Physiological measurements and analyses in motor sports: A preliminary study in racing kart athletes

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Physiological measurements and analyses in motor sports: a preliminary study in racing kart athletes.

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Abstract

The aims of this study were, firstly, to assess methods for performing physiological measurements in motor sports and, secondly, to carry out a preliminary study in athletes participating in *Kart Racing*. The measurement of physiological variables in motor sports is practically challenging, largely due to the restricted space available for sensors and instrumentation and to movement artefacts from driver's operations and car vibration, hence the paucity of publications. We performed a preliminary study of amateur racing kart athletes to assess the performance of basic measurement apparatus and to collect preliminary data on the possible influences of G on cardiovascular activity. We measured the vector magnitude of acceleration, G, instantaneous heart rate, HR, from the ECG, blood pressure, BP, with a wrist sphygmomanometer, eardrum temperature as a core body temperature, $T_{eardrum}$, with a radiation thermometer, and lap time. The instrumentation functioned satisfactorily during karting on a racing circuit. In all participants during driving we found that HR was maintained at approximately 150 beats/min. Time-frequency analysis of all HR data was performed to evaluate cardiac control mechanisms and this suggested that the observed rise in HR could be due to sympathetic acceleration. Furthermore, whilst we do not have sufficient data to draw firm conclusions, it is suggested that the rise in HR could be related to the G stresses to which the drivers were subjected. Cross-correlation analysis of the G and HR signals was performed in one subject and this showed a statistically significant correlation. We also found a statistically significant decrease in BP (P<0.01) and a rise in $T_{eardrum}$ (P<0.01) immediately after the driving period. We conclude that, whilst current sensors and instrumentation can allow basic monitoring of physiological variables in motor sport athletes, further developments are needed in order to allow more detailed investigations to be performed. Cardiovascular activity in response to G stresses warrants particular detailed investigations in the future.

Keywords

blood pressure, core body temperature, acceleration, heart rate, kart racing.

Introduction

We are concerned here with the investigation of physiological function in subjects driving motor vehicles. In its many forms motor vehicle driving challenges drivers in terms of physical strength and dexterity as well as mentally with respect to cognition, emotion and alertness. All of these facets interact to determine the overall performance of the driver and, in the general population, this performance is seen and judged in the road traffic accident statistics. There is considerable interest in identifying the major causes of road traffic accidents and to address these in order to reduce the associated mortality and morbidity. Physiological investigations have been a part of the overall effort in this area, looking at factors such as fatigue, drowsiness and alcohol consumption (Connor, 2002; Horne and Reyner, 1995; Phillip, 2001).

It is also appropriate to consider the assessment of physiological function in motor sports, due to the potential for extreme levels of physical and mental stress being placed on the competitive drivers/riders. For example, rapid decisions and actions are needed to perform appropriate maneuvers safely under the significant levels of acceleration, G, that can occur with heavy braking and cornering. Despite this there have been only a few studies done to examine detailed physiological responses and motor sport driver performance, although potential benefits have been reported (Klarica, 2001). This is in contrast to other popular sports, such as track and field athletics, water sports, cycling, wrestling and so on, which have been enthusiastically studied (Bird *et al.*, 2005; Chamari *et al.*, 2003; Cottin *et al.*, 2004; Dranitsin, 2008; Du *et al.*, 2005; Neumayr *et al.*, 2003; Sullo *et al.*, 2003).

It is reasonable to anticipate that cardiovascular, thermal, and respiratory systems will be influenced by the rigors of motor sport and indeed some studies have been aimed in these directions (Brearley & Finn, 2007; Jacobs *et al.*, 2002; Tsopanakis C & Tsopanakis A, 1998). The diverse abilities required of motor sports athletes include high dynamic visual acuity, responsiveness to the vehicle condition, and skills for rapid and precise vehicle control and decision-making. The reaction time of racing car drivers was reported to be significantly faster than controls, but no significant differences were found for postural stability, leg extensor strength, or arm strength and endurance (Baur *et al.*, 2006). Aerobic power, VO2, and heart rate response have been found to reach 45-81 % of values obtained in maximal graded exercise tests (Jacobs *et al.*, 2002; Tsopanakis C & Tsopanakis A, 1998). However, beat-by-beat heart rate changes/variability have not yet been thoroughly investigated.

For studying athletes in general, as well as persons engaged in exercise and fitness training, a variety of laboratory measurement techniques are already employed (Winter, 2007). Measurements include oxygen uptake to define the maximal value, blood lactate, muscle strength, and pulmonary function. Whilst these and other spot measurement techniques, usually performed, for example, in variants of graded exercise tests, are important tools for studying some aspects of motor sport athletes, they do not reproduce real driving and competitive conditions. In order to examine both methodological and physiological aspects of investigating motor sports athletes we consider here the sport of Kart Racing. This motor sport is generally accepted as being an accessible, relatively low cost, motor sport, under the regulation of La Commission Internationale de Karting and La Fédération Internationale de l'Automobile (CIK-FIA). It can be enjoyed by males and females from the 8 years of age. In addition, it can offer a relatively safe stepping-stone for those aspiring to move into the higher ranks of motor sports. In fact, most of the recent F1 champions grew up in racing karts, prominent among them being Ayrton Senna, Michael Schumacher and Lewis Hamilton. This is a clear indication that the racing kart can indeed provide a very real experience and challenge closely allied to what exists in F1 and probably other motor sports.

Here we describe the overall physiological measurements and responses of drivers in racing karts, anticipating that the results might be extrapolated to other motor sports. Furthermore, this study may have broader social relevance through its potential to contribute to decreasing road traffic accidents through a deeper understanding and use of physiological signals from drivers who are in so-called overload situations (Ho *et al.*, 2007; Yamakoshi *et al.*, 2009b).

Methods

Experimental setup and apparatus

Figure 1 shows a schematic diagram of the experimental setup. For this study we used the "Ishino Circuit", which was built in 2008, in the Toyota City, Japan. Careful attention had been given to the track design to include safety measures, including sufficient run-off areas and shock absorbers. The main parts of the experimental apparatus were two racing karts, devices for physiological measurement with a laptop PC (Vostro1200, DELL Inc., USA) and the appropriate interfaces. The karts were the BIESSE (B3-30/100, EIKO Co. Ltd., Japan) and the INTREPID (MT-01, SANTRAD Co. Ltd., Japan). The mounted two-stroke engines we used (KT100SD, YAMAHA Corp., Japan) are the most popular for racing karts worldwide.

