enhancements in performance through use of caffeine.

## 4.2 Training Status

Athletes are likely to gain twice as much ergogenic benefit from caffeine than non-athletes. There appears to be little difference in benefit between elite and non-elite athletes following an acute dose of caffeine. Uncertainty in the estimates allows for the possibility that there is a graded effect from least effect for non-athletes through greatest effect for elite athletes. Athletes have genetic endowment and exposure to training or exercise that differ from those of non-athletes (Hopkins et al., 1999). It is likely that a central effect of caffeine to reduce the perception of effort and fatigue may benefit an athlete greater who has the mental discipline and experience to exercise longer at a high intensity. Additionally, athletes possess muscle fibre type ratios different from non-athletes. It is also possible that caffeine's effect may be elicited primarily in oxidative muscle fiber types. As increased sensitivity has been demonstrated in slow-twitch compared with fast-twitch muscle fibers in humans (Mitsumoto et al., 1990).

## 4.3 User Status

A person who does not consume caffeine-containing foods regularly in their diet will experience greater ergogenic effect from an acute dose of caffeine than a habitual consumer. Van Soeren et al. (1993) reported that the metabolism of caffeine differed between the users and nonusers and that caffeine ingestion had a greater impact on the adrenaline response during exercise for nonusers. Studies have employed an average of 2.6 days of withdrawal from caffeine containing foods to washout existing concentrations and resensitize subjects to its effect. Our data indicate that it may take a regular caffeine consumer up to a week to gain similar benefits to a non-user.

However, this effect of withdrawal has considerable uncertainty, so that even after 2 days there is some chance that the true effect of withdrawal is complete. There has yet to be any work that has examined a dose-response relationship between users and nonusers for exercise performance. As it currently remains unclear what tissues are critical in mediating the ergogenic responses to caffeine, it is difficult to speculate about the importance of habituation within specific tissues.

## 4.4 Caffeine Dose

There is a strong dose-dependent effect of caffeine on exercise performance, with the maximum effect occurring in the range 3-10 mg/kg. A dose-response effect may vary according to the sensitivity of the individual to caffeine, as it is known that some individuals are more sensitive than others to its effects (Evans & Griffiths, 1992). The uncertainty evident in doses of <1 mg/kg leaves open the possibility that it could be just as an effective ergogenic dose. Ingestion of higher doses (10-15 mg per kilogram body weight) is not recommended, because caffeine plasma levels increase toward the reported toxic range for caffeine (200 μM) and side effects of irritability, anxiety, and nausea may become present (Fredholm, 1985).

## 4.5 Type of Caffeine

Caffeine is more effective as an ergogenic aid in performance when it is consumed as pure caffeine rather than with, or as, coffee. Coffee is known to contain many other substances capable of influencing metabolism, including trigonelline, chlorogenic acid, tannin, and ketones; non-volatile acids caffeic and quinic acid; and volitle acids including acetic, propionic, and butyric acid (Stephenson, 1971). It is possible that any or one of these substances may either partially block or interfere

with mechanisms that may be responsible for the ergogenic effect of caffeine on performance.

## 4.6 Ingestion-Exercise Delay

There appears to be little decline in the ergogenic effect of caffeine even 5 h after it is consumed, but the uncertainty allows for the true effect to decline more rapidly. Nearly 100% of orally administered caffeine is absorbed, with time to peak levels ranging from 15 to 120 min. The half-life of caffeine is variable 1.5-9.5 h, with average values in the 4- to 5-h range (Kennedy et al., 1987). Because it takes about four half-lives to effectively eliminate a drug from the body (Winter, 1988), concentrations of caffeine may still be high enough sometime after ingestion to elicit an ergogenic effect. Our results indicate an individual will most likely experience the greatest ergogenic effect with the least variability 1-2 h after ingestion.

## 4.7 Duration of Test

Caffeine clearly has more effect for endurance exercise, with peak benefit for exercise lasting 10 to 100 min. The benefit for brief explosive exercise lasting a few seconds is about half that for the longer periods of exercise, but still worth having. The effect of caffeine to reduce the perception of effort and fatigue relating to exercise performance has been reported to be greater in endurance exercise (Tarnopolsky, 1994) thereby allowing athletes to work at a higher intensity for longer at the same perceived level of effort (Cole et al., 1996).

## 4.8  Intervening Fatiguing Exercise

Caffeine has little extra effect on performance when prior exercise has produced some fatigue, although there is substantial uncertainty.  In all previous studies the fatiguing exercise has been continuous and either at the same or at lower intensity than exercise in the subsequent performance test, which was also continuous.  What has yet to be examined is the effect of caffeine on performance after repetitive fatiguing exercise typical of team sports.

## 5  Conclusion

Caffeine is a pharmacologically active drug that can produce substantial ergogenic benefit for exercise performance.  However, studies have displayed considerable variability in results and review articles have qualitatively outlined factors that might account for this variability.  This meta-analytical review is the first quantitative review that has summarized the effect of caffeine on exercise performance and provided magnitudes of effects and associated coefficients of variation.

In summary, caffeine has a greater effect on performance in athletic dietary caffeine non-users, after administration of pure caffeine, in endurance exercise.  This analysis has also identified the uncertainty of the effect in factors that are related to the study of caffeine and exercise performance.  Further research is needed to determine more precisely the performance effects of caffeine on females, in exercise following longer periods of dietary abstention, in low doses, and for brief high intensity exercise.  There is also a need to investigate the effects of caffeine on the repetitive fatiguing exercise over the duration typical of team sport performance.

## Acknowledgements

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**Appendix 1**

The following studies were not included in the meta-analysis for the reasons stated.

(Sasaki, Takaoka, & Ishiko, 1987a):  Male non-athletes; caffeine dose of 11 mg/kg; 7.5% decrease in time to exhaustion (p>0.05) following a complex preload.  We cannot convert time to exhaustion to an equivalent time-trial power output when there is a preload.  In any case, when we attempted to use error of measurement of 0.7% from Sasaki et al. (1987b), the effect was an extreme outlier with respect to magnitude of the weighting factor and with respect to the position of the study on a funnel plot.

(Kruk, Pekkarinen, & Hanninen, 1999): Non-user male non-athletes; caffeine dose of 3 mg/kg; in their 60-s repeated jump test, there were unrealistic effects of caffeine on peak power (19%, p=0.05) and mean power (10%, p=0.02).  Standard errors of measurement computed from these data indicated that the measures of peak and mean power were very unreliable (22% and 9.7% respectively).

(Jacobs, Pasternak, & Bell, 2003):  Male athletes; caffeine dose of 4 mg/kg; measure of performance was number of repetitions in three sets of a repeated leg- and bench-press test with a load of 80 %1RM (equivalent to time to exhaustion at a constant power output); effects on all six measures of performance were not statistically significant (p>0.05) and ranged from -16% through 8.8%.  We have no formula to convert performance time to equivalent time-trial time for tests of such short duration (0.3-0.7 min).

(Trice & Haymes, 1995) Male cyclist non-users; caffeine dose of 5 mg/kg in decaffeinated coffee; alternating 1-min bouts of exercise and rest for ~1 h until exhaustion; 27% increase in time to exhaustion (p<0.05).  We cannot convert changes in performance time in this protocol into an equivalent time-trial power.

(Cole et al., 1996): Male cyclists; caffeine dose of 6 mg/kg; 30 min of work at defined submaximal perceived exertion; 30% increase in work done (p<0.05).  We cannot convert changes in submaximal work into equivalent time-trial power.

(Jackman, Wendling, Friars, & Graham, 1996):  Non-athlete males and females; caffeine dose 6 mg/kg; preload of 2 min at VO2max with 6 min rest, repeated once; 20% increase in time to exhaustion at $VO_{2max}$ (p<0.05).  We cannot convert changes in performance time in this protocol into an equivalent time-trial power.

