ASSESSING THE METABOLIC DEMANDS OF WOMEN'S HOCKEY

Fiona D. Lothian

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Assessing the metabolic demands of women's hockey.

F.Lothian

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Abstract

The metabolic demands for women hockey players (n=12) were estimated during real match play using heart rate analysis and time-motion analysis. An individual heart rate - oxygen uptake regression equation, established at steady state workloads on the treadmill, was applied to heart rates recorded throughout the match to estimate energy expenditure. A specific energy cost was assigned to each of nine discrete activities to give an energy cost for the whole match. The mean estimated energy cost for a complete match from heart rate analysis was 3873 ±436 kJ and from time-motion analysis, 2846 ±284 kJ. In order to check the errors in these methodologies expired air was collected continually during 15 minutes intermittent activity on a treadmill (n=16) with the heart rates and work : rest ratios similar to those established in the earlier part of the study. The error in the use of heart rate to estimate energy expenditure was 3.7 ±5.1% and for time-motion analysis was 16.6 ±4.8%, when compared with the measured value from the analysis of expired air. It was concluded that heart rate gave a good estimation of energy expenditure during intermittent activity at workloads similar to women's hockey.

In order to gain a greater insight into the metabolic demands of women's hockey both heart rate and time-motion analysis need to be applied simultaneously. The heart rate analysis suggested that the estimated energy expenditure was similar during the first and second halves. In contrast the time-motion analysis established that less time was spent in high intensity activity during the second half. Women's hockey is played at greater intensities than previously reported with no differences in the metabolic demands when related to specific player positions.

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Chapter 1

Introduction

1.1 Women's hockey

The world of sport is continually changing as developments are made to raise standards and to enhance the appeal of the sport. One such sport is field hockey which has seen dramatic changes in the last decade (Cibich, 1991; Reilly & Borrie, 1992). Two major factors which can be attributed to this are the development of synthetic pitches (Cibich, 1991; Reilly & Borrie, 1992) and amendments to the rules which have increased the fluidity and speed of the game (Read, 1987). The inclusion in 1980 of women's hockey in the Olympics and the coverage of the British men's team, in the 1988 Olympics, winning gold, have led to an increased awareness of the sport in Britain. The more recent bronze medal for the British women's team at the 1992 Barcelona Olympics increased the media exposure of the women's game and showed the game as a fast moving, competitive and skilful sport.

These changes have been reflected in the increased number of women members of the All England Women's Hockey Association which was estimated at 30,000 in 1990 compared to the 1977 figures of 16,400 representing an 88% growth (Northern Council for Sport, 1993).

Not only have changes in the game resulted in greater participation rates, these changes have also contributed to an increase in the standards of performance at international level in terms of the skills required and the high level of physical fitness demanded in women hockey players (Dagett & Davis, 1982).

Despite these advances in the standards of play there has been very little research done with respect to women's hockey (Agiss, 1986; Cooke, 1985). What there is concentrates on the measurement of the various components of fitness in players. There can be no doubt that the changes in the sport which have led to less stoppages and a faster pace have increased the physiological demands of the game, and as a result a higher level of physical fitness is required to play the game . However due to the fact that there is almost no information concerning what a player does during a game (Reilly & Borrie, 1992) it is difficult to identify the extent of the physical stress placed on her.

Without a knowledge of the physiological demands of women's hockey, the advice given to players on the most appropriate training and diet is not based on a firm scientific foundation. Dagett & Davis (1982) suggested that most of the physical fitness training of women hockey players is a bit of a "hit and miss" affair.

The contribution of the aerobic and anaerobic systems to the total energy expenditure in hockey has been suggested by Fox (1984) and Agiss & Walsh (1985), as being 30% aerobic and 70% anaerobic. In contrast Sharkey (1986) suggested that there is a greater contribution from the aerobic system (60% aerobic, 40% anaerobic). Reilly & Borrie (1992) support this greater contribution of the aerobic system suggesting that the game is mainly aerobic in nature but interspersed with frequent bursts of anaerobic activity. The description of team games in terms of the contribution of the different energy systems does not help to define the true nature of the game, as, for example Agiss & Walsh (1985) suggested that a 5 minute maximal run will require a similar percentage contribution from the aerobic and anaerobic energy systems as a hockey match despite being continuous in nature.

The sparse literature on the energy expenditure of women's hockey gives mean values ranging from 25 $kJ.min^{-1}$ (Durnin & Passmore, 1967) to 35 $kJ.min^{-1}$ (Skubic & Hodgkins, 1967). The changes since these studies in the style of the game and the playing surface would suggest that the energy expenditure of top level women's hockey is now far greater. Values for men's hockey range between 35-50 $kJ.min^{-1}$ (Reilly & Borrie, 1992).

1.2 "Multiple-sprint" sports

Women's hockey has been classified as a "multiple-sprint" sport (Williams, 1990). "Multiple-sprint" sports, which also include the various forms of football, basketball and the racquet sports are characterised by short periods of maximal effort followed by a lower intensity recovery period, the ratio of work : rest being controlled by the game situation. Williams (1990) stated that the common factors between "multiple-sprint" sports are the periods of maximal exercise. The differences between these sports are the time spent in these periods of high intensity exercise, and the recovery time between periods of high intensity activity, which will also vary within a single sport.

Indeed it has often been assumed that hockey places similar physiological demands on a player as soccer, in that both are 11-a-side field invasive games played on a similar size pitch, the exception being that the duration of a soccer match is 90 minutes compared to 70 minutes for hockey. Both games show similar properties in that they involve intermittent high intensity periods of activity followed by periods of low intensity activity; in neither game are the periods of high and low intensity regulated or controlled.