The physiological measurements were made with a compact size heart rate recorder based on an electrocardiograph (ECG) and also containing a tri-axial sensor with which to measure accelerations (G), a wrist type sphygmomanometer, and an ear-type body thermometer. To obtain a high-quality ECG and minimise movement artefacts three pre-gelled silver/silver chloride electrodes were used and attached firmly to the chest in Lead II. Care was also taken to strap down the ECG connecting wires. With this approach the instrument was able to measure the heart rate reliably even with a significant degree of artefacts caused by physical movements.

Measurement quantities

Physiological monitoring during kart racing is made difficult by the strong vibrations from the road and the engine, as well as by the drivers' rapid movements. We were therefore limited in this study in the data that we could record and collect reliably. These measurement quantities were: beat-by-beat heart rate (HR beats/min) which was calculated from the ECG RR intervals sampled at 1 ms, vector magnitude of acceleration (G mG) (Active Tracer AC-301A, GMS Co. Ltd., Japan); systolic and diastolic blood pressure (SBP, DBP mmHg) in the subject's left wrist (HEM-6371T, OMRON Corp., Japan); eardrum temperature ($T_{eardrum}$ ℃) as core body temperature (MC-501, OMRON Corp., Japan); lap time (s). Instantaneous HR and G were recorded continuously during the experiments. However, BP, using the cuff-oscillometric method which could only be used reliably under rest conditions, and $T_{eardrum}$ were measured before and after the driving period. The environmental variables air temperature and relative humidity were also measured (TR-72U, A&D Co. Ltd., Japan). The lap time was measured by high accuracy instrumentation (PRO V2 A-105, ALFANO S.A., Italy), based on magnetic strips buried under the circuit, to 1/100 s.

Participants

Eleven amateur racing drivers, 34.4 ± 7.7 (S.D.) yrs, without known cardiovascular disorders participated in the present study. All subjects agreed to take part in the study voluntarily and signed an informed consent statement. The study was approved by the ethics commission of the faculty of medicine of Kanazawa University. All subjects had an SL kart license and were regularly involved in kart racing.

Experimental conditions

The experiment was conducted in fine weather, i.e. dry conditions, during the period between November and December in 2008. The duration of the driving period was set at 30 min, unless it was terminated earlier due to mechanical problems with the kart, or if the driver reached his physical limit. The test was conducted against the clock, by solo drive on the circuit. Before the experiment, we coached the subjects to drive with their maximum effort so as to record their best lap time during the experiment, and also to make a quick return to the main course if they spun out.

Procedure

After placing three electrodes on the chest for recording the ECG (Figure 1), the subjects were requested to sit down quietly on a chair in a temperature-controlled room. After resting for 5 min (baseline period) the subjects got into the kart and drove for approximately 30 min (driving period). Then the subject got out of the kart and rested for 5 min (recovery period). Physiological monitoring was carried out during these three periods. The timing of measurements for HR, *G*, BP, and $T_{eardrum}$ was beat-by-beat continuously, 1 s continuously, 0/2/4/35/40 min and 1/5/36/41 min, respectively. Additionally, air temperature and relative humidity measurement was done at 10 min intervals.

Data analysis

To evaluate circulatory autonomic regulation, time-frequency analysis was carried out using the collected data. Spectral analysis was carried out using the RR data by a maximum entropy method. It was applied to a dataset of 64 beats, which was updated every 16 beats. The spectral powers of RR in the low-frequency band (0.04-0.12 Hz; LF) and in the high-frequency band (0.15-0.4 Hz; HF) were calculated. It has been reported that HF power may be a marker of vagal activity (Pomeranz *et al.*, 1985; Berger *et al.*, 1989). The ratio of LF power to HF power (LF/HF) is expected to be an index of sympathetic activity (Pagani *et al.*, 1986). This spectral analysis was conducted using the special software named BIMUTUS II.

Descriptive statistical analysis was performed with means ± S.D. or ± S.E.M. Between-period differences, i.e. baseline vs. driving, were assessed by the *Wilcoxon* signed-rank test. In addition, to evaluate the correlation between HR and *G*, cross-correlation analysis was conducted. These two analyses were performed with the software of Statistical Package for Social Sciences (SPSS version 17.0).

Results

Table I shows basic information of individuals and events during the experiments. As shown in Table I, three subjects, Sub.01~03, spun out and then immediately returned back into the course, and Sub.06 stopped after 20 min (drove 15 min) due to mechanical trouble, and Sub.10 stopped at 26 min (drove 21 min) due to reaching his physical limit. We have successfully measured the variables listed above in these subjects as well as the other drivers during the active periods of their racing kart driving. **Figure 2** shows a typical recording of a 40 min trend-chart of the physiological variables obtained in Sub.09. This includes the G power, HR, HF power as an indication of vagal activity, LF/HF power as an indication of sympathetic activity, and lap time.

It can be seen in Figure 2 that the G vector magnitude periodically changed according to the layout of the course. The mean values of maximum, minimum, and mean G during the driving period were 2374 ± 349 mG, 175 ± 20 mG and 681 ± 69 mG, respectively.

It is clearly shown in Figure 2 that there was a rapid increase in HR at the start of the driving period, and this then stabilized during driving. It is of note that the HR variability during driving was very low as compared to that in the baseline period. **Figure 3** shows a summary HR profile (means ± SDs) for subjects in whom full data is available (n = 9) over the period of the experiment. Each data point was calculated from 1 minute HR averages. It is clearly shown that the HR during driving remained at a high level around 150 beats/min.

The analysis of HF and LF/HF data clearly showed that the vagal activity was suppressed and the sympathetic activity was accelerated during the driving period as compared to the baseline period. **Figure 4** presents these data as the change (means ± SEMs) of the sympatho-vagal activity balance from baseline, during driving and recovery period. The sympatho-vagal balance was analyzed by HF and LF/HF, which were normalized using the peak value as 1.0 together with the minimum value as 0. As shown in Figure 4, it is apparently demonstrated that the suppression of vagal activity and acceleration of sympathetic activity during driving were statistically significant ($P < 0.01$).

Concerning the lap time, the results indicate that the best lap tended to appear in the first half period. Also due to the demands of severe machine control, the lap time was fluctuated within approximately 0.5 s during driving.