**Appendix 2:** Effects of caffeine on exercise performance

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on… | | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | reported measure | time-trial power | | | | |
| Perkins & Williams [1] | 14 F | Unstated | Non-athlete | 4 | caffeine | 1 | 0.5 | Cycling progressive workload to exhaustion | 5 | no | Incremental TTE | 1.2 | 0.6 | >0.05 | *0.61* | *1.13* | *3* |
| | | | | 7 | caffeine | 1 | 0.5 | | | | | 0.2 | 0.1 | >0.05 | *0.93* | *1.13* | *3* |
| | | | | 10 | caffeine | 1 | 0.5 | | | | | 4.2 | 2.1 | >0.05 | *0.09* | *1.13* | *3* |
| Costill et al. [2] | 7M & 2F cyclists | Unstated | Athlete | 5.5 | coffee | 0.38 | 1 | Cycling 80% $VO_{2max}$ to exhaustion | 76 | no | Constant-power TTE | 19 | 1.6 | <0.05 | 0.05 | 0.69 | 1.5 |
| Ivy et al. [3] | 7M & 2F cyclists | Unstated | Athlete | 7 | caffeine | 0.5 | 1 | Cycling 2 h isokinetic cycling @ 80 rpm | 120 | no | Work done | 7.4 | 7.4 | <0.01 | 0.01 | 2.21 | 4.7 |
| Berglund et al. [4] | 8M & 5F trained cross-country skiers | Unstated | Elite athlete | 6 | caffeine | 0.5 | 1 | High altitude Cross-country ski course (23 km) | 102 | no | Time-trial speed | 1.7 | 1.7 | 0.06 | 0.06 | 0.82 | 2.1 |
| | 10M & 4F trained cross-country skiers | Unstated | Elite athlete | 6 | caffeine | 0.5 | 1 | Low altitude Cross-country ski course (20 km) | 100 | no | Time-trial speed | 3.2 | 3.2 | <0.001 | 0.001 | 0.76 | 2 |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on... reported measure | time-trial power | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bond et al. [5] | 12 M sprinters | Non-users | | 5 | caffeine | 2 | 1 | Dynamometer peak torque and power in 6 reps at 3 speeds | 0.005 | no | Extensor peak torque at 30°/s | -1.3 | -1.3 | >0.05 | 0.77 | 4.49 | 11 |
| | | | | | | | | | 0.025 | | Extensor peak torque at 150°/s | 0.6 | 0.6 | >0.05 | 0.89 | 4.49 | 11 |
| | | | | | | | | | 0.05 | | Extensor peak torque at 300°/s | -8 | -8 | >0.05 | 0.1 | 4.49 | 11 |
| | | | | | | | | | 0.005 | | Flexor peak torque at 30°/s | -9.6 | -9.6 | >0.05 | 0.06 | 4.49 | 11 |
| | | | | | | | | | 0.025 | | Flexor peak torque at 150°/s | -3.3 | -3.3 | >0.05 | 0.48 | 4.49 | 11 |
| | | | | | | | | | 0.05 | | Flexor peak torque at 300°/s | -2.3 | -2.3 | >0.05 | 0.62 | 4.49 | 11 |
| | | | | | | | | | 0.005 | | Extensor mean power at 30°/s | 5.9 | 5.9 | >0.05 | 0.22 | 4.49 | 11 |
| | | | | | | | | | 0.025 | | Extensor mean power at 150°/s | 2.5 | 2.5 | >0.05 | 0.59 | 4.49 | 11 |
| | | | | | | | | | 0.05 | | Extensor mean power at 300°/s | 3.7 | 3.7 | >0.05 | 0.43 | 4.49 | 11 |
| | | | | | | | | | 0.005 | | Flexor mean power at 30°/s | 2.5 | 2.5 | >0.05 | 0.59 | 4.49 | 11 |
| | | | | | | | | | 0.025 | | Flexor mean power at 150°/s | 4.3 | 4.3 | >0.05 | 0.36 | 4.49 | 11 |
| | | | | | | | | | 0.05 | | Flexor mean power at 300°/s | 5.1 | 5.1 | >0.05 | 0.28 | 4.49 | 11 |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on… reported measure | time-trial power | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sasaki et al. [6] | 5 M trained runners | Unstated | Athlete | 6 | caffeine | 0.33 | 1 | Running 45 min @ 80% $VO_{2max}$ followed by 5 min rest. Then at 80% $VO_{2max}$ till exhaustion | 85 | no | Constant-power TTE | 16 | 1.3 | <0.05 | 0.05 | 0.45 | 0.7 |
| Williams et al. [7] | 9 M | Non-users | | 7 | caffeine | 7 | 1 | Cycling 1 x 15 s maximum power test | 0.083 | no | Peak power | 0.8 | 0.8 | >0.05 | 0.59 | 1.41 | 3 |
| | | | | | | | | | 0.25 | | Total work | 3.2 | 3.2 | >0.05 | 0.06 | 1.41 | 3 |
| Flinn et al. [8] | 9 M cyclists | Non-users | Non-athlete | 10 | caffeine | 1 | 3 | Cycling incremental test to exhaustion | 15 | no | Incremental TTE | 18 | 13 | <0.01 | 0.01 | 3.87 | 8.2 |
| | | | | | | | | | | | Lactate threshold | 9.3 | 9.3 | <0.05 | 0.05 | 4.03 | 8.6 |
| Collomp et al. [9] | 3M & 3F untrained | Unstated | | 5 | caffeine | 7 | 1 | Cycling 1 x 30 s Wingate test | 0.083 | no | Peak power | 1.6 | 1.6 | >0.05 | 0.39 | 1.73 | 3 |
| | | | | | | | | | 0.5 | | Work done | 2.2 | 2.2 | >0.05 | 0.26 | 1.73 | 3 |
| Graham & Spriet [10] | 6M & 1F trained runners | 2 heavy users, 3 users, 2 non-users | | 9 | caffeine | 2 | 1 | Running ~85% $VO_{2max}$ to exhaustion | 49 | no | Constant-power TTE | 44 | 3.3 | <0.05 | 0.05 | 1.59 | 3 |
| | | | | | | | | Cycling ~85% $VO_{2max}$ to exhaustion | 39 | | Constant-power TTE | 51 | 3.9 | <0.05 | 0.05 | 1.35 | 2.5 |
| Anselme et al. [11] | 10M & 4F untrained | Unstated | | 4 | caffeine | ? | 0.5 | Cycling Repeated 6 sec sprints: force/velocity exercise test | 0.1 | no | Peak power | 6.7 | 6.7 | 0.02 | 0.02 | 2.52 | 6.7 |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on... reported measure | time-trial power | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Collomp et al. [12] | 3M & 4F trained swimmers | Unstated | Athlete | 4.3 | caffeine | 7 | 1 | Swimming 2 x 100m freestyle separated by 20 min recovery | 1.1 | no | Time-trial speed | 2.4 | 7.3 | <0.01 | 0.01 | 1.97 | 3.7 |
| | | | | | | | 1.4 | | 1.1 | yes | Time-trial speed | 4 | 12 | <0.01 | 0.01 | 3.21 | 6 |
| | 2M & 5F untrained swimmers | Unstated | Non-athlete | 4.3 | caffeine | 7 | 1 | | 1.4 | no | Time-trial speed | -0.6 | -1.9 | >0.05 | 0.37 | 1.98 | 3.7 |
| | | | | | | | 1.4 | | 1.4 | yes | Time-trial speed | 0.7 | 2 | >0.05 | 0.36 | 1.98 | 3.7 |
| Jacobsen et al. [13] | 20 M resistance trained athletes | Non-users | | 7 | caffeine | 7 | 1 | Dynamometer strength & power of knee flexors & extensors for 3-15 reps | 0.3 | no | Extensor peak torque at 30°/s | 12 | 12 | <0.05 | 0.05 | 5.96 | 18.9 |
| | | | | | | | | | 0.3 | | Flexor peak torque at 30°/s | 4.6 | 4.6 | >0.05 | 0.24 | 3.79 | 12 |
| | | | | | | | | | 0.067 | | Extensor peak torque at 150°/s | 2.6 | 2.6 | >0.05 | 0.5 | 3.79 | 12 |
| | | | | | | | | | 0.067 | | Flexor peak torque at 150°/s | 4.5 | 4.5 | >0.05 | 0.25 | 3.79 | 12 |
| | | | | | | | | | 0.15 | | Extensor peak torque at 300°/s | 9.2 | 9.2 | <0.05 | 0.05 | 4.4 | 13.9 |
| | | | | | | | | | 0.15 | | Flexor peak torque at 300°/s | 4.6 | 4.6 | >0.05 | 0.24 | 3.79 | 12 |
| | | | | | | | | | 0.15 | | Extensor mean power at 300°/s | 10 | 10 | <0.05 | 0.05 | 4.79 | 15.1 |
| | | | | | | | | | 0.15 | | Flexor mean power at 300°/s | 7.5 | 7.5 | >0.05 | 0.06 | 3.79 | 12 |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on... reported measure | time-trial power | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spriet et al. [14] | 7 M & 1F cyclists | 1 heavy user, 2 users, 5 non-users | | 9 | caffeine | 3 | 1 | Cycling ~80% $VO_{2max}$ to exhaustion | 76 | no | Constant-power TTE | 27 | 2.2 | <0.05 | 0.05 | 0.93 | 1.9 |
| Wiles et al. [15] | 18 M trained runners | Users | Athlete | 2.5 | coffee | 1 | 1 | Running 1500 m time trial | 4.7 | no | Time-trial speed | 1.5 | 1.5 | <0.005 | 0.003 | 0.42 | 1.3 |
| | 10 trained runners | M Users | Athlete | 2.5 | coffee | 1 | 1 | 400-m sprint speed following ~3-min high-intensity pre-load | 4.7 | yes | Time-trial speed | 2.6 | 2.6 | <0.05 | 0.003 | 0.65 | 1.4 |
| Graham & Spriet [16] | 8 M trained runners | 3 heavy users, 3 users, 2 non-users | | 3 | caffeine | 2 | 1 | Running 85% $VO_{2max}$ to exhaustion | 49 | no | Constant-power TTE | 45 | 3.4 | <0.05 | 0.05 | 1.44 | 2.9 |
| | | | | 6 | caffeine | 2 | 1 | | 49 | | Constant-power TTE | 44 | 3.3 | <0.05 | 0.05 | 1.4 | 2.8 |
| | | | | 9 | caffeine | 2 | 1 | | 49 | | Constant-power TTE | 13 | 0.9 | >0.05 | *0.55* | *1.43* | *2.9* |
| MacIntosh et al. [17] | 7M & 4F trained swimmers | Users | Athlete | 6 | caffeine | 2 | 2 | 1,500-m swim | 21 | no | Time-trial speed | 1.8 | 5.5 | <0.05 | 0.05 | 2.46 | 5.8 |
| Pasman et al. [18] | 9 trained cyclists | 4 heavy users, 5 users | | 5 | caffeine | 3 | 1 | Cycling 80%$W_{max}$ to exhaustion | 47 | no | Constant-power TTE | 23 | 1.9 | <0.05 | 0.05 | 0.82 | 1.7 |
| | | | | 9 | caffeine | 3 | 1 | | 47 | | Constant-power TTE | 26 | 2 | <0.05 | 0.05 | 0.87 | 1.8 |
| | | | | 13 | caffeine | 3 | 1 | | 47 | | Constant-power TTE | 23 | 1.9 | <0.05 | 0.05 | 0.82 | 1.7 |
| Bell et al. [19] | 8 M | Users | Athlete | 5 | caffeine | 0.33 | 1.5 | Cycling 5 min @ 50% $VO_{2max}$ then at 85% $VO_{2max}$ to exhaustion | 13 | no | Constant-power TTE | 14 | 1.1 | >0.05 | *0.32* | *1* | *2* |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on… reported measure | time-trial power | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Graham et al. [20] | 8M & 1F trained runners | Users | Athlete | 4.5 | caffeine | 2 | 1 | Running 85% VO2max to exhaustion | 30 | no | Constant-power TTE | 3.3 | 2.5 | <0.05 | 0.05 | 1.08 | 2.3 |
| | | | | 4.5 | decaffeinated coffee + caffeine | 2 | 1 | | 33 | | Constant-power TTE | -1.3 | -0.1 | >0.05 | 0.93 | 1.08 | 2.3 |
| | | | | 4.5 | Regular coffee | 2 | 1 | | 33 | | Constant-power TTE | -1.6 | -0.1 | >0.05 | 0.91 | 1.08 | 2.3 |
| Greer et al. [21] | 9 M untrained | Unstated | | 6 | caffeine | 2 | 1 | Cycling 4 x 30 sec Wingate tests | 0.08 | no | Peak power | 7.1 | 7.1 | >0.05 | 0.06 | 3.3 | 7 |
| | | | | | | | 1.075 | | | yes | Peak power | 3 | 3 | >0.05 | 0.39 | 3.3 | 7 |
| | | | | | | | 1.15 | | | yes | Peak power | 1.5 | 1.5 | >0.05 | 0.65 | 3.3 | 7 |
| | | | | | | | 1.225 | | | yes | Peak power | -7.9 | -7.9 | <0.05 | 0.05 | 3.44 | 7.3 |
| | | | | | | | 1 | | 0.5 | no | Mean power | 1.2 | 1.2 | >0.05 | 0.54 | 1.84 | 3.9 |
| | | | | | | | 1.075 | | 0.5 | yes | Mean power | 0.6 | 0.6 | >0.05 | 0.76 | 1.84 | 3.9 |
| | | | | | | | 1.15 | | 0.5 | yes | Mean power | -4.3 | -4.3 | <0.05 | 0.05 | 1.85 | 3.9 |
| | | | | | | | 1.225 | | 0.5 | yes | Mean power | -7.3 | -7.3 | <0.05 | 0.01 | 2.18 | 4.6 |
| Kovacs et al. [22] | 15 M trained cyclists and triathletes | Users | Elite athlete | 2.1 | caffeine | 2 | 1.1 | Cycling ~60 min time trial | 60 | no | Mean power in fixed-work TT | 1.4 | 1.4 | >0.05 | 0.24 | 1.1 | 3 |
| | | | | 3.2 | caffeine | 2 | 1.1 | | | | Mean power in fixed-work TT | 4.4 | 4.4 | <0.001 | 0.001 | 1.06 | 2.9 |
| | | | | 4.5 | caffeine | 2 | 1.1 | | | | Mean power in fixed-work TT | 4.7 | 4.7 | <0.001 | 0.001 | 1.15 | 3.1 |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on… | | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | reported measure | time-trial power | | | | |
| Van Soeren & Graham [23] | 6 M cyclists | Heavy users | | 6 | caffeine | 4 | 1 | Cycling 80-85% $VO_{2max}$ to exhaustion | 60 | no | Constant-power TTE | 28 | 2.2 | <0.05 | 0.05 | 0.85 | 1.5 |
| | | | | | | 2 | 1 | | | | Constant-power TTE | 36 | 2.8 | <0.05 | 0.05 | 1.1 | 1.9 |
| | | | | | | 0 | 1 | | | | Constant-power TTE | 27 | 2.1 | <0.05 | 0.05 | 0.81 | 1.4 |
| Bruce et al. [24] | 8 M trained rowers | Unstated | Elite athlete | 6 | caffeine | 3 | 1 | Rowing 2000m test | 6 | no | Mean power in fixed-distance TT | 3.1 | 3.1 | 0.01 | 0.01 | 0.89 | 1.8 |
| | | | | 9 | caffeine | 3 | 1 | | | | Mean power in fixed-distance TT | 2.4 | 2.4 | 0.03 | 0.03 | 0.88 | 1.8 |
| Greer et al. [25] | 8 M | Unstated | Non-athlete | 6 | caffeine | 2 | 1.5 | Cycling 80% $VO_{2max}$ to exhaustion | 33 | no | Constant-power TTE | 26 | 2.1 | <0.05 | 0.05 | 0.89 | 1.8 |
| Bell et al. [26] | 16 M untrained | 11 users, 5 non-users | | 6 | caffeine | 1 | 1.5 | Cycling 1 x 30 sec Wingate test | 0.083 | no | Peak power | -0.7 | -0.7 | >0.05 | *0.53* | *1.06* | *3* |
| | | | | | | | | | 0.5 | | Mean power | 0.6 | 0.6 | >0.05 | *0.58* | *1.06* | *3* |
| Paton et al. [27] | 16 M | Unstated | | 6 | caffeine | 2 | 1 | Ten 20 m sprints , each performed within 10 s and followed by rest for the remainder of each 10 s | 1 | no | Sprint speed | -0.1 | -0.1 | 0.9 | 0.9 | 0.78 | 2.2 |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on... reported measure | time-trial power | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bell et al. [28] | 13 M & F | Users | Non-athlete | 5 | caffeine | 0.5 | 1 | Cycling 80% VO2max; to exhaustion performed 1, 3, & 6 hours after treatment ingestion | 24 | no | Constant-power TTE | 18 | 1.4 | <0.05 | 0.05 | 0.65 | 1.6 |
| | | | | | | | 3 | | | | Constant-power TTE | 21 | 1.7 | <0.05 | 0.05 | 0.78 | 2 |
| | | | | | | | 6 | | | | Constant-power TTE | 4 | 0.3 | >0.05 | *0.64* | *0.71* | *1.8* |
| | 8 M & F | Non-users | Non-athlete | 5 | caffeine | 0.5 | 1 | | 24 | no | Constant-power TTE | 35 | 2.8 | <0.05 | 0.05 | 1.19 | 2.4 |
| | | | | | | | 3 | | | | | 24 | 2 | <0.05 | 0.05 | 0.83 | 1.7 |
| | | | | | | | 6 | | | | | 37 | 2.9 | <0.05 | 0.05 | 1.24 | 2.5 |
| Cox et al. [29] | Study A: 12M cyclists and triathletes | Users | Elite athlete | 6 | caffeine | 2 | 3 | Cycled for 120min at 70% VO2max a)after caff, b)caff during, c)coke during, followed by 7kJ/kg time trial | 29 | yes | work rate for fiixed-work TT | 3.4 | 3.4 | 0.04 | 0.04 | 1.46 | 3.6 |
| | | | | | | | 1 | | | | work rate for fiixed-work TT | 3.1 | 3.1 | 0.06 | 0.06 | 1.48 | 3.6 |
| | Study B: 8M cyclists and triathletes | Users | Elite athlete | 0.65 | caffeine | 2 | 0.5 | Cycled for 120min at 70% VO2max a) after caff, b)decaf coke during, c)coke during, followed by 7kJ/kg time trial | 27 | yes | work rate for fiixed-work TT | 1.8 | 1.8 | 0.11 | 0.11 | 0.98 | 2 |
| | | | | | | | 0.5 | | | | work rate for fiixed-work time trial | 2.5 | 2.5 | <0.05 | *0.04* | *1* | *2* |

**Appendix 2:** Effects of caffeine on exercise performance (continued)

| Reference | Subjects | User status | Training status | Dose in mg/kg | Type caffeine | Period of withdrawal (days) | Ingestion of time prior to testing (h) | Test protocol | Duration of exercise in control (min) | Preload | Reported performance measure | Effect of caffeine (%) on… reported measure | time-trial power | Reported p value | p value used | Standard error (%) | Typical error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bell et al. [30] | 9M cyclists | Users | Non-athlete | 5 | caffeine | 0.5 | 1 | Cycle 80% of $VO_{2max}$ to exhaustion a) am caff 5mg/kg, pm 2.5mg/kg; b)plac; c) am 5mg/kg, pm plac; d) am plac, pm 5mg/kg | 18 | no | Constant-power TTE | 31 | 2.5 | <0.05 | 0.05 | 1.08 | 2.3 |
| | | | | | | | | | | | | 24 | 1.9 | <0.05 | 0.05 | 0.83 | 1.8 |
| | | | | | | | | | | | | 17 | 1.3 | <0.05 | 0.05 | 0.58 | 1.2 |
| Conway et al. [31] | 9 M trained cyclists | Unstated | Elite athlete | 6 | caffeine | 2 | 2.5 | Cycled for 90 mins at 68% $VO_{2max}$; then self paced fixed-work time trial (80% of $VO_{2max}$ over 30 min) | 28.3 | yes | work rate for fiixed-work TT | 19 | 19 | 0.08 | 0.08 | 9.48 | 20.1 |
| Doherty et al. [32] | 11 M cyclists | Users | Athlete | 5 | caffeine | 1 | 1.2 | Cycle 60-s all-out test | 1 | no | Mean power | 5.9 | 5.9 | 0.05 | 0.05 | 2.65 | 6.2 |

**Chapter 2**

# Multiple Effects of Caffeine on Simulated High-Intensity Team-Sport Performance

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Running head: Caffeine and team-sport performance

**ABSTRACT**

Caffeine appears to enhance performance of single bouts of high-intensity exercise, but its effects on repeated bouts typical of those in team sports are less clear. **Purpose:** To examine the effects of caffeine on performance of a test simulating some of the physical and skill demands of a rugby game. **Methods:** The study was a randomized cross-over trial in which 9 high-level competitive male rugby players ingested either caffeine (6 mg/kg body mass) or placebo (dextrose) before performing 3-4 trials of a rugby-specific circuit test, with one week between trials. Each trial consisted of 14 circuits in two 40-min halves, with a 2-min rest after Circuit 4 in each half and a 10-min half-time rest. Each circuit consisted of stations for measurement of five straight-line and agility sprints, power generation in two consecutive drives, and accuracy of passing balls. Plasma was sampled indirectly by a non-invasive transdermal technique before administration of treatments, immediately before testing, at half-time and at full-time; samples were assayed chromatographically for caffeine and adrenaline concentrations. **Results:** The effects of caffeine on mean performance (±90% confidence limits) were: sprint speeds, 0.5% (±1.7%) through 2.9% (±1.3%); first-drive power, 5.0% (±2.5%); second-drive power, -1.2% (±6.8%); and passing accuracy, 9.6% (±6.1%). The enhancements were mediated partly through a reduction in fatigue that developed throughout the test, and partly by enhanced performance for some measures in the first circuit. There was evidence of individual responses for some measures of performance, and those for the drives had strong associations with individual changes in plasma caffeine and adrenaline concentrations. **Conclusion:** Caffeine is likely to produce substantial enhancement of several aspects of high-intensity team-sport performance.
**Key Words:** ADRENALINE, FATIGUE, POWER, RUGBY, SPRINT, TEST.

**INTRODUCTION**

The ergogenic effects of caffeine on endurance exercise performance are well documented (for review see Graham, 2001). These studies have reported significant enhancements in mean power production in fixed distance time-trials and times to exhaustion. The examination of caffeine on short-term higher intensity types of exercise performance has received considerably less attention. However, ergogenic benefit has been shown for performance of single sprints, and strength following caffeine ingestion (Graham, 2001). Furthermore, studies of caffeine's effect on repeated bouts of high-intensity exercise that may provide support for its use to enhance performance of most games of team sport are limited and less clear (Paton, Hopkins, & Vollebregt, 2001).

Team sport performance characterized by repeated bouts of high-intensity exercise over the duration of a game can incur substantial fatigue (Green, 1997). In competitive team sports the outcome can often be determined late in the second half when athletes may experience lapses in concentration and an inability to perform maximally because of fatigue. Caffeine has been shown to reduce the perception of exertion thereby allowing athletes to work at a higher intensity at the same perceived level of effort (Cole et al., 1996) and improve psychomotor performance (Hogervost, Riedel, Kovacs, Brouns, & Jolles, 1999) after strenuous exercise. Caffeine could therefore enhance the performance of team sports that involve prolonged repeated bouts of high-intensity exercise combined with psychomotor skills (such as accuracy of passing or shooting a ball) by attenuating fatigue. It was therefore the purpose of the present study to examine the effect of caffeine on a simulated team sport performance that reflects the physical and skill demands of a rugby game.

It is apparent that caffeine is a powerful drug that affects many tissues throughout the body, including the brain, adipose tissue, skeletal, smooth and cardiac muscles, and adrenal glands (Daley, Burns, & Snyder, 1981). Because caffeine enters both the nervous system and skeletal muscle, central and peripheral effects would be difficult to distinguish. It also seems likely that different mechanisms could be responsible for performance enhancement with caffeine in different types of exercise (Spriet, 1995). Caffeine has been shown to elevate circulating levels of plasma adrenaline (Graham, 2001) leading to the "metabolic" theory to explain caffeine's ergogenic effect (Costill, Dalsky, & Fink, 1978; Essig, Costill, & Van Handel, 1980; Ivy, Costill, Fink, & Lower, 1979). However, ergogenic benefits of caffeine on prolonged exercise have also been found when the dose of caffeine was insufficient to elevate plasma adrenaline (Graham & Spriet, 1995). Therefore the second purpose of our study was to examine whether changes in performance following caffeine ingestion could be mediated via changes in plasma adrenaline concentration.

**METHODS**

**Study design.** The study was a randomized cross-over trial, in which subjects performed 3-4 simulated rugby tests. The subjects and research assistants who supervised the stations of the performance test were blind to the treatment. A familiarization and three treatment trials of either caffeine or placebo were each separated by a week. Owing to subject injury and the breakage of an essential piece of measuring equipment during the second trial, a fourth trial was added to ensure adequate data for each subject for each treatment. Subjects arrived 75 min prior to exercise testing, where

they where weighed and had a transdermal fluid sample drawn from the forearm. One hour prior to exercise testing the subjects ingested capsules containing either caffeine or placebo (dextrose). One hour post ingestion a further fluid sample was drawn immediately before exercise testing. At that stage subjects were asked to comment if they were reasonably aware of whether they had received caffeine. Subjects then performed two 40-min halves of a rugby-specific circuit test. Fluid samples were drawn at the end of each half. Fluid samples were later assayed for caffeine and adrenaline concentrations.