Figure 5 shows the means ± SEMs of the SBP, DBP, and $T_{eardrum}$ changes from baseline at immediately after driving and 5 min after driving. Immediately after driving, SBP and DBP were significantly decreased ($P < 0.01$) as compared to the baseline period, and $T_{eardrum}$ was significantly raised ($P < 0.01$). Moreover, significant decreases in SBP ($P < 0.01$) and DBP ($P < 0.05$), and increases in $T_{eardrum}$ ($P < 0.05$) were confirmed in the measurements 5 min after driving.

Figure 6 shows a correlation between HR and *G*, HR and lap time. This data was derived from lap 10 to the end of driving in all subjects ($n = 11$), and *G* and HR data were averaged during each lap over this period. Due to the narrow range of HR, *G*, and lap time levels in this experiment, each variable is shown as a normalized value using z-score method. It is demonstrated that the HR has a significant association with *G* and lap time ($r = 0.743$, $P < 0.01$, $r = -0.639$, $P < 0.01$) according to *Spearman* test. This analysis was based on mean values, but to discover more detail a cross-correlation analysis was performed between HR and *G*. **Figure 7** shows the time course of *G* and HR changes during the time period from 20 to 25 min in Sub.09 as shown in Fig.2. The HR was re-sampled at a frequency of 1 Hz, that is the same sampling rate as *G,* to produce the trend-chart shown, The numbers shown along the top of each chart indicate the corner in the circuit (see Fig.1). Looking at this section of recordings, there appears clearly some kind of correlation. Accordingly, the cross-correlation analysis was conducted for this section of data indicated in Fig.7, that is 300 paired-data set, and shifting 20 times. The result is shown in **Figure 8**. The two lines of $r = \pm 0.117$ (df = 279) indicate the limit value of 5% significance level. It is clearly demonstrated that there is a statistically significant correlation between HR and *G* for time shifts between 5~15 s, although not at 10 s.

Discussion

Acceleration, G

The results show that during driving the kart drivers experienced an average acceleration of about 0.7 *G*, and a maximum acceleration of about 2.4 *G*. This compares with a F1 car, which can achieve a lateral acceleration of about 4.5 *G* on cornering, whilst a high-performance road car is said to achieve a maximum of 1 *G* (Lippi *et al.*, 2007; Watkins, 2006). Although the *Gs* during kart driving are approximately twice as small as those during F1 driving, it could be considered that the physical load during motor sports can be quite high. During this situation, it is worth investigating the measurement of BP, although it is speculated that the body fluid including blood is also under the influence of these high *G* forces.

Investigation of the physical and physiological implications of exposure of motor sport athletes to various modes of acceleration could be performed in complex test-rigs, but reproducing the actual changes in *G* that occur under live driving conditions is by no means straightforward. Thus on-track monitoring is preferred, even though this approach has its own challenges. The study of the effects of *G* on the human body has mostly been conducted within the context of aerospace medicine (Balldin, 2002). In this field the concern is that acceleration along the axis of the spine, $G\pm z$, can impede blood flow to the brain, leading to 'greyout' or 'blackout' of pilots or astronauts. The study of *G* is also important in vehicle crash testing (Huang, 2002). Here, both forward-reverse accelerations, $G\pm x$, and lateral accelerations, $G\pm y$, are important in terms of blood volume shifts and impact injury. A similar situation pertains in the study of contact sport head injury (Manoogian *et al.*, 2006), where crash helmet design is of interest.

In the present study the athletes experienced high levels of lateral accelerations, $G\pm y$. This is discussed further below in relation to the changes found in HR.

Blood pressure

The BP responses investigated in this study were for two conditions, namely, immediately after driving and five minutes after driving. It is widely known that the BP can act as a physiological stress marker (Sawada *et al.*, 2002). Therefore, it might be anticipated that BP would be significantly raised during motor sports. However, we found that both systolic and diastolic pressures were statistically significantly decreased immediately after driving ($P < 0.01$) as compared to the pre-driving baseline. This finding differs from the results of reported studies where BP was raised immediately after exercise (Du *et al.*, 2005; Laukkanen *et al.*, 2004; Molina *et al.*, 1999). We suggest that after driving the relief and sense of safety could be dominant. Our results could suggest a rebound reaction.

It would be valuable to measure BP continuously during motor sports but this is technically difficult with current instruments. However, we have recently developed a BP system utilizing the volume-compensation principle (Nakagawara & Yamakoshi, 2000; Tanaka *et al.*, 2007; Yamakoshi, 2003; Yamakoshi *et al.*, 2000), which is capable of measuring instantaneous BP (Yamakoshi, 1991; Yamakoshi *et al.*, 1980). Instantaneous BP response during simulated monotonous driving has already been measured with this method (Yamakoshi *et al.*, 2009a & 2009b). We will now consider the feasibility of using this method during motor sports.

Core body temperature

It was confirmed that the core body temperature, $T_{eardrum}$, was significantly increased ($P < 0.01$) at the end of the driving session by approximately 0.5 °C. Although this temperature is not really reflected as a steady-state one, as mentioned below, it could be suggested that motor sports can have considerably increased the core temperature. The mechanism for this rise during exercise was reported by Nielsen to be physiological thermoregulation (Nielsen, 1938), and it was also found that the steady-state core body temperature is reached after 40-50 min from the beginning of exercise. This steady-state temperature has been reported to be proportional to the magnitude of exercise intensity (Saltin & Hermansen, 1966). These authors also found that the core temperature is not influenced by the ambient temperature over the range 5-36 °C for the same level of exercise intensity. It is therefore likely in our own study that the core temperature obtained was little influenced by air temperature during the experiment since this was relatively constant, at 16.2 ± 3.9 (S.D.) °C (Table I). In fact, there was a large difference between the ambient temperatures in our study. Comparing the cloudy weather group (ambient temperature= 13.1 ± 1.0 S.D., $T_{eardrum}$= 36.3 ± 0.3

S.D. °C: n = 6) to the fine weather group (ambient temperature= 20.4 ± 1.6 S.D., $T_{eardrum}$= 36.6 ± 0.6 S.D. °C: n = 5), the averaged core temperature at the immediately after driving shows no statistically significant differences. Nevertheless, it is possible that core temperature could be increased by large environmental temperatures higher that 36 °C. In fact, the temperature in a closed cockpit can rise to about 70 °C in unusually hot conditions (Jareno *et al.*, 1987), or about 50 °C in hot conditions (Brearley & Finn, 2007). Furthermore, it should be noted that the driver must wear a racing suit, gloves, high-cut shoes and a full-face helmet for safety. Evaporation of sweat from the driver's skin is therefore prevented, seriously impairing evaporative heat dissipation, which is the only mechanism for losing excess body heat when environmental temperature rises above body temperature, that is beyond 36 °C. In fact, it has been reported that the core body temperature during supercar racing was rising to about 39 °C in hot conditions (Brearley & Finn, 2007). Monitoring of continuous core temperature during motor sports must therefore be regarded as an important aspect of driver protection. In addition, although there was no evidence of correlation between core body temperature and lap time, monitoring of core temperature could possibly be useful in assessing driver's performance.

Heart rate

It is well known that the beat-by-beat HR data contains information on circulatory autonomic regulation (Berger *et al.*, 1989; Pagani *et al.*, 1986; Pomeranz *et al.*, 1985) and so we conducted spectral analysis of RR data to explore this. We found significant suppression of vagal nerve activity ($P < 0.01$) and acceleration of sympathetic nerve activity ($P < 0.01$) during driving. It seems highly likely that this is beta-adrenergic sympathetic acceleration and is the underlying mechanism of the rise in HR.

As shown in Figure 3, HR increased rapidly and then stabilized at about

150 beats/min (approximately twice the baseline value) for the first half of the driving period. There was a small but steady decrease in HR from around the middle of the driving period until the end. From the HR variability point of view, analysis of the CVs (coefficients of variation) showed that this was statistically higher in the baseline period than in the driving period (driving = 0.062; baseline = 0.119: $P < 0.01$). It could be speculated that during driving the cardiac performance in terms of cardiac reserve or margin, was decreasing in our amateur participants, as influenced by vagal suppression (Berger *et al.*, 1989; Pomeranz *et al.*, 1985). However, it has been reported that physically trained athletes are strengthened in terms of this vagal activity (Levy *et al.*, 1993), so the extremely hard-trained racing driver, such as those in F1, might not exhibit this decreasing cardiac performance.

The correlation between *G* and HR, shown if Figs. 6-8, is of interest. It has been reported that the vagal activity for the heart has a relatively quick response of approximately 1 s as compared with that of sympathetic activity, which is approximately 10 s (Berntson *et al.*, 1997). In motor sports athletes, we have demonstrated, by using the time frequency analysis, that sympathetic acceleration is dominant. So, we can speculate that the HR phase shift of 5~15 s is mainly due to the sympathetic nerve control. Taking these results into consideration, whilst we do not have sufficient data to draw firm conclusions, it could therefore be suggested that the HR is influenced by the accelerations, *G*, to which the driver is subjected, and possibly also it will be related to the lap time.

A consideration of muscle behaviour appears to support this hypothesis further. Key muscle groups used in motor sport may be considered to require a mostly reactive role, as they maintain posture in the face of the rapidly changing G forces, whereas other sports generally require muscles to perform in a proactive way. Therefore, once again, this suggests that the HR levels and changes that we have observed in our study are closely related to the drivers' responses to the G forces to which they were subjected. Further investigation of this finding of the relationship between HR and G will be required.

Although our findings were obtained in amateur racing drivers, HR trends obtained in F1 drivers by Ceccarelli, who was a doctor in the TOYOTA F1 Racing Team, and Watkins tend to be similar (f1.panasonic.com, 2009; Watkins, 2006). It could therefore be argued that our results are representative of the general physiological responses in motor sports.

The HR was found in our study to be raised and maintained at about 150 beats/min, due to sympathetic nerve activity and adrenergic sympathetic activity simultaneously. Although, bearing in mind the finding that HR is closely related to core body temperature (Ladell & Watkins, 1956), HR during motor sports could be elevated even more in hot condition, this HR response being similar to that seen in the long-distance runner (Du *et al.*, 2005). The physiological purpose of this rise in HR is of course to meet the oxygen requirements of the muscles but also of the brain. Cerebral oxygenation is especially important in motor sport, where perception, judgment and rapid decision-making are arguably more important than in many other sports. Overall, it could be said that the motor racing driver must be a super athlete, needing to face tough competition with a clear and cool head, under extreme physiological conditions.

Conclusion

A physiological measurement study in racing kart drivers has found clear BP, core body temperature and HR responses, related in part to the imposed *G* forces experienced by the drivers. Our results clearly confirm the heavy physiological burden that must be tolerated by participants in motor sports. The muscle dynamism and the bodily conflict clearly visible in many other popular sports, may not easily be perceived by observers, as the racing driver is completely obscured by the racing suit and full-face helmet with a mirrored shield. We emphasise the importance of physiological measurement during motor sports and conclude that more research is needed to pursue further the detailed physiological aspects under full competitive racing conditions.

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References

Balldin, U. I. (2002). Acceleration effects on fighter pilots. In: *Medical Aspects of Harsh Environments, Volume 2*. (pp. 1014-1027). Washington DC: Borden Institute.

Baur, H., Müller, S., & Hirschmüller, A., Huber, G., Mayer, F. (2006). Reactivity, stability, and strength performance capacity in motor sports. *British Journal of Sports Medicine*, *40*, 906-911.

Berntson, G. G., Bigger, J. T. Jr, Eckberg, D. L., Grossman, P., Kaufmann P. G., Malik, M., Nagaraja, H. N., Porges, S. W., Saul, J. P., Stone, P. H., van der Molen M. (1997) Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology*, *34*, 623-648.

Berger, R. D., Saul, J. P., & Cohen, R. J. (1989). Transfer function analysis of autonomic regulation. I. Canine atrial rate response. *American Journal of Physiology*, *256*, 142-152.

Bird, S., George, M., Balmer, J., & Davison, R. C. R. (2009). Heart rate responses of women aged 23-67 years during competitive orienteering. *British Journal of Sports Medicine*, *37*, 254-257.

Brearley, M. B., & Finn, J. P. (2007). Responses of Motor-Sport Athletes to V8 Sipercar Racing in Hot Conditions. *International Journal of Sports Physiology and Performance*, *2*, 182-191.