**Subjects.** Eleven elite amateur male rugby players where recruited from the Auckland premier rugby competition. All were regular consumers of food and beverages containing caffeine. The players were all members of a team that had recently won the regional championship. Owing to injury only 9 players completed the study. The characteristics of the subjects were: age of 25 ± 4 y, weight of 98 ± 22 kg, and height of 181 ± 4 cm (mean ± SD). The study was conducted three weeks following the final championship game. Subjects reported in a questionnaire a current training volume of 4.8 ± 0.8 h per week. All gave voluntary informed consent as required by the institutional ethics committee [see Appendix A for Participant Information Sheet and Appendix B for Consent to Participate in Research form].

**Treatments.** A moderate dose of caffeine (6 mg/kg body mass) and the same dose of a placebo (dextrose) were weighed and placed inside gelatine capsules. The chosen dose of caffeine was within the suggested range for optimal performance enhancement (L.L Spriet, 1995). The large between-subject standard deviation for weight resulted in a large variation of administered caffeine dose (589 ± 129 mg). When recruited, subjects were provided with a list of common foods containing caffeine and were requested to

refrain from consuming these foods 48 h prior to exercise testing [see Appendix C].
Other studies examining caffeine's effect on short-term high-intensity exercise have
implemented a similar period of abstinence (Anselme, Collomp, Mercier, Ahmaidi, &
Prefaut, 1992; Collomp, Ahmaidi, Audran, Chanal, & Prefaut, 1991; Pasman, van Baak,
Jeukendrup, & de Haan, 1995). We measured caffeine concentration in plasma before
administration of the treatments to encourage and check on compliance with this request.
We also provided subjects with a 48-h diet record questionnaire prior to their first testing
session so that they could replicate that diet before each testing session, as changes in diet
1-2 d before a performance test may affect performance (Hopkins, Hawley, & Burke,
1999)[see Appendix D].

**Performance test.** The Rugby-Specific Circuit Test is based on a time-motion
analysis of rugby games to simulate physical and skill demands of a rugby game
(Deutsch, 2004). The test measures time for straight-line sprints, agility sprints
(offensive, defensive, and tackling), peak power generation in two consecutive drives,
and accuracy of ball passes. The test consists of the following 11 stations [see Appendix
E for illustration of layout]:

Station 1. 20-m straight-line sprint

Station 2. 22-m offensive swerving agility sprint [see Appendix F for details of station
layout]

Station 3. Walking to next station

Station 4. Dynamic drives: 2x ~5 s maximal drives of a dynamometer cart

Station 5. Walking to next station

Station 6. 33-m defensive agility sprint [see Appendix G for details of station layout]

Station 7. Walking to next station

Station 8.  31-m tackling agility sprint [see Appendix H for details of station layout]

Station 9. Ball passing accuracy

Station 10. 30-m straight-line sprint

Station 11. Walk back to Station 1 to start circuit again

Subjects began at Station 1 and proceeded through the 11 stations at 30 s intervals. Once the required task was completed, the subject had the remainder of the 30 s to rest and move to the next station.  A whistle was blown at 30 s intervals to indicate the start. For the sprint stations, subjects began 20 cm behind the start line and the sprint time was measured with electronic timing lights set at knee height (Speed-Light, Swift Performance Equipment, Goonellabah, Australia).   The dynamometer cart for measurement of peak power in the drives was a prototype (School of Physical Education, Dunedin NZ) that measured peak power via transducers for speed of the cart and force in a bungee tether [see Appendix I]. Subjects began 1 m behind the cart and drove it until complete extension of the attached bungee. For ball passing accuracy subjects had to rapidly pass and hit the middle of a 3 ft x 3 ft target, 2 m above the ground, 4 m from the player, the number of hits were counted from 5 balls passed.

Subjects completed 7 circuits each half (30 s x 11 stations x 7 circuits = 38.5 min). There was a 2-min rest after Circuit 4 in each half and a 10-min half-time rest to simulate real game time.   Research assistants verbally encouraged subjects before and during performance at each station and recorded performance.

**Plasma caffeine and adrenaline concentrations.**  These were determined in samples collected transdermally using the technique of electrosonophoresis, which offers a non-invasive alternative to venepuncture for blood sampling.  Samples were collected

as previously described (Cook, 2002) and analyzed for caffeine and adrenaline concentrations by high-performance liquid chromatography (HPLC). The concentrations in the samples were converted to concentrations in plasma using equations derived from a separate calibration study. Briefly, for the caffeine calibration, venous blood and transdermal samples were drawn concurrently from 16 adult males on 8 occasions. For some occasions subjects varied their caffeine intake. A validity analysis of the paired samples (using a spreadsheet available at http://newstats.org) revealed that log transformation produced satisfactory uniformity of percent error above plasma concentrations of 2.0 μg/ml (to the maximum of 9.0 μg/ml). The calibration equation was $P = aT^b$, where P is the plasma concentration, T is the transdermal concentration, a = 9.93, b=0.996, with a standard error of the estimate of 6.8%. The plasma concentration of caffeine was thus effectively 10x that of the transdermal sample. Below a plasma concentration of 2.0 μg/ml there was insufficient caffeine in the transdermal sample to measure with HPLC. For the adrenaline calibration study, eight adult males undertook five cycle ergometry sessions, each 2-3 days apart, of varying duration (30, 45 and 60 min). Venous blood and transdermal samples were collected concurrently immediately before and after the exercise. A validity analysis similar to that for caffeine showed uniformity of the percent error over the full range of observed plasma adrenaline concentrations (0.79 to 4.98 nM). The calibration equation was $P = aT^b$, where a = 7.89, b=0.988, with a standard error of the estimate of 6.0%. The plasma concentration of adrenaline was thus effectively 8x that of the transdermal sample.

**Statistical analyses.** All variables representing performance were log transformed before analysis to reduce non-uniformity of error and to express effects as percent changes (Hopkins, 2002). Repeated-measures analyses were performed with a mixed-

modeling procedure (Proc Mixed) in the Statistical Analysis System (Version 8.2 SAS Institute, Cary, NC). Fixed effects in the mixed model were Trial (first to fourth), Treatment (practice, caffeine and placebo), and Circuit (first to fourteenth). Trial was included only as a main effect to account for familiarization; the other effects were included with their interactions. Random effects were the identity of the athletes and terms representing within-athlete variation in performance between trials and between circuits within trials. Individual responses to caffeine were estimated for the mean effect over the 14 circuits via a random effect representing better or worse performance for the individual relative to the mean. The random effects were estimated as variances with an option that allowed the estimates and their confidence limits to be negative. Negative variances were transformed to negative standard deviations by a change of sign before and after taking the square root.

Means for measures of performance shown in tables and graphs are least-squares means (that is, means adjusted for any missing values using the fixed-effects model). Between-subject variations for measures of performance in the tables are coefficients of variation derived from the statistical model; these represent typical variation between subjects for the measure in any one circuit. They were converted to standard deviations for display in the figures. The between-subject variations for caffeine and adrenaline concentrations in the figures were derived directly from raw data.

Analyses for adrenaline and caffeine concentrations were similar to those for measures of performance, except that the fixed and random effects for Circuit were replaced with Time (with levels pre, mid and post exercise). An additional random effect representing individual responses in the first trial also produced positive variance for adrenaline and was therefore included. The possibility that individual responses in adrenaline and

caffeine concentrations accounted for individual responses in performance was investigated by examining scatter plots of the individual values of the random effects of representing individual responses to performance (Y axis) against those of adrenaline and caffeine (X axes) and deriving correlation coefficients.

To make inferences about true (population) values of the effect of caffeine on performance, we expressed the uncertainty in the effect as 90% confidence limits and as likelihoods that the true value of the effect represents substantial change (harm or benefit) (Hopkins, 2002). The smallest substantial change in sprint performance was assumed to be a reduction or increase in sprint time of more than 0.8% (Paton et al., 2001). In the absence of any published information on substantial changes in drive power and accuracy of passing, we used the between-subject standard deviation for these measures to convert the log-transformed changes in performance into standardized (Cohen) effect sizes. The smallest standardized effect size was assumed to be 0.20 (Cohen, 1988).

## RESULTS

### Plasma caffeine concentration

Figure 1 shows the increase in plasma caffeine concentration following ingestion of caffeine. The peak concentration occurred at 1 h post ingestion (8.18 µg/ml) and was well maintained throughout the performance test. Individual responses expressed as a coefficient of variation around the overall mean concentration were 13% (90% confidence limits -2 to 19%).
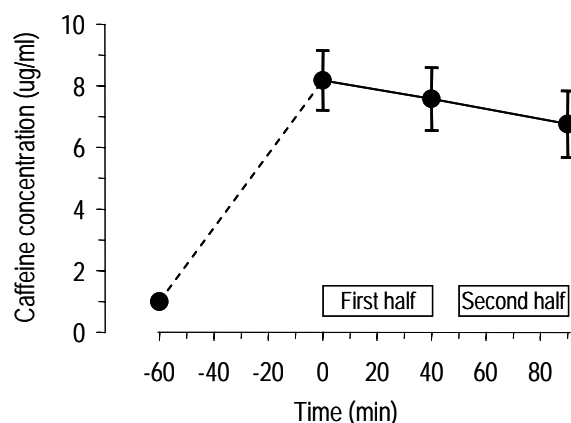
**FIGURE 1–Plasma caffeine concentration prior to caffeine ingestion and during the performance test. Values are means; bars are between-subject standard deviations.**

The caffeine concentration prior to ingestion was below the level of detection in the assay for all subjects; the value is shown on the graph as 1 μg/ml. Caffeine concentration was also below the level of detection for all subjects at all time points in the placebo condition (data not shown). Immediately prior to start of the performance test, none of the subjects stated that they felt they had received caffeine.

**Performance**

Table 1 shows mean performance over the 14 circuits in the placebo condition. In the caffeine condition there were enhancements of mean performance for all measures except power in the second drive, although the effects were unclear for this measure and for the 20-m and offensive sprints (Table 2).

TABLE 1. Performance in placebo condition averaged over the 14 circuits of the rugby test, with the between-subject coefficient of variation (CV) for any one circuit.

| Performance Task | Mean | Between-subject CV |
|---|---|---|
| 20-m sprint time (s) | 3.3 | 8.8% |
| Offensive sprint time (s) | 6.0 | 13% |
| Drive 1 power (W) | 1690 | 24% |
| Drive 2 power (W) | 1470 | 24% |
| Defense sprint time (s) | 13.6 | 9.2% |
| Tackle sprint time (s) | 9.3 | 9.8% |
| Passing accuracy (per 5) | 4.2 | 20% |
| 30-m sprint time (s) | 5.0 | 11% |

TABLE 2. Effect of caffeine (relative to placebo) on mean performance over the 14 circuits of the rugby test, and the reduction in fatigue with caffeine (relative to placebo) between the two halves of the test. Confidence limits, chances that the true effects were substantial, and practical assessments of the effects are also shown.

| Performance Task | Mean Change (%) | ±90% confidence limits (%) | Chances that the true effect has substantial[a]... | | Practical assessment[b] |
| --- | --- | --- | --- | --- | --- |
| | | | benefit (%) | harm (%) | |
| **Effect of Caffeine on Mean Performance** | | | | | |
| 20-m sprint speed | 0.5 | 1.7 | 37 | 9 | Unclear |
| Offensive sprint speed | 1.3 | 4.1 | 59 | 19 | Unclear |
| Drive 1 power | 5.0 | 2.5 | 55 | <0.1 | Benefit possible |
| Drive 2 power | -1.2 | 6.8 | 7 | 18 | Unclear |
| Defense sprint speed | 2.4 | 2.8 | 84 | 3 | Benefit likely |
| Tackle sprint speed | 2.9 | 1.3 | 99 | <0.1 | Benefit almost certain |
| Passing accuracy | 9.6 | 6.1 | 95 | <0.1 | Benefit likely |
| 30-m sprint speed | 2.3 | 2.5 | 85 | 2 | Benefit likely |
| **Reduction in Fatigue with Caffeine** | | | | | |
| 20-m sprint speed | 1.4 | 1.9 | 71 | 2 | Benefit possible |
| Offensive sprint speed | 2.1 | 1.8 | 87 | 0.6 | Benefit likely |
| Drive 1 power | 3.4 | 3.6 | 26 | <0.1 | Benefit possible |
| Drive 2 power | -4.4 | 4.8 | 0.1 | 45 | Harm possible |
| Defense sprint speed | 1.5 | 1.6 | 76 | 0.9 | Benefit likely |
| Tackle sprint speed | 1.7 | 1.8 | 80 | 1 | Benefit likely |
| Passing accuracy | 10 | 7.6 | 91 | 0.1 | Benefit likely |
| 30-m sprint speed | 3.4 | 2.2 | 97 | 0.1 | Benefit very likely |

±90%CL: add and subtract this number to the mean effect to obtain the 90% confidence limits for the true difference.

[a] *Substantial* is an absolute change in performance of >0.8% for measures of sprint time, >4.7% for drive power, and >4.1% for passing accuracy (see Methods).

[b] If chance of benefit and harm both >5%, true effect was assessed as unclear (could be beneficial or harmful). Otherwise, chances of benefit or harm were assessed as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99, very likely; >99%, almost certain.

The effects on performance in each circuit are shown in Figure 2 for tackle sprints (which showed the greatest mean enhancement and greatest chance of benefit with caffeine), the two drives, and target accuracy. Most measures showed an enhancement of performance with caffeine in the first circuit, as can be seen in Figure 2. Analysis of

performance for the first circuit revealed a possible beneficial effect for the first drive (5.5%; 90% confidence limits, ±5.7%) and a likely beneficial effect for target accuracy (12%; ±13%). Effects for the other measures in the first circuit were unclear; the observed values were beneficial for offensive sprint speed (1.6%; ±4.7%), second-drive power (1.9%; ±9.6%), defensive sprint speed (2.7%; ±3.6%), tackle sprint speed (2.1%; ±3.0%), and 30-m sprint speed (2.0%; ±4.1%), but harmful only for 20-m sprint speed (-1.6%; ±3.3%).
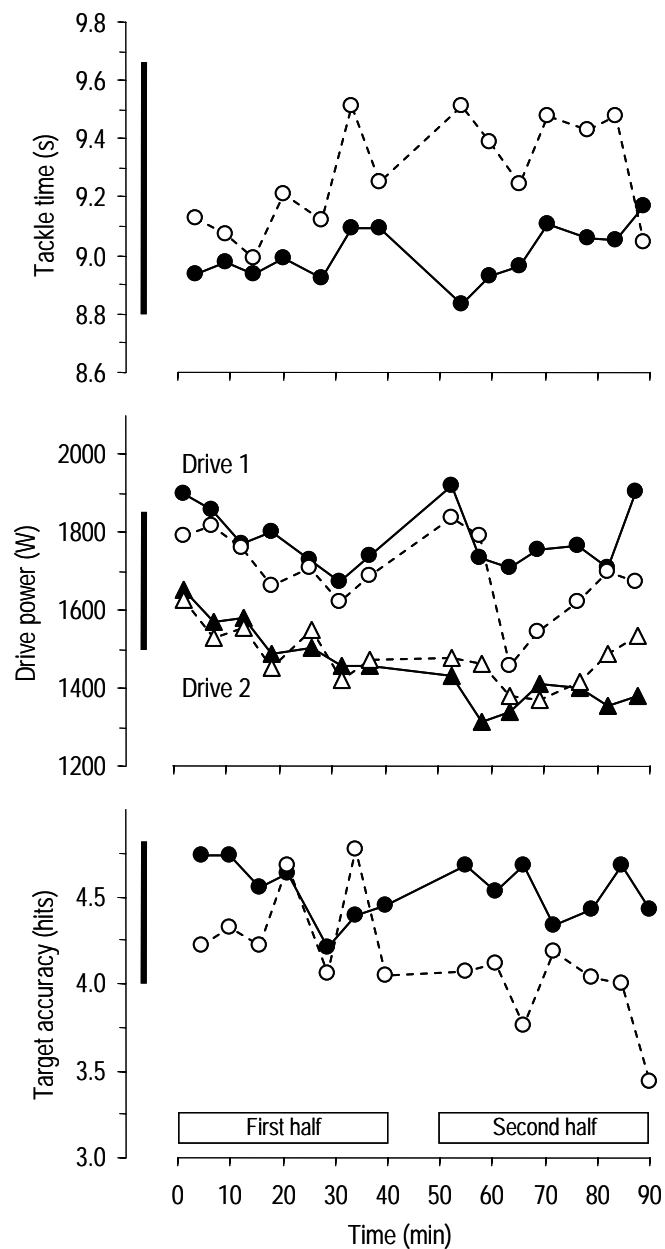
**FIGURE 2–Upper panel: Mean tackle sprint times for each circuit for caffeine (●) and placebo (○) treatments. Middle panel: Mean drive power outputs for Drive 1 and Drive 2 in each circuit for caffeine (●▲) and placebo (○△). Lower panel: Mean number of target hits from 5 ball-passing attempts for each circuit for caffeine (●) and placebo (○) treatments. All Values are means; bars are between-subject standard deviations.**

It is also apparent in Figure 2 and in the figures for the other sprints (not shown [see Appendix J, K, and L]) that the mean enhancements with caffeine arose partly through a reduction in fatigue as the test progressed. We quantified fatigue in the test by calculating the decline in the performance in the second half relative to the first. In the placebo condition the declines were: 20-m sprint speed, 2.1% (90% confidence limits, ±1.4%); offensive sprint speed, 2.8% (±1.4%); first-drive power, 3.7% (±2.6%); second-drive power, 5.0% (±3.7%); defense sprint speed, 0.9% (±1.2%); tackle sprint speed, 2.0% (±1.4%); passing accuracy, 9.0% (±4.7%); and 30-m sprint speed, 5.4% (±1.8%). The effects of caffeine on fatigue were decisive for all measures: possible through very likely reductions in fatigue for all but power in the second drive, where a *harmful* effect of caffeine was possible (Table 2).

For some measures, fatigue was not evident in the last circuit of the placebo condition relative to the first circuit. Indeed, for the 20-m sprint there was even a very likely *increase* in performance of 5.5% (±3.2%) relative to the first circuit, and there were also substantial although less clear improvements for defense, tackle and 30-m sprints. The other measures showed declines in performance, which were unclear for the offensive sprint and second drive, but possible for the first drive (6.5%; ±7.8%), and very likely for target accuracy (18%; ±11%). It was only for these latter two measures that the effect of caffeine was clear in the last circuit: a likely benefit for the first drive (12%; ±11%) and an almost certain benefit for target accuracy (28%; ±19%).

Most estimates of individual responses in performance were unclear. The standard deviations representing individual responses and their 90% confidence limits were: 20-m sprint speed, -1.7% (-3.4 to 2.4%); offensive sprint speed, 4.8% (-4.9 to 8.5%); drive 1 power, -3.2% (-5.7 to 3.3%); drive 2 power, 3.7% (-12 to 13%); defense sprint speed,

3.6% (-2.6 to 5.8%); tackle sprint speed, 1.3% (-1.6 to 2.4%); passing accuracy, -5.5% (-6.9 to -3.7%); 30-m sprint speed, -0.5% (-3.6 to 3.6%). The only clear finding from these data is the absence of individual responses for passing accuracy.

**Plasma adrenaline concentration**

Figure 3 shows the adrenaline concentration before, during and after the performance test for the caffeine and placebo conditions. Averaged over these three time points, adrenaline concentration was 51% (±11%) higher in the caffeine condition than in the placebo condition. Individual responses for this mean effect were substantial but unclear (7.4%, 90% confidence limits, -5.6 to 12%).
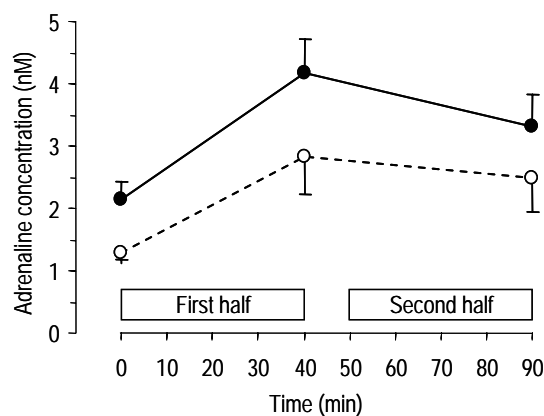


**FIGURE 3–Plasma adrenaline concentration for caffeine (●) and placebo (○) treatments 1 h post ingestion (0 min), at half time (40 min) and full time (90 min). Values are means; bars are between-subject standard deviations.**

**Relationships Between Individual Responses**

Subjects who experienced the larger change in caffeine concentration responded with larger changes in adrenaline concentration, although the correlation was unclear (r=0.45;

-0.18 to 0.82). For the measures of performance that indicated there might be individual responses, their relationship with caffeine concentration was mostly unclear, except for performance on Drive 1 (r=0.86; 90% confidence limits, 0.56 to 0.96). Relationships of individual responses of performance and adrenaline concentration are mostly unclear except for performance of Drive 1 (r=0.68; 0.16 to 0.91) and Drive 2 (r=-0.59; 0.01 to 0.87).

## DISCUSSION

A considerable volume of literature has indicated ergogenic benefit of caffeine for exercise lasting more than 60 min, whereas studies that have examined the effect of caffeine on sprint exercise are limited and less clear (Graham, 2001). These previous studies can provide only suggestive evidence of the effects of caffeine on performance of repeated bouts of sprinting and explosive power over durations typical of games in team sports. Our study is the first to report the effects of caffeine on the physical and skill demands required in an intermittent high-intensity team sport. We have found evidence of benefits not only on physical performance but also on a task requiring coordinated skill. Most of the mean effects on sprint performance were clear, and all were positive. The magnitude of the effect of caffeine on our sprint performance is closer to that reported on endurance exercise rather than sprint exercise (G.R. Stuart and W.G. Hopkins, unpublished observations 2004 [Chapter 1]). The effect of caffeine on accuracy of ball passing is a unique finding and not directly comparable with that of any previous study, although many other studies of the effect of caffeine on cognitive function and psychomotor performance have shown benefits (Smith, 2002).

The repeated sprints of our performance test do not allow any direct comparisons with other studies that have examined single-sprint performance (Bell, Jacobs, & Ellerington, 2001; Collomp et al., 1991; Williams, Signorile, Barnes, & Henrich, 1988), because each sprint after the first 20-m sprint of the first circuit must be considered as a repeated sprint. Studies that have examined the effect of caffeine on repeated sprints have measured performance following recovery periods of 4-5 min (Anselme et al., 1992; Greer, McLean, & Graham, 1998). These periods are substantially longer than the recoveries in the present study, which limits any direct comparisons of performance outcomes. Paton et al. (2001), on the other hand, examined ten 20-m sprints each performed within 10 s with recovery of ~6 s between bouts. This meant that the test was over in 100 s, and with the short recoveries between bouts, it to would unlikely be comparable to performance we have observed.

Fatigue was apparent for every type of exercise as the test progressed in the placebo condition, and we found possible to very likely reductions in fatigue for all but one component of the performance test in our analysis of the first versus second half. This finding is unique, as other studies of repeated sprints have not reported any substantial reduction in fatigue with caffeine (Anselme et al., 1992; Greer et al., 1998; Paton et al., 2001). Studies that have examined endurance exercise performance following prior fatiguing exercise are unclear, but typically there is similar performance enhancement with or without a fatiguing preload (G.R. Stuart and W.G. Hopkins, unpublished observations 2004 [Chapter 1]). The only component of the test for which caffeine *increased* fatigue in the second half compared with the first half was Drive 2. The drive is an all-out bout of duration similar to that of the sprints, and caffeine's effect on fatigue with the first drive was similar to that with the sprints. It is therefore not obvious why

caffeine's effect on fatigue for the second drive should be so different from its effect on the first, but a unique characteristic of the second drive is the brief preceding rest period of only ~5 s, compared with ~25-55 s preceding the other bouts in the circuit. This observation suggests that, for caffeine to reduce fatigue, there needs to be an adequate period of recovery for caffeine to exert an ergogenic effect. The fact that the drive is also a more intense form of exercise than the sprints and the fact that caffeine had a greater effect on the first drive following the largest overall rest interval of ~55 s further suggest the need for a period of recovery during which caffeine can act to enhance performance.

The effect of caffeine on performance in the last circuit relative to the first is consistent with the notion that caffeine works by reducing fatigue: the effects were clear only where there was clear evidence of fatigue. But is there any evidence of frank enhancement in the early stages of the test, when fatigue was less developed? We addressed this question by analyzing performance in the first circuit, and we found possible and likely enhancements respectively for the first drive and passing accuracy. However, these enhancements could still be due to a reduction in fatigue, because only the first bout of exercise (the 20-m sprint) in the first circuit was performed without prior fatiguing exercise. The effect on the 20-m sprint in the first circuit was unclear but favoured impairment. Other studies have reported a range in performance effects on maximal sprint tests from -0.7% through 7.1%, but the effects were mostly unclear (Anselme et al., 1992; Bell et al., 2001; Collomp et al., 1991; Greer et al., 1998; Williams et al., 1988).

The enhancements of performance with caffeine were apparently not due to a placebo effect at the start of the performance test, because no subject stated that they were confident about what treatment they had received. However, we did not ask the subjects

to comment about the treatment at the end of the performance test, so we do not know whether subjects perceived that there was less fatigue or changes in psychological state when they were on caffeine (especially those who received caffeine after placebo). The possibility of a placebo effect developing part way through the performance test therefore cannot be ruled out.

The 6 mg/kg dose of caffeine produced a peak plasma concentration of 8.18 μg/ml, which is similar to that previously reported for the same dose of caffeine (Blanchard, 1983; Collomp, 1991; Conway, Orr, & Stannard, 2003). Before administration of treatments at each trial, subjects showed levels of caffeine below the 2 μg/ml threshold of detection for the assay. For the average subject, who weighed 98 kg, the dose was 600 mg of caffeine, which is equivalent to about six cups of coffee (Tarnopolsky, 1994). The detection threshold is therefore equivalent to about 1.5 cups of coffee consumed an hour before the fluid sample. The assay was therefore not sensitive enough to confirm rigorous compliance with the instruction to abstain from caffeine-containing products before testing. In a meta-analysis of the effects of caffeine on performance (G.R. Stuart and W.G. Hopkins, unpublished observations 2004 [Chapter 1]), abstention from caffeine-containing food and drink for at least several days produces an additional performance enhancement of ~1.5%. The effects we have observed on performance could therefore be underestimates of the effect expected with full abstention.

Regarding the potential mechanisms of the effects of caffeine on performance, our results confirm previous reports of substantial caffeine-induced elevations in plasma adrenaline concentration at rest and during exercise (Graham & Spriet, 1991, 1995; Spriet et al., 1992). Clear relationships were evident between individual responses for Drive 1 and caffeine concentration, and for Drives 1 and 2 and adrenaline concentration.

It is possible that these correlations are larger than the real effect; with so many correlations, and given the wide confidence interval, some correlations are likely to be inflated substantially by chance. These correlations indicate that the effect of caffeine and adrenaline on drive performance may have a different mechanism from that of the sprints.

For the performance of the drives, which require high force, a high level of activation of all of the synergistic muscles is required. The twitch-interpolation technique has shown that caffeine increases activation of skeletal muscle at the onset of maximal voluntary contractions (Kalmar & Caffarelli, 1999). This increase in activation is associated with a substantial increase in force. Caffeine may therefore possess the ability to recruit motor units that are otherwise inactive during maximal voluntary effort to account for the initial enhancement of drive power in the first circuit and later in the test. Caffeine could also act directly on the muscle to increase contractility, although the concentrations required to produce this effect are generally in the millimolar range, far exceeding the concentrations found in this study (Fredholm, 1985; Weber & Herz, 1968; Wood, 1978; Yamaguchi, 1975). Elevated levels of adrenaline may have provided an enhanced stimulus for glycogenolysis to enhance performance in the first drive of each circuit, which may then have resulted in rapid accumulation of metabolic by-products. The subsequent decline in performance of the second bout would therefore be a result of incomplete recovery from Drive 1.

The mechanism and even the site of fatigue in an athlete exercising at near maximum effort is a controversial issue (Fitts, 1996; Green, 1997). If fatigue results in reduction in CNS drive to the muscle during exercise, caffeine could act in the CNS to increase the drive by decreasing thresholds for neuronal activation (Waldeck, 1973), possibly via

inhibiting the binding of adenosine to adenosine receptors (Daley et al., 1981). This effect would reduce the perception of work intensity (Cole et al., 1996; Costill et al., 1978), which would result in performance improvement, by allowing athletes to work at a higher intensity at the same perceived level of effort (Cole et al., 1996). The ability for subjects to perform maximally on the last circuit would indicate that changes that occur in the muscle might be responsible for the feelings of fatigue during the test, but when motivation of performance was high in the last circuit the ability of the muscle to output power was not limiting.

At the peripheral level, an inability to generate action potentials repeatedly at the high frequency required for maximal or near maximal force generation by the muscle fibers may be the result of excitation failure or a failure to translate fully the neural signal to the interior of the fiber (Green, 1997). This form of fatigue, often referred to as high-frequency fatigue (Fitts, 1994), appears to occur because of an inability to restore Na+ and K+ gradients across the sarcolemma before the next neural impulse (Clausen & Neilsen, 1994). Both caffeine and adrenaline have a stimulatory effect on skeletal muscle Na-K pump activity (Clausen, 1986; Lindinger, Graham, & Spriet, 1993). K+ has an important role in skeletal muscle function, and in certain situations where substrate supply is not limited, contraction-induced decreases in intracellular [K+] and increases in extracellular [K+] appear to contribute directly to fatigue (Lindinger & Sjogaard, 1991; Sjogaard, 1990). Lindinger et al. (1993) found that an acute dose of caffeine increased tissue Na-K pump activity and attenuated the increase in plasma [K+] during exercise. The caffeine induced increases in plasma adrenaline concentrations in the present study may have been the stimulus for an increase in tissue Na-K pump activity, or caffeine or one of its metabolites may have directly stimulated increases in 3',5'-cyclic

monophosphate (cAMP) and tissue Na-K pump activity to regulate [K+] concentration and attenuate the onset of fatigue during the second half of performance.

The development of fatigue also depends to a large extent on the ratio of the time of exercise to the time of relaxation or recovery (Green, 1997). In the present study this ratio was determined by the speed with which subjects performed each station and by the position of active recovery stations within the circuit. Following a period of high-intensity activity characteristic of the drive performance, the muscles and muscle fibers display large metabolic perturbations (Green, 1997). Although we did not measure any metabolic by-products, it has been shown that after caffeine ingestion large power outputs result in greater accumulation (Anselme et al., 1992; Collomp et al., 1991), which could inhibit the ability to use ATP at high rates in repeated bouts. This effect is likely to explain the substantial reduction in performance we have observed on Drive 2 immediately following Drive 1.

As the number of total repetitions of exercise increased late in the performance test, activation of both glycolysis and oxidative phosphorylation would have been essential for maintaining power output, depending on the work:rest ratio. Recovery periods ensure that aerobic glycolysis contributes to regeneration of phosphagens and quicker restoration of energy potential (Green, 1997). The preferential recruitment of fast-twitch fibers is desirable during intense exercise, given their specialized capability for high rates of ATP synthesis; however, the recruitment of slow-twitch fibers within a muscle appears to be invariable regardless of the force generated (Deluca, 1985). Caffeine's effect may be exerted primarily on oxidative muscle fibers, as increased sensitivity to caffeine has been demonstrated in slow twitch fibers in humans (Mitsumoto et al., 1990). Caffeine may have elicited a greater contribution of slow-twitch fibers toward force generation and

enhanced the recovery and replenishment of phosphagen stores late in performance, thereby allowing greater power production and accelerated recovery for energy supply on successive performances.

We have also found substantial improvements in passing accuracy, which is a skill present in most ball game sports that requires finer motor coordination than in all-out sprint and drive performances. Caffeine is known to have effects on cognitive function (attentional, complex psychomotor, and memory) during fatigue (Lorist, Snel, & Kok, 1994a, 1994b). Hogervost et al. (1999) demonstrated for the first time that caffeine improves complex cognitive function in athletes after strenuous exercise. This effect of caffeine is likely to be important in competitive sports where the ability to perform skills like passing and shooting accurately while fatigued is widely regarded as the key to successful performance (Moran, 1996). From the perspective of the motor control system, caffeine is likely to have beneficial effects not only at the level of the individual motor units within the muscle but between groups of agonist and antagonist muscles as well (Deluca, 1985). These neuromuscular effects would be most apparent during and after those types of exercise in which concentration and technical/tactical skills have a major influence on performance, as in most ball game sports (Fluery, Bard, Jobin, & Carriere, 1981; Hancock & McNaughton, 1986).

Despite strong verbal encouragement throughout testing, fatigue was evident as a decline in sprint performance and drive power of up to 5% between the first and second halves of the rugby performance test. Fatigue of this magnitude has been reported for total running distance between the first and second halves of soccer games (Bangsbo, Norregaard, & Thorso, 1991; Reilly & Thomas, 1976), and is presumably present in most rugby games and other high-intensity team sports. Analysis of the change in performance

between the first and second halves in our study showed that caffeine attenuated fatigue, except where there was little time for recovery between bouts. It is reasonable to expect similar effects in real games. This study has uniquely tracked and examined the effect of caffeine on fatigue over the course of a team sporting performance. The only other study of this kind examined repeated sprints of team sport athletes with minimal rest between each sprint over a brief amount of time (Paton et al., 2001), which does not reflect the demands of team sport performance over the duration of a game. Other studies that have examined exercise performance following a pre-load have used sub-maximal exercise over a longer duration, which is also not typical of team sport.