Chamari, K., Moussa-Chamari, I., Gary, O., Chaouachi, M., Koubaa, D., Hassen, C., & Hue, O. (2003). Correlation between heart rate and performance during Olympic windsurfing competition. *European Journal of Applied Physiology*, *89*, 387-392.

Connor, J., Norton, R., Ameratunga, S., Robinson, E., Civil, I., Dunn, R., Bailey, J., & Jackson, R. (2002). Driver sleepiness and risk of serious injury to car occupants: population based case control study. *British Journal of Sports Medicine*, *324*, 1125.

Cottin, F., Durbin, F., & Papelier, Y. (2004). Heart rate variability during cycloergometric exercise or judo wrestling eliciting the same heart rate level. *European Journal of Applied Physiology*, *91*, 177-184.

Dranitsin, O. V. (2008). The effect on heart rate variability of acclimatization to a humid, hot environment after a transition across five time zones in elite junior rowers. *European Journal of Sport Science*, *8(5)*, 251-258.

Du, N., Bai, S., Oguri, K., Kato, Y., Matsumoto, I., Kawase, H., & Matsuoka,

T. (2005). Heart rate recovery after exercise and neural regulation of heart rate variability in 30-40 year old female marathon runners. *Journal of Sports Science and Medicine*, *4*, 9-17.

f1.panasonic.com. Available online at http://f1.panasonic.com/features/2006/vol01/index.html/ (accessed 3 August 2009)

Ho, C., Reed, N., & Spence, C. (2007). Multisensory in-car warning signals for collision avoidance. *Human Factors*, *49(6)*, 1107-1114.

Horne, J. A. & Reyner, L. A. (1995). Sleep related vehicle accidents. *British Medical Journal*, *310*, 565-567.

Huang, M. (2002). *Vehicle crash mechanics*. Boca Raton, FL: CRC Press.

Jacobs, P. L., Olvey, S. E., Johnson, B. M., & Cohn, K. (2002). Physiological responses to high-speed, open-wheel race car driving. *Medicine & Science in Sports & Exercise*, *34(12)*, 2085-2090.

Jareno, A., De La Serna, J. L., Cercas, A., Lobato, A., & Uyá, A. (1987). Heat stroke in motor car racing drivers. *British Journal of Sports Medicine*, *21(1)*, 48.

Klarica, A. J. (2001). Performance in motor sports. *British Journal of Sports Medicine*, *35*, 290-291.

Ladell, W. S., & Watkins, E. S. (1956). Prediction of body temperature from heart rate. *Journal of Physiology*, *135*, 51.

Laukkanen, J. A., Kurl, S., Salonen, R., Lakka, T. A., Rauramaa, R., & Salonen, J. T. (2004). Systolic blood pressure during recovery from exercise and the risk of acute myocardial infarction in middleaged men. *Hypertension*, *44*, 820-825.

Levy, W. C., Cerqueira, M. D., Abrass, I. B., Schwartz, R. S., & Stratton, J. R. (1993). Endurance exercise training augments diastolic filling at rest and during exercise in healthy young and older men. *Circulation*, *88*, 116-26.

Lippi, G., Salvagno, G. L., Franchini, M., & Guidi, G. C. (2007). Changes in technical regulations and drivers' safety in top-class motor sports. *British Journal of Sports Medicine*, *41*, 922-925.

Manoogian S, McNeely D, Duma S, Brolinson G, Greenwald R. (2006). Head acceleration is less than 10 percent of helmet acceleration in football impacts. *Biomed Sci Instrum*, *42*, 383-8.

Molina, L., Elosua, R., Marrugat, J., & Pons, S. (1999). Relation of maximum blood pressure during exercise and regular physical activity in normotensive men with left ventricular mass and hypertrophy. *American Journal of Cardiology*, *84*, 890-893.

Nakagawara, M., & Yamakoshi, K. (2000). A portable instrument for non-invasive monitoring of beat-by-beat cardiovascular haemodynamic parameters based on the volume-compensation and electrical-admittance method. *Medical & Biological Engineering & Computing*, *38*, 17-25.

Neumayr, G., Pfister, R., Mitterbauer, G., Gaenzer, H., Sturm, W., & Hoertnagl, H. (2003). Heart rate response to ultraendurance cycling. *British Journal of Sports Medicine*, *37*, 89-90.

Nielsen, M. (1938). Die Reguration der Korpertemperatur bei Muskelarbeit. *Scandinavian Arch Physiology*, *79*, 193-230.

Pagani, M., Lombardi, F., Guzzetti, S., Rimoldi, O., Furlan, R., Pizzinelli, P., Sandrone, G., Malfatto, G., Dell'Orto, S., Piccaluga, E., Turiel, M., Baselli, G., Cerutti, S., & Malliani, A. (1986). Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interaction in man and conscious dog. *Circulation Research*, *59*, 178-193.

Philip, P., Vervialle, F., Breton, P. L., Taillard, J., & Hornem, J. A. (2001). Fatigue, alcohol, and serious road crashes in France: factorial study of national data. *British Medical Journal*, *322*, 829-830.

Pomeranz, B., Macaulay, R. J. B., Caudill, M., Kutz, I., Adam, D., Gordon, D., Kilborn, K. M., Barger, A. C., Shannon, D. C., Cohren, R. J., & Benson, H. (1985). Assessment of autonomic functions in human by heart rate spectral analysis. *American Journal of Physiology*, *248*, 151-153.

Saltin, B., & Hermansen, L. (1966). Esophageal, rectal, and muscle temperature during exercise in humans. *Jounal of Applied Physiology*, *21*, 1757-1762.

Sawada, Y., Nagano, Y., & Tanaka, G. (2002). Mirror tracing and the provocation of vascular-dominant reaction pattern through heightened attention. *Journal of Psychophysiology*, *16*, 201-210.

Sullo, A., Brizzi, G., Cardinale, P., Mercadante F., Fabbri, B., & Maffulli, N. (2003). Prognostic evaluation of bradyarrhythmias and heart rate variability in endurance master athletes. *European Journal of Sport Science*, *3(2)*, 1-10.

Tanaka, S., Nogawa, M., Yamakoshi, T., & Yamakoshi, K. (2007). Accuracy assessment of a non-invasive device for monitoring beat-by-beat blood pressure in the radial artery using the volume-compensation method. *IEEE Transactions on Biomedical Engineering*, *54(10)*, 1892-1895.