This study has found that caffeine can provide a worthwhile performance enhancing effect on simulated intermittent high-intensity sport performance. Confidence limits allow for the possibility that the true effect on mean performance could be small and beneficial or trivial, with a very unlikely chance that it will do harm. The enhanced performance of passing accuracy observed late in the performance test may suggest that caffeine has a role in precision and motor coordination in types of exercise in which concentration and technical/tactical skills have a major influence on performance when fatigued. Although the mechanism of action through which caffeine exerts its ergogenic effect remains unclear, it is possible that the drive performance could be mediated through changes in adrenaline concentrations as far as our individual responses indicate. If caffeine affects psychological factors like attention and motivation during exercise performance, and athletes are likely to be more highly motivated in competitive game environments than in the lab simulation, then caffeine might have less of an effect in competitions. Therefore further research should examine the effect of caffeine during sporting performance in real game environments using match-analysis methodology.

**Chapter 3**

# Conclusion

## Overview

Caffeine is a pharmacologically active drug that can produce substantial ergogenic benefit for exercise performance. However, studies have displayed considerable variability in results due mainly to their testing protocols. Numerous review articles have been limited to narrative summaries of the research. The first part of our research was therefore to meta-analyze the effects of caffeine on exercise performance so that an estimate of an effect of caffeine on a factor likely to cause variability in exercise performance may be computed. We identified 90 estimates of performance effects of caffeine in 32 peer-reviewed studies. All estimates were converted to mean power in an equivalent time trial then subjected to a mixed-model meta-analysis. The fixed effects of interest were gender, training status (elite athlete, non-elite athlete, non-athlete), dietary caffeine status (habitual consumer, non-consumer), caffeine abstention period, caffeine dose (mg/kg body mass), type of caffeine (pure or in coffee), delay between ingestion and performance test, duration of test, and presence or absence of fatiguing exercise before the test. The random effects accounted for within- and between-study variance. We have found that an athlete, who is a habitual non-consumer of dietary caffeine, after ingesting pure caffeine, performing endurance exercise, is likely to gain the most benefit from caffeine. We also identified the effects of caffeine were less clear with females, following longer periods of dietary abstention, in low doses, and for brief exercise. For an athlete or a recreational person it would be advised to withdraw from any dietary sources of caffeine for at least two

days, then supplement with a dose of about 6 mg/kg body mass an hour before performing exercise to gain the most benefit.

While compiling literature for the meta-analysis, it was evident that there had been no previous research on the effect of caffeine on performance of repeated bouts of high-intensity exercise over durations typical of games in team sports. It was therefore the purpose of the second part of our research to examine the effects of caffeine on performance of a test simulating some of the physical and skill demands of rugby. A rugby-specific circuit test was used that had been developed from a comprehensive time-motion analysis of rugby super 12 games. Nine high-level competitive male rugby players ingested either caffeine (6 mg/kg body mass) or placebo (dextrose) before performing 3-4 trials of the rugby test, with one week between trials. Each circuit of the simulation consisted of stations for measurement of sprint speed (20-m straight-line, 30-m straight-line, 22-m offensive, 33-m defensive, and 31-m tackling), power generation in two drives, and accuracy of passing balls. Each trial consisted of 14 circuits in two halves. There was a 2-minute rest after Circuit 4 in each half and a 10-minute half-time rest. Blood plasma was sampled indirectly by a non-invasive transdermal technique and measured for caffeine and adrenaline concentrations; samples were collected before administration of treatments, immediately before testing, at half-time and at full-time. The effects of caffeine on mean performance (±90% confidence limits) were: sprint speeds, 0.5% (±1.7%) through 2.9% (±1.3%); first-drive power, 5.0% (±2.5%); second-drive power, -1.2% (±6.8%); and passing accuracy, 9.6% (±6.1%). It is evident that the enhancements were mediated partly through a reduction in fatigue that developed throughout the test, particularly in the second half and partly by enhanced performance for some measures in the first circuit. There was evidence of individual responses for drive

performance that had association with individual changes in plasma caffeine and adrenaline concentrations.

The findings of our controlled trial indicate that a team sport athlete is likely to gain substantial enhancement of several aspects of high-intensity exercise performance over the course of a game. The effect of caffeine is greatest in the second half of performance, which is a timely finding considering that the outcome in most international rugby games are now decided late in the second half. It would be expected that athletes who compete in similar repeated high-intensity sports like soccer, basketball, and tennis would benefit from caffeine. A particularly interesting finding of our research has shown that accuracy of passing balls was substantially enhanced whilst fatigued. This may have significant impact on the outcome of a game if an athlete is able to be accurate with a crucial pass or shoot after enduring nearly a whole game of repeated high-intensity exercise.

# Strengths and Limitations

## Study Design

This study has been the first to examine the effect of caffeine on the simulated intermittent high-intensity physical and skill demands over duration typical of most team sports. Following the completion of the performance test, we did not ask the subjects whether they had a clear conviction of which treatment they had received, so we do not know whether subjects perceived during the performance test that they had received caffeine. The possibility of a placebo effect developing part way through the performance test therefore cannot be ruled out.

## Subjects

In sport research it is important to use the most highly trained subjects available when making inferences about enhancing elite athletic performance. Elite athletes may have less scope for performance enhancement in comparison to sub-elite or lower caliber athletes and they are more accustomed to performing at high intensities. They may also be more reliable in performance tests. I recruited as many of the highest caliber rugby players who train and play alongside full professional players.

## Validity of Performance Measures

The game-length simulation test used in this study has been a unique method to examine the effect of caffeine on a team sport like rugby. The test was first designed in 1996 from a comprehensive time-motion analysis of the Super 12 rugby competition. The style of the game is now faster and more physical, which may limit comparison of our results to game performance at the elite level today. For example, kickers no longer deliberately kick the ball out to extend periods of play. As a result, recovery time is shorter between maximal efforts, which may reduce caffeine's potential to enhance performance in rugby games.

## Mechanisms

The main purpose of this project was to measure the effect of caffeine on simulated rugby performance. In an attempt to gain an understanding of an underlying physiological mechanism responsible for any changes in performance, I compared individual responses of performance and adrenaline concentration. The physiological tests were not aimed at pinning down the particular mechanism/s, but indirectly gave an understanding of the possible mechanisms that may or may not be involved.

Measurement of lactate concentration in the blood might have indicated whether changes in anaerobic glycolysis were associated with the effects of caffeine on performance. Changes in muscle associated with caffeine's effects (for example, depletion of glycogen) would need to be studied with muscle biopsies.

## Future Research

Our meta-analysis has identified where the confidence limits of the effects on performance are wide. Further research is needed to reduce this uncertainty in these effects. In particular, more research is required on the effects of caffeine in females, following longer periods of dietary abstention, in low doses, and for brief exercise.

Now that our research has shown that caffeine can enhance various aspects of performance in a rugby game simulation, further research should examine whether these effects are evident in real games studied with video match analysis.

It would also be interesting to examine the effects of caffeine in similar high-intensity sports like soccer, which is of longer duration, and basketball, which is shorter in duration. Another issue is the amount of time each player spends on the field, which varies between sports and playing positions.

To date it is still unclear what physiological mechanism might explain the effect of caffeine on exercise performance. It is likely to be a combination of an effect on the CNS and directly on the muscle. It is difficult to suggest experiments that could identify the mechanisms at either site.

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**Appendix A**

# Participant Information Sheet

**Project Title**

Effect of caffeine ingestion on a simulated intermittent
high-intensity sport performance

**Invitation**

As elite rugby players you are invited to participate in this research with the
assistance of the New Zealand Rugby Football Union

**What is the purpose of the study?**

To determine the effect of caffeine ingestion on simulated rugby performance

**What happens in the study?**

You will be required to attend 3 testing sessions;
**Session 1 Thursday 25th September**
**Session 2 Thursday 2nd October**
**Session 3 Thursday 9th October**

You will be asked to keep a diet history for the two days prior to the first session so
that you may replicate that diet two days prior to sessions 2 and 3. You will also be
asked not to eat caffeine containing foods and beverages (e.g. chocolate, coffee, tea,
red bull, and V) during this time.
On arrival you will have, a fluid sample taken from your arm with a new painless
method called electrosonophoresis. This gives us information about your blood
without the use of needles. Following that you will consume capsules containing
either caffeine or an inactive 'placebo' sugar and allowed to rest for 1 hour. At the
end of the hour, you will have another fluid sample taken and asked to perform an 80-
minute rugby simulation. The simulation incorporates repeated sprints, explosive
strength (rucking, mauling, and scrummaging), tackling and active recovery. Half-
way through the simulation a fluid sample will be taken. Following the end of the
test, one more fluid sample will be drawn.

**How much time is involved?**

On arrival and after caffeine ingestion you will be asked to rest for 1 hour then
complete an 80 minute rugby simulation. The simulation requires you to complete 7
circuits each half. A circuit takes 5 minutes and 30 seconds to complete. There will
be a 2 minute break after circuits 4 and 11 and a 10 minute break at half time. This is
a total time of 2 hours and 34 minutes.

**What are the discomforts and risks?**

There is no discomfort or risk associated with the fluid sampling technique. The
rugby simulation is similar to a hard training session without contact, with a very
small risk of injury.

**What are the benefits?**

You will be part of the latest research in rugby performance and become familiar with testing methods used with teams like the Blues and the All Blacks.  It will also indicate whether caffeine will be useful to enhance your performance in a game.


**Access to results?**

At the conclusion of the research you may obtain any of your results on request.


**How is my privacy protected?**

At all stages throughout the research project your name and results will remain confidential to the researchers and yourself.

**Withdrawal?**

At any stage during this study you are free to withdraw with no explanation required.


**Participant Concerns** -
Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Will Hopkins 917 9999 ext. 9793 or alternatively Gene Stuart 021 424 123
Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Madeline Banda, madeline.banda@aut.ac.nz, 917 9999 ext 8044.
**Approved by the Auckland University of Technology Ethics Committee on** 30th June 2003
**AUTEC Reference number** 03/86

**Appendix B**

# Consent to Participation in Research

| Title of Project: | **Effect of caffeine ingestion on a simulated intermittent high-intensity sport performance** |
|---|---|
| Project Supervisor: | **Professor Will Hopkins** |
| Researcher: | **Gene Stuart** |

- I have read and understood the information provided about this research project.

- I have had an opportunity to ask questions and to have them answered.

- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. If I withdraw, I understand that all relevant tapes and transcripts, or parts thereof, will be destroyed

- I agree to take part in this research.

Participant signature: .....................................................

Participant name:

Date:

Project Supervisor Contact Details:  Professor Will Hopkins (09) 917 9793

**Approved by the Auckland University of Technology Ethics Committee on** 30th June, 2003
**AUTEC Reference number** 03/86

# Caffeine Food Information Sheet

**Project Title**

Effect of caffeine ingestion on a simulated intermittent
high-intensity sport performance

**Request**

As part of your 2-day diet record can you also please refrain from consuming foods that contain any amounts of caffeine. A list of common foods containing caffeine is provided.
This is an important request as any recent consumptions of caffeine may affect our results. A fluid sample will be taken prior to administration of treatments to confirm your compliance.

Thanks guys!

**Common foods that contain caffeine**

- **Coffee**
- **Tea**
- **Coca-cola**
- **Pepsi**
- **Mountain Dew**
- **Chocolate**
- **Red Bull**
- **V**
- **Any other type of energy drink (please check it does not contain caffeine)**
- **Medications/pain killers (please check it does not contain caffeine)**

**Appendix D**

# Diet Record Sheet

**Project Title**

Effect of caffeine ingestion on a simulated
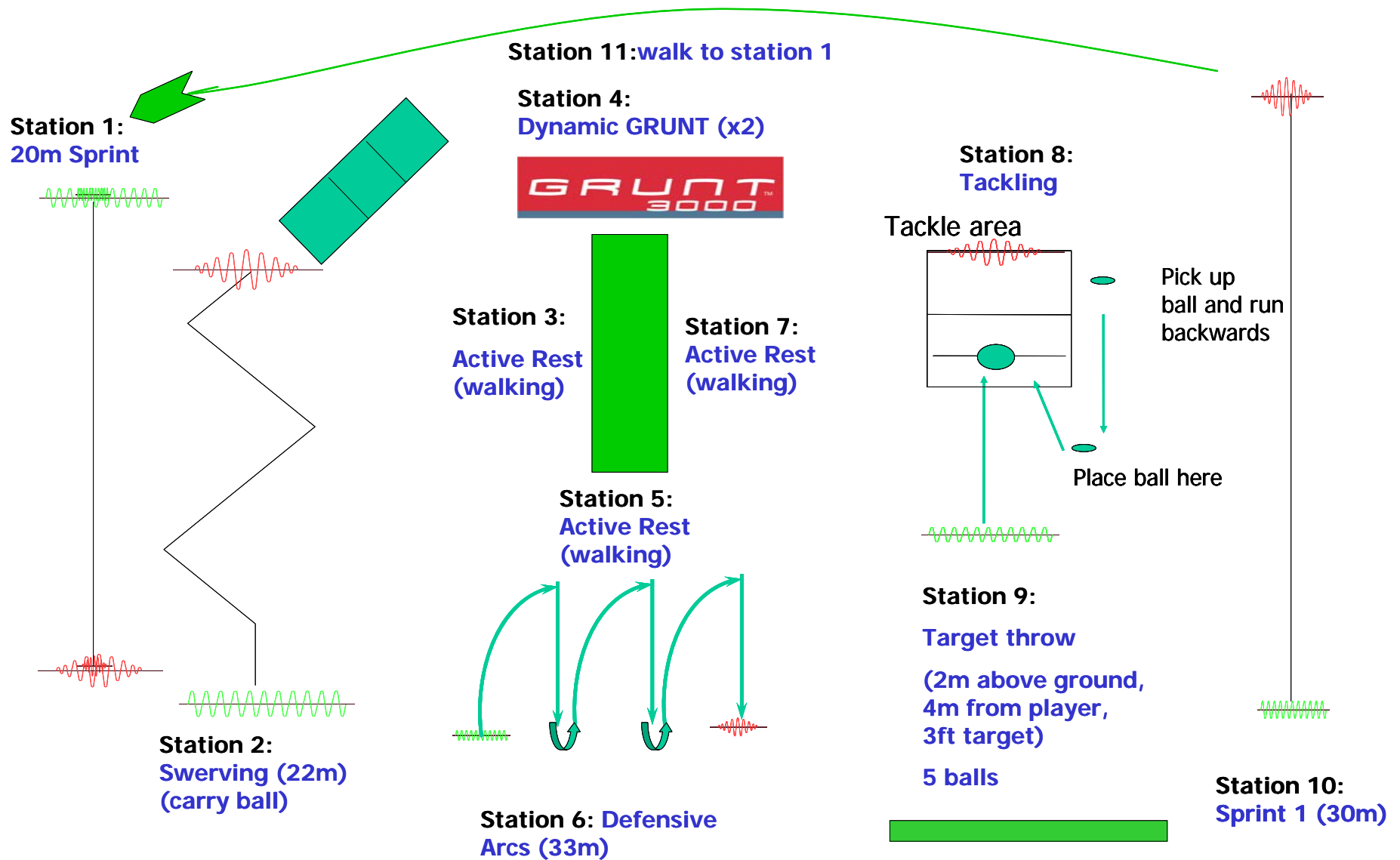intermittent high-intensity sport performance

**Request**

As part of this project can you please take time to record your diet 2 days prior
(Monday & Tuesday) to the first testing session (Wednesday) so that you may be able
to replicate this diet prior to further testing sessions.

| Quantity | | | | | | |
|---|---|---|---|---|---|---|
| **Food(s)** | | | | | | |
| **Date/Time** | | | | | | |
| **Breakfast** | **Snack** | **Lunch** | **Snack** | **Dinner** | **Snack** | |

# Diet Record Sheet

| Date/Time | Food(s) | Quantity |
|---|---|---|
| Breakfast | | |
| Snack | | |
| Lunch | | |
| Snack | | |
| Dinner | | |
| Snack | | |

Station 11:walk to station 1

Station 4:
Dynamic GRUNT (x2)

Station 1:
20m Sprint

GRUNT 3000

Station 8:
Tackling

Tackle area

Pick up
ball and run
backwards

Station 3:
Active Rest
(walking)

Station 7:
Active Rest
(walking)

Place ball here

Station 5:
Active Rest
(walking)

Station 9:

Target throw

(2m above ground,
4m from player,
3ft target)

5 balls

Station 2:
Swerving (22m)
(carry ball)

Station 10:
Sprint 1 (30m)

Station 6: Defensive
Arcs (33m)