Tsopanakis, C., & Tsopanakis, A. (1998). A Stress hormonal factors, fatigue, and antioxidant responses to prolonged speed driving. *Pharmacology Biochemistry & Behavior*, 60, 747-751.

Watkins, E. S. (2006). The Physiology and Pathology of Formula One Grand Prix Motor Racing. *Clinical Neurosurgery*, *53*, 145-152.

Winter, E. M. (2007). *Sport and Exercise Physiology Testing Guidelines, Vol. 1: Sport Testing.* Abingdon, UK: Routledge.

Yamakoshi, K. (1991). Non-invasive techniques for ambulatory blood pressure monitoring and simultaneous cardiovascular measurements. *Journal of Ambulatory Monitoring*, *4*, 123-143.

Yamakoshi, K. (2003). Non-invasive cardiovascular haemodynamic measurements. In: P. A. Oberg, T. Togawa, & F. Spelman (Eds), Sensors in Medicine and Health Care (Sensors Applications. 3) (pp. 107-160). Weinheim, Wiley-VCH Verlag.

Yamakoshi, K., Nakagawara, M., & Tanaka, S. (2000). Current development in beat-by-beat cardiovascular monitoring with non-invasive and ambulatory techniques. In: M. Singh, S. Radhakrishnan, K. M. Ratil, & M. R. S. Reddy (Eds), Medical Diagnostic Techniques and Procedures (pp. 132-141). New Delhi, Narosa Publishing House.

Yamakoshi, T., Park, S. B., Jang, W. C., Kim, K., Yamakoshi, Y., & Hirose, H. (2009). Relationship between Salivary Chromogranin-A and Stress Induced by Simulated Monotonous Driving, *Medical & Biological Engineering & Computing*, *47(4)*, 449-456.

Yamakoshi, T., Rolfe, P., Yamakoshi, Y., & Hirose, H. (2009). A novel physiological index for driver's activation state derived from simulated monotonous driving studies. *Transportation Research Part C*, *17(1)*, 69-80.

Yamakoshi, K., Shimazu, H., & Togawa, T. (1980). Indirect measurement of instantaneous arterial blood pressure in the human finger by the vascular unloading technique. *IEEE Transactions on Biomedical Engineering*, *BME-27*, 150-155.

Figure captions

Figure 1. Outline of experimental setup for physiological measurements during racing kart driving.

Figure 2. Typical examples of 40 min trend-charts of Acceleration, HR, HF, LF/MF and Lap Time obtained in one subject.

Figure 3. Time course of heart rate changes (means ± SDs) throughout the study period.

Figure 4. Means ± SEMs of the sympatho-vagal activity balance from baseline during driving and recovery period analyzed by the normalized HF & LF/HF trend-charts. Asterisks indicate significant deviation according to the *Wilcoxon* test (* $P < 0.05$, ** $P < 0.01$). See text for details.

Figure 5. Means ± SEMs of the SBP, DBP, and $T_{eardrum}$ changes from baseline at immediately after driving and 5 min after driving. Asterisks indicate significant deviation according to the *Wilcoxon* test (* $P < 0.05$, ** $P < 0.01$). See text for details.

Figure 6. Correlation between HR and *G*, HR and Lap Time. Each variable are shown as normalized value.

Figure 7. Time course of acceleration (*G*) and re-sampled heart rate changes during 20 to 25 min in the Sub.09 as shown in Figure 2. Re-sampling of HR was 1 s, which was the same as *G* sampling rate. The numbers shown along

the top of each chart indicate the corner in the circuit.

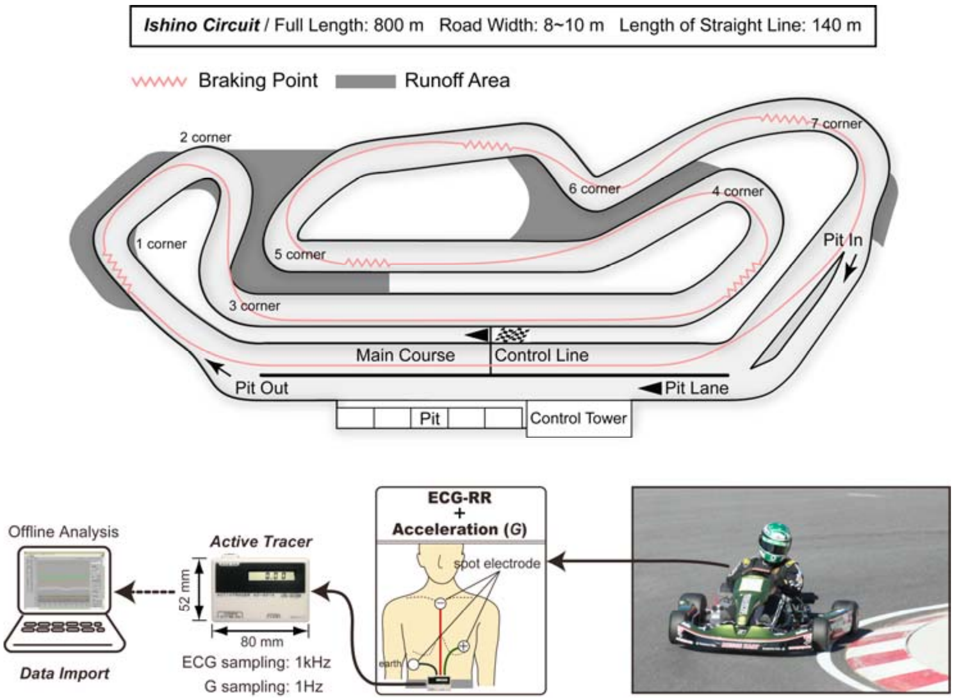
Figure 8. Results of cross-correlation analysis. The two lines of $r = \pm 0.117$ indicates the limit value of 5% significance level.

Table captions

Table I. Basic information of the volunteer racing kart drivers.

Ethical standards: The study was approved by the ethics commission of the faculty of medicine of Kanazawa University.

Competing Interest: The authors declare that they have no conflict of interest.



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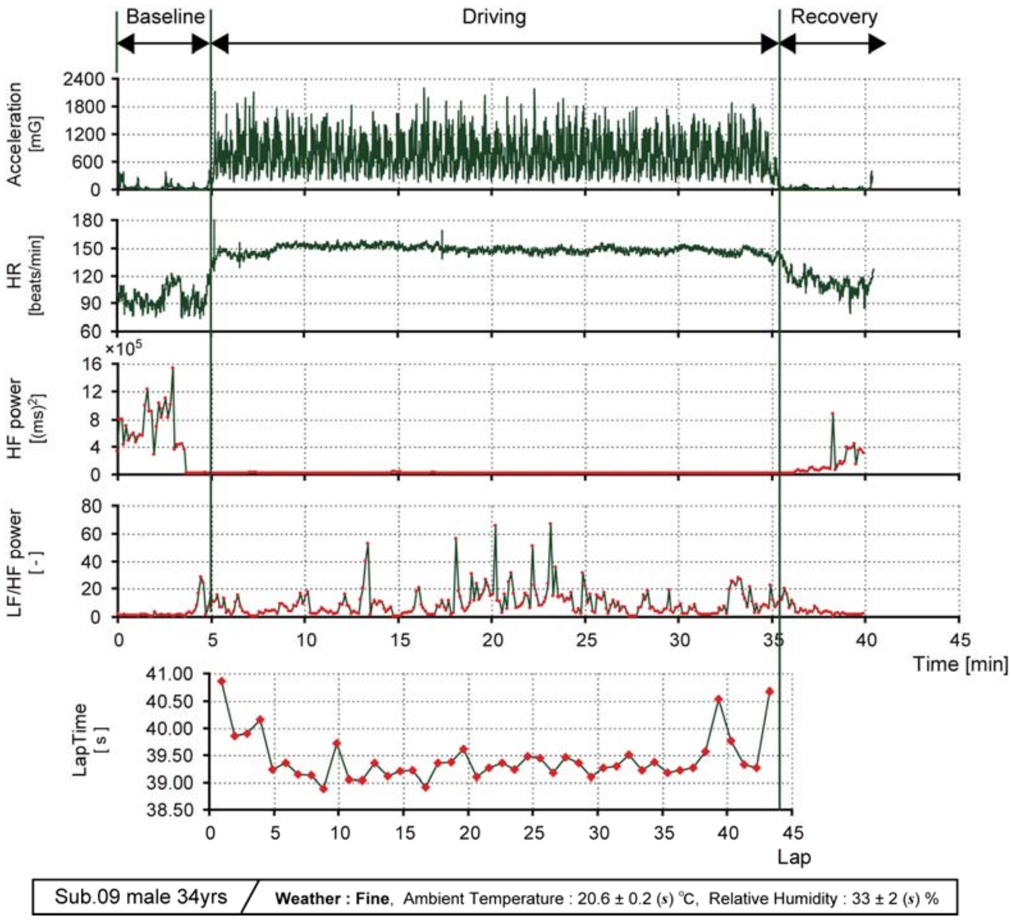

HR, heart rate; HF, spectral power of high frequency band; LF/HF, ratio of low frequency power to HF power.

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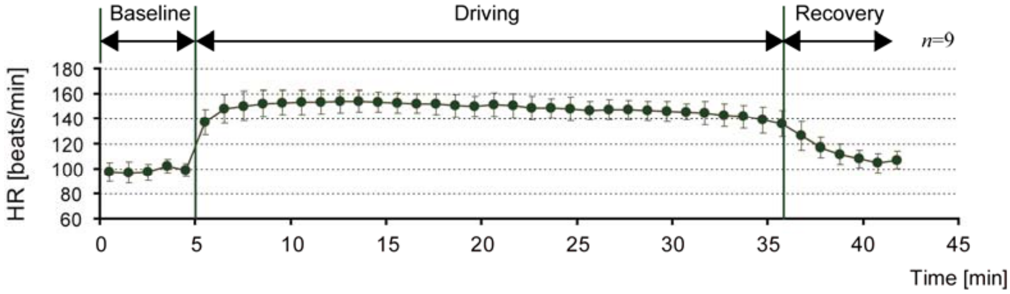

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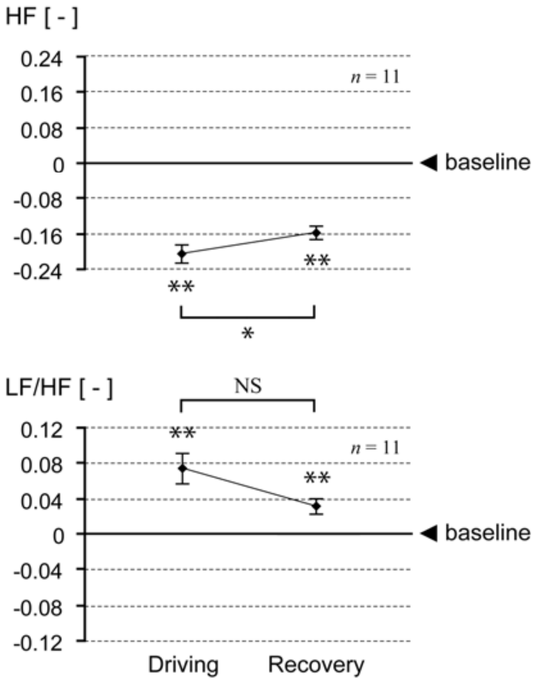