**Appendix E**

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**Appendix F**

## Detailed Setup Plan – Station 2: *Swerving*

Total Running Distance: 22m



Place & Tackle

3m · 6m · 2m · 6m · 3m · 3m · 2m · 2m · 1m
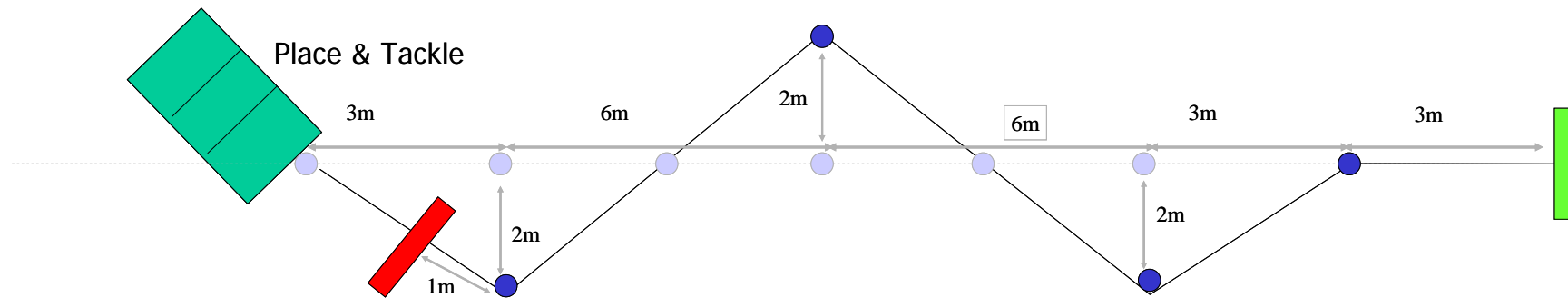
**Station Description**
• Player starts from static start holding ball in two hands
• Player sprints around blue markers and through the stop gate (red)
• Player places the ball on the ground and completes the tackle
• Note: Player must knock tackle bag a distance of 1m to successfully complete tackle
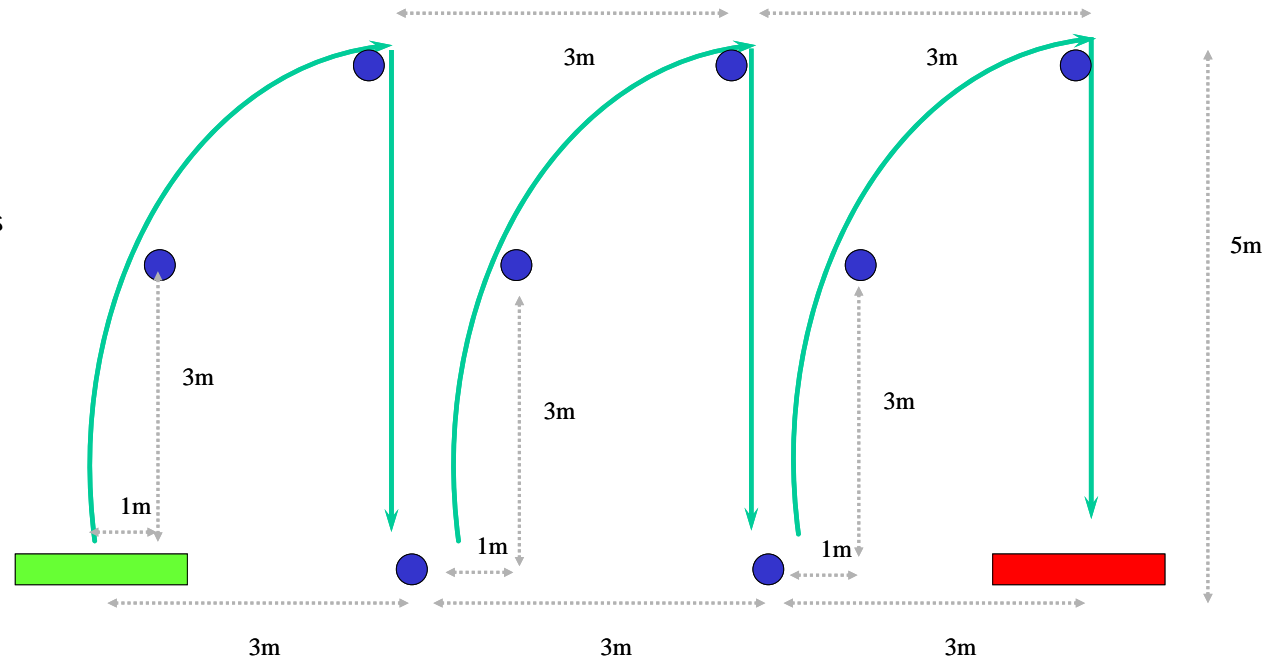
**Setup Description**
• Place markers every 3m along the centre line (dotted)
• Place flags or large cones 2m either side of the centre line every 6m from the start gate
• Place stop gate 1m along line to tackle mat from final turning cone
• Remove centre line marking cones when setup complete

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# Detailed Setup Plan – Station 6: *Defensive Arcs*

Total Running Distance: 33m

**Station Description**
• Player starts from static start
• Player sprints forwards and backwards in arcs around blue markers
• Player faces forward through whole section
• Player runs backwards through finish gate

3m

3m

3m

1m

1m

1m

3m

3m

3m

5m

3m

3m

3m

**Setup Description**
• Measure out parallel lines 5m apart and 9m long
• Place flags at 3 m intervals along lines
• Mark 1m from start gate and base cone, then 3m out from each of these points
• These markers form the arc shape for each arc

**Appendix G**

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# Detailed Setup Plan – Station 8: *Tackling*

Total Running Distance: 31m

## Station Description
• Player starts from static start
• Player sprints forwards and knocks tackle bag over 1m line
• Player picks up ball and runs backwards to ball placement line
• Player again sprints forward and knocks tackle bag over 1m line
• Player gets up and sprints forward through finish gate

## Setup Description
• Measure out 15m from start to stop gate
• Secure tackle mat at 8m and place 3 tape lines on mat at 1m intervals
• Place tackle bag on 1st tape line
• Place ball next to mat on 3rd tape line
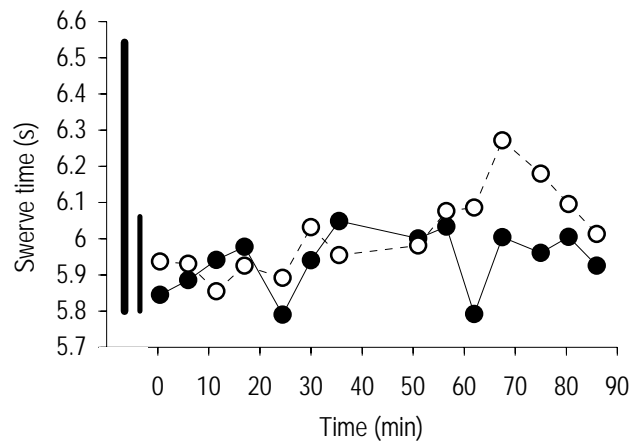• Mark another tape line 3m from start gate

5m

1m

Pick up
ball and run
backwards

1m

1m

8m

1m

5m

8m

Place ball here

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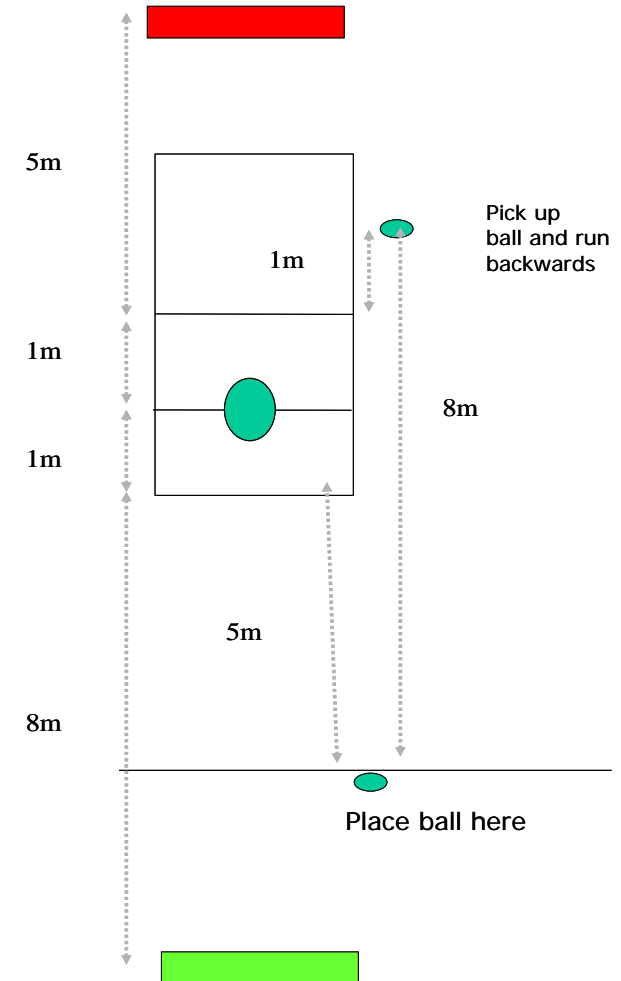
**Appendix I**– Drive dynamometer cart.
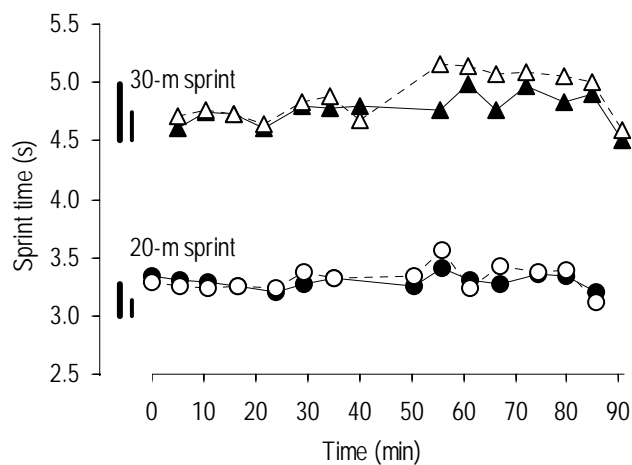
**Appendix J**– **Mean times for Sprint 1 (20-m) and Sprint 2 (30-m) in each circuit for caffeine (●▲) and placebo (○△).   Values are means; bars are between- and within-subject standard deviations (thick and thin bars respectively).**

**Appendix K** – **Mean offensive sprint times for each circuit for caffeine (●) and placebo (○) treatments. Values are means; bars are between- and within-subject standard deviations (thick and thin bars respectively).**
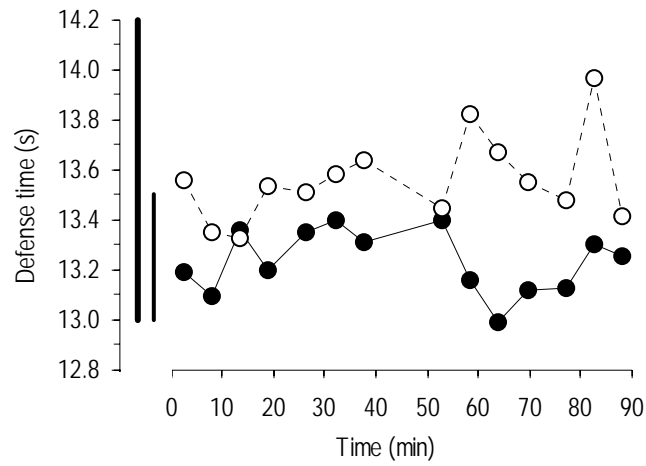
**Appendix L– Mean defense sprint times for each circuit for caffeine (●) and placebo (○) treatments. Values are means; bars are between- and within-subject standard deviations (thick and thin bars respectively).**

## Appendix M

THE EFFECT OF CAFFEINE INGESTION ON SIMULATED INTERMITTENT HIGH-INTENSITY SPORT PERFORMANCE

Gene R. Stuart, Simeon P. Cairns, Christian Cook, and Will G. Hopkins
Auckland University of Technology, Auckland and HortResearch, Hamilton

*Gene Stuart performed this study as part of a masters degree. He is interested in continuing the examination of caffeine's effect on sport and exercise performance.*

Caffeine supplementation is known to enhance endurance performance, but its effects on performance in high-intensity team sports are less clear. We therefore investigated its effect on performance in a test designed to simulate the demands of rugby. The study was a double-blind randomized cross-over trial in which 9 trained male rugby players ingested either caffeine (6 mg/kg body mass) or placebo (dextrose) 1 hour before performing the test. They repeated the test at weekly intervals for a total of 3-4 trials. The test consisted of 11 stations for measurement of movement speed (straight-line, offensive, defensive, and tackling), power generation in a drive, and accuracy of a pass. Athletes completed a total of 14 circuits of the stations in 80 minutes, with a 10-minute rest at half time and 2-minute rests after the fourth circuit in each half. Plasma was sampled by a non-invasive transdermal technique and assayed chromatographically for caffeine and adrenaline concentrations. Fluid samples were collected before administration of treatments, immediately before testing, at half-time and at full-time.

The main effect of caffeine supplementation was a reduction of fatigue, especially in the second half. Relative to placebo, the enhancements averaged over all circuits in the second half were: 20-m straight-line sprint, 1.3% (90% confidence limits, ±2%); swerve sprint, 2.3% (±4.1%); defensive sprint, 3.1% (±2.9%); tackle sprint, 3.8% (±1.6%); target pass, 15% (±7%); and 30-m straight-line sprint, 4.0% (±2.7%). Caffeine elevated adrenaline by 51% (±11%) during testing. There was evidence of individual responses of some measures of performance, but these had no substantial association with individual changes in caffeine and adrenaline concentrations. We conclude that caffeine supplementation provides worthwhile enhancements of performance in rugby and presumably other intermittent high-intensity team sports.

**Appendix N**

# Multiple Effects of Caffeine on Simulated High-Intensity Team-Sport Performance

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Running head: Caffeine and team-sport performance

**ABSTRACT**

Caffeine enhances performance of single bouts of endurance exercise, but its effects on repeated bouts typical of those in high-intensity team sports are unclear. **Purpose:** To investigate effects of caffeine in a performance test simulating physical and skill demands of a rugby union game. **Methods:** The study was a double-blind randomized cross-over in which nine competitive male rugby players ingested either caffeine (6 mg.kg$^{-1}$ body mass) or placebo (dextrose) 70 min before performing a rugby test. Each test consisted of seven circuits in each of two 40-min halves with a 10-min half-time rest. Each circuit included stations for measurement of sprint time (two straight-line and three agility sprints), power generation in two consecutive drives, and accuracy for passing balls rapidly. Interstitial fluid was sampled transdermally by electrosonophoresis before ingestion of caffeine or placebo, then prior to testing, at half-time and immediately after testing; samples were assayed chromatographically for caffeine and epinephrine concentrations. **Results:** The effects of caffeine on mean performance (±90% confidence limits) over all 14 circuits were: sprint speeds, 0.5% (±1.7%) through 2.9% (±1.3%); first-drive power, 5.0% (±2.5%); second-drive power, -1.2% (±6.8%); and passing accuracy, 9.6% (±6.1%). The enhancements were mediated partly through a reduction of fatigue that developed throughout the test, and partly by enhanced performance for some measures from the first circuit. Caffeine produced a 51% (±11%) increase in mean epinephrine concentration; correlations between individual changes in epinephrine concentration and changes in performance were mostly unclear, but there were some strong positive correlations with sprint speeds and a strong negative correlation with passing accuracy. **Conclusion:** Caffeine is likely to produce substantial enhancement of several aspects of high-intensity team-sport performance.

**Key Words:** epinephrine, ergogenic, fatigue, rugby, sprint.

## INTRODUCTION

Paragraph #1

The ergogenic effects of caffeine are well documented for endurance events, with significant increases in the time to exhaustion or mean power output in time trials (9, 11, 15, 24, 30). There is also mounting evidence for enhanced performance during short-term intense exercise lasting 4-10 min (4, 14, 21). However, effects of caffeine on brief bouts of single or repeated sprints lasting less than one minute are mostly unclear (3, 7, 17, 27, and there has been no research on repeated bouts of high-intensity exercise over durations typical of team sports, which can last over an hour. In such sports the outcome is often determined late in the game, when players are fatigued {Green, 1997 #16). Caffeine might enhance performance in these sports by attenuating fatigue. Therefore, the main purpose of the present study was to estimate the effects of caffeine on simulated team-sport performance, specifically the physical activity and skill demands of a rugby union game.