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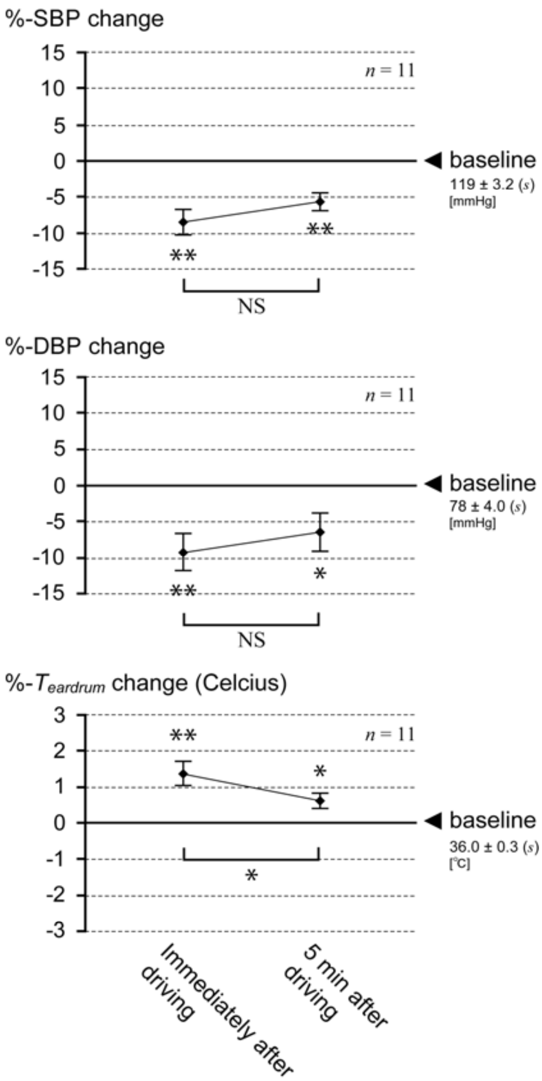
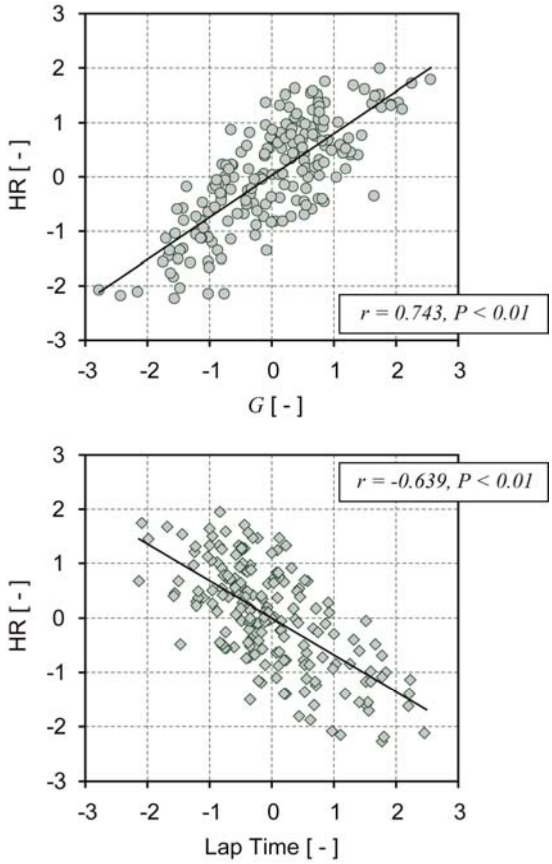


SBP, systolic blood pressure; DBP, diastolic blood pressure; $T_{eardrum}$, eardrum temperature.

Figure 5. Means ± SEMs of the SBP, DBP, and $T_{eardrum}$ changes from baseline at immediately after driving and 5 min after driving. Asterisks indicate significant deviation according to the *Wilcoxon* test (*P< 0.05, **P< 0.01). See text for details.



N-HR, normalized heart rate; N-G, normalized G force power, N-Lap time, normalized Lap Time.

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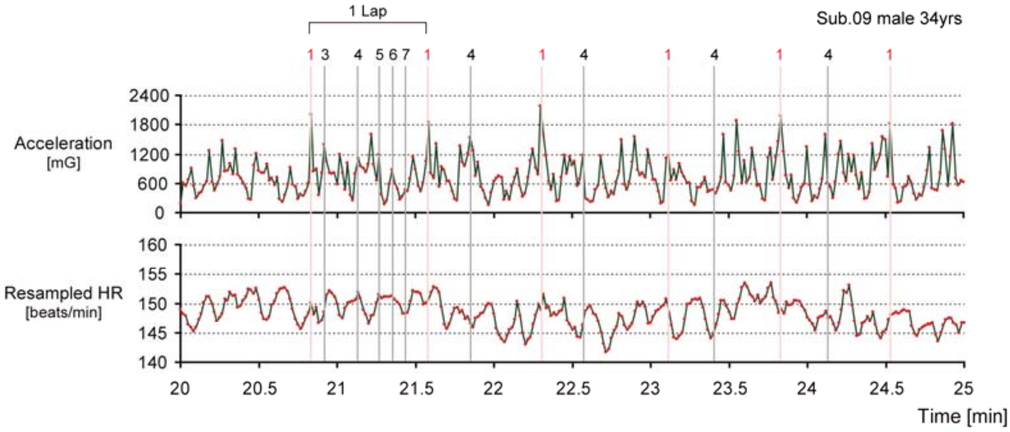

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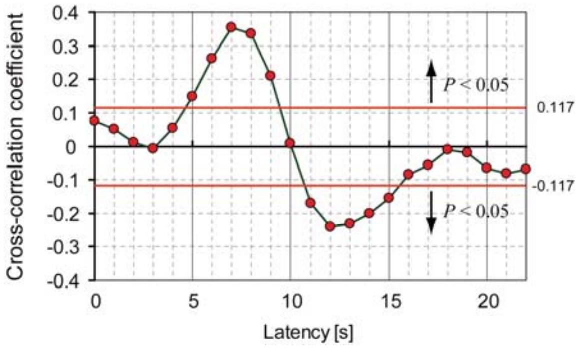

Figure 8. Results of cross-correlation analysis. The two lines of $r = \pm 0.117$ indicates the limit value of 5% significance level.

Table I. Basic information of the volunteer racing kart drivers.

Subject No.	Age [yrs]	Kart Experience [yrs]	Weather	Mean (S.D.) of Ambient Temp. [°C]	Mean (S.D.) of Relative Humidity [%]	Events
01	34	3	Cloudy	13.1 (0.2)	66 (4)	Spinout at 24 min
02	30	3	Cloudy	14.0 (0.5)	62 (1)	Spinout at 20 min
03	26	2	Cloudy	13.9 (0.2)	66 (5)	Spinout at 26 & 31 min
04	31	4	Cloudy	13.7 (0.4)	70 (2)	–
05	34	5	Cloudy	12.1 (0.2)	82 (1)	–
06	30	6	Cloudy	11.5 (0.3)	84 (2)	Machine trouble at 20 min
07	33	4	Fine	18.0 (0.1)	40 (2)	–
08	28	2	Fine	18.8 (0.4)	39 (1)	–
09	34	5	Fine	20.6 (0.2)	33 (2)	–
10	58	18	Fine	21.5 (0.6)	31 (1)	Reach the end of his tether at 26 min
11	30	1	Fine	21.3 (0.3)	34 (1)	–
Mean	33.46	4.82		16.2	49	
S.D.	8.15	4.41		3.9	20	