Paragraph #2

The mechanisms of the ergogenic effects of caffeine are unclear (15, 22). In an early study Costill and coworkers suggested that caffeine could improve endurance performance by elevating plasma free fatty acids, thereby sparing muscle glycogen (9). However, they also found that caffeine attenuated the rise in perceived exertion during exercise, which may have contributed to the ergogenic effect. Recent elegant experiments using animal models have provided evidence to support the notion that caffeine may act via the central nervous system (CNS) (11). Furthermore, it has repeatedly been suggested that the effects of caffeine may be mediated indirectly via elevated plasma epinephrine (15, 24), which, in principal could act via the CNS or on peripheral tissues. Therefore, another purpose of the present study was to examine the relationship between changes in performance with caffeine and changes in plasma epinephrine concentration.

## METHODS

Paragraph #3

**Subjects.** Eleven high-level amateur male rugby union players, of Polynesian or Polynesian-Caucasian ethnicity, were recruited from a team in the Auckland premier club competition. Owing to injuries independent of the present study two players did not complete the study. The subject characteristics were (mean ± SD, n = 9): age, 25 ± 4 y; body mass, 98 ± 22 kg; and height, 181 ± 4 cm. The study was conducted three weeks after the final championship game when the subjects reported a current training volume of 4.8 ± 0.8 h per week. All subjects gave voluntary informed consent with protocols approved by the AUT ethics committee.

Paragraph #4

**Study design.** The study was a randomized cross-over in which subjects performed a simulated rugby performance test. Sample size was determined by availability of subjects and resources and was similar to that of many studies of effects of caffeine. We could not determine a priori the minimum sample size for adequate precision of effects, because the reliability of the performance measures was unknown. The subjects and research assistants who supervised the stations of the test were blind to the treatment. A familiarization and two treatment trials of either caffeine or placebo were each separated by a week. Owing to failure of the drive ergometer after the first half of the second trial, a fourth trial was added one week after the third. Eight of the nine subjects returned for this fourth trial.

Paragraph #5

The subjects were weighed and a fluid sample was obtained transdermally 70 min prior to the start of the test. Subjects then ingested capsules containing either caffeine or placebo. A further fluid sample was taken one hour later. Just prior to testing the subjects performed their normal warm-up (~10 min), which included light jogging, stretching and some touch rugby. The rugby test was then undertaken in two 40-min halves with a half-time 10 min rest period. Fluid samples were drawn at the end of each half and later assayed for caffeine and epinephrine concentrations.

Paragraph #6

**Treatments.** A moderate dose of caffeine (6 mg.kg$^{-1}$ body mass) was chosen which has well documented ergogenic effects for endurance events [15]. Caffeine (Bronson and Jacobs, Sydney, Australia) or the same dose of placebo (dextrose) was weighed (589 ± 129 mg) and placed in gelatine capsules, then swallowed with water. This dose of dextrose is calculated to increase plasma glucose concentration by <0.3 mmol.L$^{-1}$. All subjects stated that they were regular consumers of caffeine in their diet. They were provided with a list of foods and beverages that contained caffeine and asked to refrain from consuming these for 48 h prior to exercise testing. Subjects were also provided with a 48-h diet record questionnaire prior to their first testing session so that they could replicate their diet before each of the subsequent testing sessions.

Paragraph #7

**Rugby test.** This test was designed, based on time-motion analysis of first-class level rugby union games, to simulate the activities of a game. (For details see 12.) In brief, the test consisted of fourteen circuits with each circuit made up of eleven stations for activities that included sprinting (straight-line and agility sprints), peak power generation in two consecutive drives, accuracy for passing balls, but also allowed for rest periods that included standing or walking (Table 1).

Table 1 here.

Paragraph #8

For sprint tasks, the subjects began ~20 cm behind the start line in a static position and sprint time (to the nearest 0.001 s) was measured using electronic timing lights (Speed-Light, Swift Performance Equipment, Goonellabah, Australia) set at knee height at the start and finish gates. The offensive sprint involved a forward run with swerving, while carrying a ball, then making a tackle on a tackle bag after the final timing gate. The defensive sprint involved running three arcs,

first forwards then backwards. The tackle sprint involved making a tackle on a tackle bag, picking up a ball and running backwards, placing the ball, making another tackle and then running forwards. Total distance covered with sprinting over the test was 1904 m. For the dynamic drive task a dynamometer cart (GRUNT 3000, School of Physical Education, University of Otago, Dunedin, New Zealand) measured peak power via transducers for speed of the cart and for force (load cell) attached to a bungee tether. Subjects began 1 m behind the cart then drove into the cart as quickly as possible for 5 s using shoulders, arms and legs (Drive 1), with the drive repeated from the starting position ~5 s later (Drive 2). For the passing accuracy task, the subjects were instructed to pass a ball as rapidly as possible at a target (dimensions of 1x1 m), placed 4 m from the player with its center being 2 m above the ground. After each pass the subject picked up another ball from the ground and repeated the pass. The time for this activity was ~10-15 s. The number of successful target hits out of five balls passed was counted.

Paragraph #9

The fourteen circuits were split into two 40-min halves with a 10-min half-time rest to simulate a game. There were seven circuits in each half, with a 2-min rest after circuit 4 (first half) and circuit 11 (second half). Subjects began at Station 1 and proceeded through the eleven stations at 30 s intervals. Once the task at each station was complete, the subject had the remainder of the 30 s to rest and move to the next station. Research assistants were present at each station to verbally encourage the subjects and record performance measures. Water was available for consumption at Station 11. The tests were performed in the early evening in an indoor sports stadium on a wooden floor at an ambient temperature of 21-23°C.

Paragraph #10

**Plasma caffeine and epinephrine concentrations.** Fluid samples were collected transdermally from the forearm using the non-invasive technique of electrosonophoresis (8), then analyzed for caffeine and epinephrine concentrations by high-performance liquid chromatography (HPLC). Plasma concentrations were predicted from the concentrations in the samples using equations derived in separate calibration studies. For the caffeine calibration, venous blood and transdermal fluid samples were drawn concurrently from 12 men on up to eight days sampled twice daily (129 samples in total). Some subjects varied their caffeine intake. Validity analysis of the paired samples (using a spreadsheet available at http://newstats.org) revealed that log transformation produced satisfactory uniformity of percent error over the range of plasma concentrations (1.9 to 8.2 $\mu g.mL^{-1}$). The calibration equation was $P = aT^b$, where P is the plasma concentration, T is the transdermal concentration, a = 9.93, b = 0.996, with the standard error of the estimate of 6.8%. There was insufficient caffeine in the transdermal sample for accurate measurement by HPLC, when the corresponding plasma concentrations were less than 2.0 $\mu g.mL^{-1}$. For the epinephrine calibration, eight men undertook five cycle ergometry sessions of varying duration (30, 45 and 60 min) with each session 2-3 days apart. Venous blood and transdermal samples were collected concurrently immediately before and after the exercise. A validity analysis similar to that for caffeine showed uniformity of the percent error over the range of observed plasma epinephrine concentrations (0.79 to 4.98 $nmol.L^{-1}$). The calibration equation was $P = aT^b$, where a = 7.89, b = 0.988, with a standard error of the estimate of 6.0%.

Paragraph #11

**Statistical analyses.** Data from all trials were included in the analyses. All variables representing performance were log transformed before analysis to reduce non-uniformity of error and to express effects as percent changes (20). Repeated-measures analyses were performed with a mixed-modeling procedure (Proc Mixed) in the Statistical Analysis System (Version 8.2 SAS Institute, Cary, NC). Fixed effects in the mixed model were trial (first to fourth), treatment (familiarization, caffeine and placebo), and circuit (first to fourteenth). Trial was included only as a main effect to account for familiarization; the other effects were included with their interactions. Random effects were the identity of the athletes and terms representing within-athlete variation in performance between trials and between circuits within trials. Analyses for epinephrine and

caffeine concentrations were similar to those for measures of performance, except that the fixed and random effects for Circuit were replaced with Time (with levels pre-, mid- and post-exercise). The possibility that individual responses in epinephrine and caffeine concentrations accounted for individual responses in performance was investigated by deriving correlations of changes in performance between caffeine and placebo conditions with changes in plasma caffeine and changes in plasma epinephrine. For plasma caffeine the correlations were derived for the concentration averaged for pre-, mid- and post-exercise in the caffeine condition, the concentrations in the placebo condition being zero. For plasma epinephrine separate correlations were derived for the pre-exercise caffeine-placebo change and for the average of the mid- and post-exercise changes. Magnitudes of correlations were interpreted using Cohen's thresholds (<0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; >0.5, large) (6).

Paragraph #12

Means for measures of performance shown in tables and figures are least-squares means (that is, means adjusted for any missing values using the fixed-effects model). Between-subject variations for measures of performance in the tables are coefficients of variation derived from the statistical model; these represent typical variation between subjects in either group for the measure in any one circuit. They were converted to standard deviations for display in the figures. The between-subject variations for caffeine and epinephrine concentrations in the figures were derived directly from raw data.

Paragraph #13

To make inferences about true (population) values of the effect of caffeine on performance, the uncertainty in the effect was expressed as 90% confidence limits and as likelihoods that the true value of the effect represents substantial change (harm or benefit) (20). An effect was deemed unclear if its confidence interval overlapped the thresholds for substantiveness; that is, if the effect could be substantially positive and negative, or beneficial and detrimental.  The smallest substantial change in sprint performance was assumed to be a reduction or increase in sprint time of more than 0.8% (27). The between-subject standard deviation for these measures was used to convert the log-transformed changes in performance into standardized (Cohen) changes in the mean. The smallest standardized change was assumed to be 0.20 (6). Inferences about the correlations between plasma caffeine, plasma epinephrine and performance were made with respect to a smallest worthwhile correlation of 0.10  (6). Based on eight observations, only correlations greater than 0.56 were conclusive (true correlation likely to be substantial of the same sign and very unlikely to be substantial of the opposite sign).

## RESULTS

Paragraph #14

**Performance.**  Prior to each test, all subjects expressed uncertainty about the identity of the treatment they had received. Table 2 shows the mean performance values for the various tasks obtained by averaging all circuits of the test in the placebo condition. The rugby test involved brief (~3-14 s) all-out exercise bouts. The total exercise time for each circuit amounted to ~60 s; the remainder of each 5.5 min circuit consisted of periods of rest or walking (~20-55 s).

Table 2 here.

Paragraph #15

In the caffeine condition there were enhancements of mean performance for all measures except Drive 2 power, although the effects were unclear for this measure and for the 20-m and offensive sprints (Table 3). The effects on performance in each circuit are shown in Figure 1 for tackle sprints (which had the greatest mean enhancement and greatest chance of benefit with caffeine), the two drives, and passing accuracy. Most measures showed an enhancement of performance with caffeine in the first circuit, as can be seen for the measures in Figure 1. Analysis of performance for the first circuit revealed a possible beneficial effect for Drive-1 power (5.5%; 90% confidence limits, ±5.7%) and a likely beneficial effect for passing accuracy

(12%; ±13%). Effects for the other measures in the first circuit were unclear; the observed values were beneficial for offensive sprint speed (1.6%; ±4.7%), Drive-2 power (1.9%; ±9.6%), defensive sprint speed (2.7%; ±3.6%), tackle sprint speed (2.1%; ±3.0%), and 30-m sprint speed (2.0%; ±4.1%), but detrimental only for 20-m sprint speed (-1.6%; ±3.3%).

Paragraph #16

It is also apparent in Figure 1 and for the other sprints (data not shown) that the mean enhancements with caffeine arose partly through a reduction in fatigue as the test progressed. We quantified fatigue in the test by calculating the decline in the performance in the second half relative to the first. In the placebo condition the declines were: 20-m sprint speed, 2.1% (90% confidence limits, ±1.4%); offensive sprint speed, 2.8% (±1.4%); Drive-1 power, 3.7% (±2.6%); Drive-2 power, 5.0% (±3.7%); defensive sprint speed, 0.9% (±1.2%); tackle sprint speed, 2.0% (±1.4%); passing accuracy, 9.0% (±4.7%); and 30-m sprint speed, 5.4% (±1.8%). The effects of caffeine on fatigue were decisive for all measures: possible through very likely reductions in fatigue for all but power in Drive 2, where a *detrimental* effect of caffeine was possible (Table 3).

Table 3 here.

Paragraph #17

For some measures, fatigue was not evident in the last circuit of the placebo condition relative to the first circuit. Indeed, for the 20-m sprint there appeared to be an *increase* in performance of 5.5% (±3.2%) relative to the first circuit, and there were also substantial although less clear improvements for defensive, tackle and 30-m sprints. The other measures showed declines in performance, which were unclear for the offensive sprint and Drive 2, but possible for Drive 1 (6.5%; ±7.8%), and very likely for passing accuracy (18%; ±11%). It was only for these latter two measures that the effect of caffeine was clear in the last circuit: a likely benefit for the first drive (12%; ±11%) and an almost certain benefit for passing accuracy (28%; ±19%).

Figure 1 here.

Paragraph #18

**Plasma caffeine and epinephrine.** Figure 2 shows that 1 h after ingestion of caffeine the plasma caffeine concentration increased to 8.2 µg.mL$^{-1}$ (equivalent to 42 µmol.L$^{-1}$) then declined somewhat during the rugby test. The caffeine concentration prior to ingestion was below the level of detection in the assay for all subjects; the value is shown on the figure as 1 µg.mL$^{-1}$. Caffeine concentration was also below the level of detection for all subjects at all time points in the placebo condition. Figure 2 also shows the plasma epinephrine concentration before, during and after the rugby test for the caffeine and placebo conditions. Averaged over these three time points, the epinephrine concentration was 51% higher (90% confidence limits ±11%) in the caffeine condition than in the placebo condition.

Paragraph #19

There was a strong positive correlation (r = 0.59; 90% confidence limits -0.06 to 0.89) between plasma caffeine concentration during the caffeine condition and the change in epinephrine concentration between placebo and caffeine conditions; both concentrations were averaged in each subject over the pre-, mid- and post-exercise assays. Correlations between plasma caffeine and changes in performance were inconclusive, with the exception of a strong positive correlation with tackle sprint speed (r = 0.63) and a strong negative correlation with Drive-1 power (r = -0.80). All but one of the correlations of changes in epinephrine concentration before and during the test with changes in sprint speed were substantial and positive, and two were conclusive (range -0.03 through 0.64). All the correlations of changes in epinephrine with changes in drive power were substantial and negative, but none was conclusive (range -0.27 through -0.49). There was also a strong negative correlation between passing accuracy and epinephrine concentration before the performance test (r = -0.63), and the correlation during the test was negative but unclear (r = -0.27).

Figure 2 here.

# DISCUSSION

## Effects of caffeine on exercise performance

Paragraph #20

The present study is the first to report that caffeine has multiple beneficial effects on the physical and skill activities required in an intermittent high-intensity team sport. Such effects were demonstrated for five sprint tasks (high speed requirement), a power task (high force requirement), and an accuracy task performed rapidly (high motor skill requirement). The enhancements of performance were apparently not due to a placebo effect at the start of the rugby test, because no subjects stated that they were confident about what treatment they had received.

Paragraph #20a

Our conclusions are based on the approach to inferential statistics that emphasizes precision of estimation rather than null-hypothesis testing. To that end we have followed recommendations to show and interpret the practical importance of confidence limits (for example, 2, 29), which represent the uncertainty in the true value of each effect. We have built on these recommendations by enunciating a rule for deciding when an effect is clear or unclear and by making quantitative assertions about likelihood that the effect is beneficial or detrimental (20).

Paragraph #21

For the sprint tasks, most of the effects of caffeine averaged over the entire test were clear and all were positive (Table 3). The improvements of 0.5-2.9% were of similar magnitude to those effects reported for endurance exercise (9, 15, 24) or high-intensity exercise of 4 to 10 min duration (4, 14, 21). The positive effects in the present study cannot be compared with those of other studies on repeated sprints (17, 27) because the duration of the test was considerably longer. This point is important because the influence of caffeine on the sprints was more apparent in the second half of the test (Fig. 1). We demonstrated that caffeine protects against fatigue during sprints, firstly from our caffeine versus placebo analysis of the first versus second half sprint performances (Table 3) and secondly because caffeine was without substantial effect when there was no apparent fatigue, as seen during the super efforts for the sprints of the last circuit (Fig. 1).

Paragraph #22

Caffeine increased the peak power of Drive 1 over the entire test by 5% (Table 3, Fig. 1). Specifically, this involved enhancement in the first circuit and diminished fatigue as shown over the two halves, and in the last circuit. Caffeine has also been shown to improve other activities requiring high force production such as competitive rowing (4) and maximum isometric voluntary contractions (MVC) (22, 23). The peak MVC force for the quadriceps can increase by 5% (23), but such effects are only detected in situations where there is submaximal voluntary activation (23, 25, 31). The only clear detrimental effect with caffeine in the present study was for Drive 2, which showed increased fatigue in the second half compared with the first half. Similar detrimental effects have been shown for the latter sprints during repeated Wingate testing (17).

Paragraph #23

The largest and possibly most exciting new finding with caffeine was a 10% improvement in the ability to pass balls accurately while pressured to pass rapidly (simulating game conditions). This was observed both early in the test and later when the subjects were fatigued (Table 3, Fig. 1). The importance of this observation is that over the course of a game the subjects would deliver a pass successfully 90% of the time with caffeine compared with 83% in the placebo condition, or a difference of about 5 passes out of 70. This supplement-induced improvement in a skill task requiring coordinated movements of several muscle groups is not found in current literature..

Paragraph #24

Ingestion of 6 mg.kg$^{-1}$ caffeine produced a peak plasma concentration of ~8 µg.mL$^{-1}$, which is similar to that previously reported for the same dose of caffeine (15, 17). Before administration of treatments, the subjects showed levels of caffeine below the 2 µg.mL$^{-1}$ threshold of detection for the assay. For the average subject, who weighed 98 kg, the dose was 600 mg of caffeine, which is

equivalent to ~6 cups of coffee (30). The detection threshold is therefore equivalent to ~1.5 cups of coffee consumed one hour before the assay. The assay was therefore not sensitive enough to confirm rigorous compliance with the instruction to abstain from caffeine-containing products. In a meta-analysis of the effects of caffeine on performance (G. R. Stuart and W. G. Hopkins, unpublished observations), abstention from caffeine-containing food and drink for at least several days produced an additional performance enhancement of ~1.5%. The effects we have observed on performance could therefore be underestimates of the full effect expected with abstention.

**Mechanisms for the effects of caffeine on performance**

Paragraph #25

Caffeine exerted its beneficial effects by causing obvious reductions in fatigue and in some cases by enhancement in the first circuit. However, apart from the first station in the first circuit (the 20-m sprint), all bouts were performed after prior exercise and therefore some fatigue could be involved. We discuss first the extent and nature of fatigue for the different activities, and then how caffeine may exert its performance enhancing effects by reducing fatigue or enhancement when the subjects were fresh.

Paragraph #26

The nature of the rugby test was one of repeated high-intensity exercise, with fatigue being apparent in every type of activity in the placebo condition (Fig. 1). The rugby test involved a much greater volume of supramaximal exercise (~14 min) compared with other studies on intermittent exercise, yet compared with typical endurance studies the volume was much less. The etiology of fatigue in repeated intermittent exercise could in principal involve several factors (16). It should also be noted that fatigue during any one activity in the rugby test is likely to depend on the cumulative effects imposed by all other previous physical activities. Fatigue mechanisms that are plausible for rugby include changes of muscle high-energy phosphates (16), acidosis (13, 16), lowered muscle glycogen levels (16, 17), rundown of electrolyte gradients such as for potassium ($K^+$) (17, 24), and/or a reduced motor drive from the CNS, that is central fatigue (11, 22).

Paragraph #27

With the sprint tasks an astounding finding was that in the very last circuit the subjects were able to restore sprint times relative to that of the first circuit (or even improve the time). This observation (Fig. 1) strongly suggests that the working muscles could still function maximally and therefore the slowing of sprints over the course of the test resulted from a diminished motor drive from the CNS. The slowing may be related to an inability to sustain exercise at the high levels of perceived exertion which occur in the latter stages of intermittent high-intensity shuttle running (10, 14, 26) or with endurance exercise (9).

Paragraph #28

The magnitude of fatigue in the drives (Fig. 1) is comparable to the reduction in peak MVC force (~10%) seen for leg muscles after a soccer test (28). Indeed, the drives are likely to require near maximal recruitment of motor units in the working muscles as is necessary for MVCs. Several neural or muscular mechanisms already alluded to could be involved in fatigue of the drives but the present study cannot discriminate between the possibilities. The fact that peak power for Drive 2 was always less than for Drive 1 (by 10-15%) throughout the test and even in the last circuit (Table 1, Fig. 1), could be explained by a substantial contribution from processes in muscle and may involve high-energy phosphates that had not recovered in the 5-s rest period between drives (16).

Paragraph #29

Impairment of the ball passing accuracy task (Fig. 1) could involve either a loss of concentration or another effect via the CNS that diminishes coordinated motor drive to the muscle groups involved in passing the ball. Other studies involving intermittent high-intensity exercise tests have revealed a loss of ground-stroke hitting accuracy in a tennis performance test (10) or diminished ability to dribble a soccer ball quickly (26). However, the impaired performance in

both of these tests may have been due to players moving more slowly, which did not contribute to the skill impairment in the present study.

Paragraph #30

Caffeine is known to influence many processes that could explain performance enhancement. These processes include several aspects of excitation-contraction coupling in skeletal muscles (1, 5), attenuation of the rundown of the $K^+$ gradient during exercise (18, 24), mobilization of free fatty acids from adipose tissue (4, 9), slowing of muscle glycogen depletion (15), and modifications to CNS activity (11, 22). Moreover, caffeine may act indirectly via inhibition of adenosine receptors (11, 15, 22), inhibition of cyclic AMP phosphodiesterase activity (15), elevation of the plasma epinephrine concentration (9, 24), or via theophylline or paraxanthine–the breakdown products of caffeine (15, 18). The only unlikely mechanisms include some of the excitation contraction coupling processes (1, 5) and phosphodiesterase inhibition (15), which require much higher concentrations of caffeine than in the present study.

Paragraph #31

We examined for a possible role of epinephrine but did not systematically investigate for other mechanisms. In the placebo condition the plasma epinephrine concentration exceeded 2 nmol.L$^{-1}$ throughout the rugby test (Fig. 2), which is comparable to that seen with intense exercise (17, 21). Also, in the caffeine condition plasma epinephrine was elevated both at rest and throughout the test (Fig. 2), making it a potential mediator for the enhancements. However, the correlation analysis revealed that epinephrine could be a mediator of performance improvement but only for the sprint activities. On the contrary, the higher epinephrine levels tended to dampen the beneficial effects of caffeine with the drives and the passing accuracy task.

Paragraph #32

We attributed the fatigue during repeated sprints to impaired motor drive. Caffeine could act either by attenuating this central fatigue or by acting directly on muscle. However, because the sprint time in the last circuit showed no fatigue in the placebo condition and caffeine did not improve this performance measure (Fig. 1), we propose that the entire effect of caffeine on the earlier sprints is mediated via the CNS. If this is the case then one explanation could be that caffeine inhibits the binding of adenosine to adenosine receptors in the brain (11, 15) and thereby reduces perception of exertion (9, 14). Another possibility, based on the positive correlation between changes in plasma epinephrine and sprint speed, is that a restoration of motor drive to the exercising leg muscles with caffeine may actually be mediated by epinephrine acting on the CNS.

Paragraph #33

Caffeine may have improved Drive 1 performance through increased motor drive (23), changes in metabolism (9, 15), or direct effects on muscle (24, 25, 31). This effect is unlikely to be mediated via epinephrine acting on muscle to potentiate excitation-contraction coupling (5) because the correlation analysis suggested that elevated epinephrine is, if anything, detrimental for this response. The mechanism for the decline in performance of Drive 2 with caffeine is uncertain. Nevertheless this negative effect is of minor concern given the notable gain in power output with caffeine during Drive 1.

Paragraph #34

It is difficult to imagine that the improved passing accuracy with caffeine would involve anything other than an effect somewhere in the motor control areas in the CNS. This effect could involve an increased level of attention (19) or arousal (15). The negative correlation between change in epinephrine concentration and change in performance suggests that epinephrine attenuates this effect. This effect of caffeine is likely to be important in competitive sports where the ability to perform skills like passing balls, hitting balls, or shooting goals with accuracy late in the event is a key to successful performance.

**Conclusions**

Paragraph #35

Caffeine provides several valuable performance enhancing effects on simulated intermittent high-intensity team-sport performance, making it a potentially useful supplement for games such as rugby, football, soccer, hockey, basketball or tennis. Although the mechanisms for the effects of caffeine are not fully understood, we speculate that caffeine influences several processes in the CNS to reduce fatigue with repeated sprint and permit a higher level of motor drive and motor skills throughout games.

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FIGURE 1–Performance in three of the tasks of the rugby test following caffeine (●) and placebo (○) ingestion. Values are means; bars are between-subject standard deviations.
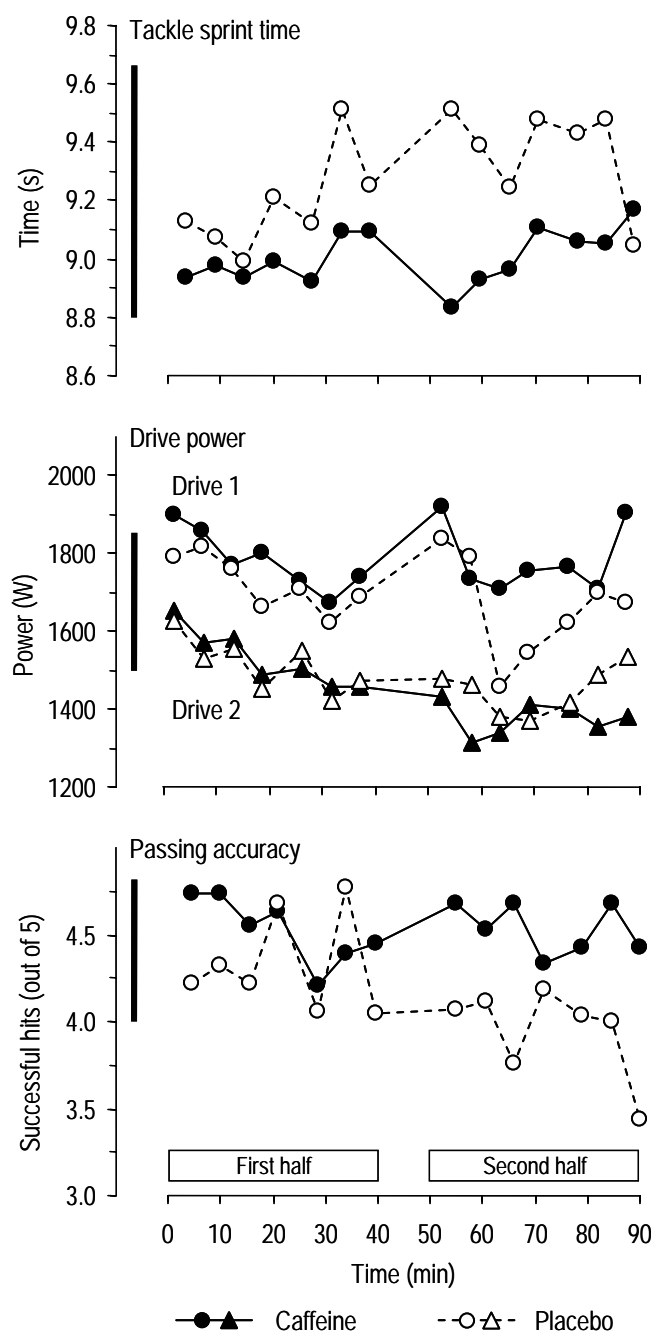
FIGURE 2–Plasma caffeine and epinephrine concentrations during caffeine (●) and placebo (○) testing sessions. Ingestion occurred 70 min before the start of the rugby test (at 0 min). Values are means; bars are standard deviations.
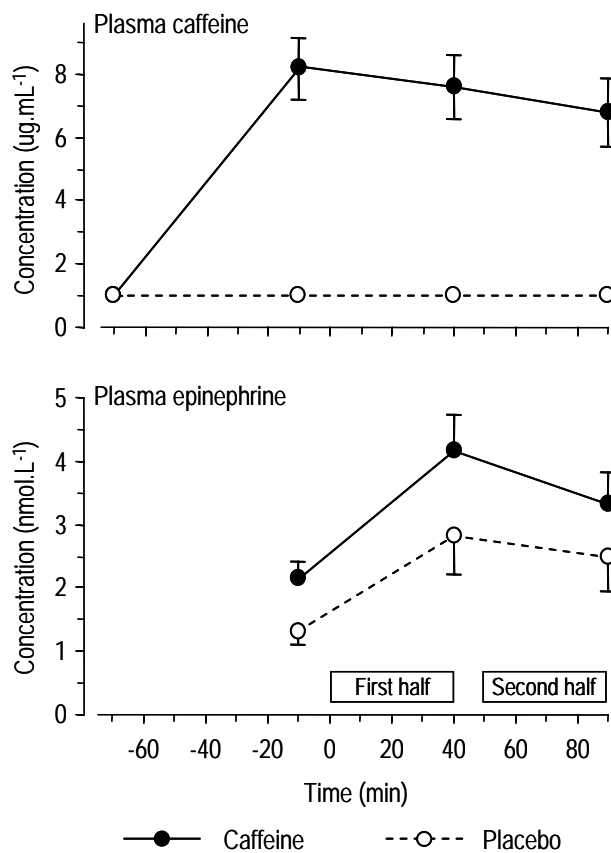
TABLE 1: Performance tasks at each station in the rugby test.

| Station | Task | Task description | Performance measure |
|---|---|---|---|
| 1 | 20-m sprint | 20-m straight-line sprint | Time |
| 2 | Offensive sprint | 22-m agility sprint | Time |
| 3 | Walk | Walk to next station | |
| 4 | Drive 1 | Dynamic drive | Peak power |
| | Drive 2 | Dynamic drive | Peak power |
| 5 | Walk | Walk to next station | |
| 6 | Defensive sprint | 33-m agility sprint | Time |
| 7 | Walk | Walk to next station | |
| 8 | Tackle sprint | 31-m agility sprint | Time |
| 9 | Passing accuracy | Ball passing at a target | Number of hits |
| 10 | 30-m sprint | 30-m straight-line sprint | Time |
| 11 | Walk | Walk to Station 1 | |

TABLE 2. Performance in placebo condition averaged over the 14 circuits of the rugby test, with the between-subject coefficient of variation (CV) for any one circuit.

| Performance measure | Mean | CV |
|---|---|---|
| 20-m sprint time (s) | 3.3 | 8.8% |
| Offensive sprint time (s) | 6.0 | 13% |
| Drive 1 power (W) | 1690 | 24% |
| Drive 2 power (W) | 1470 | 24% |
| Defensive sprint time (s) | 13.6 | 9.2% |
| Tackle sprint time (s) | 9.3 | 9.8% |
| Passing accuracy (per 5) | 4.2 | 20% |
| 30-m sprint time (s) | 5.0 | 11% |

TABLE 3. Effect of caffeine (relative to placebo) on mean performance over the 14 circuits of the rugby test, and the reduction in fatigue with caffeine (relative to placebo) between the two halves of the test. Confidence limits, chances that the true effects were substantial, and practical assessments of the effects are also shown.

| Performance Measure | Mean Change (%) | ±90% Confidence Limits (%) | Chances that the True Effect has Substantial[a]… | | |
| --- | --- | --- | --- | --- | --- |
| | | | Benefit (%) | Harm (%) | Practical Assessment[b] |
| **Effect of Caffeine on Mean Performance** | | | | | |
| 20-m sprint speed | 0.5 | 1.7 | 37 | 9 | Unclear |
| Offensive sprint speed | 1.3 | 4.1 | 59 | 19 | Unclear |
| Drive 1 power | 5.0 | 2.5 | 55 | <0.1 | Benefit possible |
| Drive 2 power | -1.2 | 6.8 | 7 | 18 | Unclear |
| Defensive sprint speed | 2.4 | 2.8 | 84 | 3 | Benefit likely |
| Tackle sprint speed | 2.9 | 1.3 | 99 | <0.1 | Benefit almost certain |
| Passing accuracy | 9.6 | 6.1 | 95 | <0.1 | Benefit likely |
| 30-m sprint speed | 2.3 | 2.5 | 85 | 2 | Benefit likely |
| **Reduction in Fatigue with Caffeine** | | | | | |
| 20-m sprint speed | 1.4 | 1.9 | 71 | 2 | Benefit possible |
| Offensive sprint speed | 2.1 | 1.8 | 87 | 0.6 | Benefit likely |
| Drive 1 power | 3.4 | 3.6 | 26 | <0.1 | Benefit possible |
| Drive 2 power | -4.4 | 4.8 | 0.1 | 45 | Harm possible |
| Defensive sprint speed | 1.5 | 1.6 | 76 | 0.9 | Benefit likely |
| Tackle sprint speed | 1.7 | 1.8 | 80 | 1 | Benefit likely |
| Passing accuracy | 10 | 7.6 | 91 | 0.1 | Benefit likely |
| 30-m sprint speed | 3.4 | 2.2 | 97 | 0.1 | Benefit very likely |

±90%CL: add and subtract this number to the mean effect to obtain the 90% confidence limits for the true difference.

[a] *Substantial* is an absolute change in performance of >0.8% for measures of sprint time, >4.7% for drive power, and >4.1% for passing accuracy (see Methods).

[b] If chance of benefit and harm both >5%, true effect was assessed as unclear (could be beneficial or harmful). Otherwise, chances of benefit or harm were assessed as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99%, very likely; >99%, almost certain.