The major difference between hockey and soccer is that due to the nature of the hockey stick, players are in a stronger position when they have the ball to the right of their body or "stick side". As a result of this the majority of attacks are on the right side of the pitch (Hughes & Cuncliffe, 1987) and players are likely to have to work harder to get in the correct position in relation to the ball especially when defending (Reilly & Borrie, 1992). Another major difference is that for the majority of the time in hockey the ball is played on the ground whereas in soccer it can be played overhead, i.e. in hockey the ball has to be played round and worked through defences, in soccer this is also the case but there is the additional option of playing over the defence. In addition to these factors, the stooped position required to play the ball will also increase the physiological demands of the game (Reilly & Seaton, 1990). As a result, it is likely that hockey will place a slightly greater physiological demand on players than the equivalent time in soccer for male players (as there is little literature on women's soccer, comparisons cannot be made between the differences in physiological demands between male and female soccer players).

There is speculation about whether there are greater physical demands placed on certain positions within teams. In soccer, Ali & Farrally (1990) estimated a greater energy expenditure, Reilly & Thomas (1976) estimated a greater distance covered, and Van Gool et al. (1983) recorded a greater mean heart rate by midfielders in comparison with other positions. In women's hockey earlier studies found positional differences in the fitness profiles of players (Bale & McNaught-Davis, 1982; Cooke, 1985); however a study by Reilly & Bretherton (1986) failed to find any fitness component which could be related to position. Burke (1982) suggested that positional variations will become indistinguishable as players are now expected to be involved in both defence and attack. By establishing whether positional variations exist in terms of the total work required and the nature and intensity of this work, it can be determined, firstly, whether individual training programmes are required in relation to position played and secondly whether there are specific positions which due to the total work requirements are more subject to fatigue.

The performance of players in most sports is related to the effects of fatigue, that is, the longer that the limiting effects of fatigue can be delayed the better a player's performance (Williams, 1990). In the "multiple-sprint" sports where there is a mixture of both maximal efforts and endurance based activities, fatigue will be related to two factors, the first being an increase in lactate, the second being the depletion of the muscle glycogen stores (Williams, 1990).

It is now recognised that during short periods of maximal exercise energy is provided simultaneously by both the breakdown of creatine phosphate (PCr) and by glycolysis and that there will be some accumulation of lactic acid (Boobis, 1987). There is some debate as to the mechanisms of fatigue during short periods of maximal activity. It was previously thought that the adenosine tri phosphate (ATP) utilisation was greater than the ATP production. However studies by Brooks (1987) and Boobis (1987) have suggested that fatigue is caused by a lowering of muscle pH (as a result of H^+ ions and Pi) rather than a decrease of available PCr and glycogen. The effect of the lower muscle pH is to inhibit the use of available ATP, lowering the contractile force of the muscle (Boobis, 1987; Brooks, 1987). Hence the accumulation of lactic acid and the resultant lowering of muscle pH will be contributory factors to fatigue. Indeed Williams (1990) suggested that this is the main factor limiting performance in "multiple sprint" sports.

Saltin (1973) demonstrated the importance of pre-game glycogen levels with respect to fatigue, observing that those players with low pre-game concentrations covered less distance and spent less time in high intensity activity than those players with normal pre-match levels.

Despite the large number of participants in "multiple-sprint" sports there has not been the same amount of research into this type of activity when compared to endurance based activities (Williams, 1990).

1.3 Analysis of team sports

The analysis of team games has traditionally been for the coach to assess a team's or individual performance in order that any areas of strength or weakness can be identified. This type of analysis has tended to be of a subjective and qualitative nature (Franks & Goodman, 1986). It is characterised by observational techniques relying on the coachs' evaluation of the game.

This type of analysis is required for on-the-spot evaluations in a team's play so that any appropriate actions may be taken, e.g. substitutions or changes in tactics. There is a problem in that there is a limit to the amount of information that one person can commit to memory or note form and secondly, Morris & Bell (1985) suggested that the overall evaluation of performance tends to be marred by specific incidents which directly influence the result. In the long term, more objective and quantitative means of collecting relevant data should be applied to improve both performance through the design of game-related training schedules and practices (Smith et al., 1982), and to give an insight into the physiological demands of the game (Franks & Goodman, 1986).

When assessing the performance of individual players it must be noted that the very nature of team games demands an interaction with other team members and that the actions of the opposition will to a large extent determine the behaviour of the individual player (McKenna et al., 1988). This is supported by Franks & Goodman (1986) who stated that "One major problem with attempting to analyse team games is the large number of potentially interacting variables" (p. 50).

There is a number of variables which can affect the physiological demands of the game other than the interaction between the players. Firstly, environmental conditions can greatly increase the physiological demands on a player, for example a strong wind will require a greater energy expenditure to overcome the added resistance (a 16 $km.h^{-1}$ head wind can mean an increase in oxygen uptake of 5.5% per minute (McArdle et al., 1986); extremes of temperature will also affect the physiological demands. In "hot" conditions a higher than expected heart rate for a given workload will be obtained as through the effects of dehydration blood volume is decreased and heart rate is subsequently increased to maintain cardiac output (Astrand & Rodahl, 1986). Secondly, the importance of the match and the result can often influence a player's work rate. For example in a game which has been "decided" by half time the work rate of both teams is likely to be reduced in the second half whereas in a closely contested game both teams' work rate will remain high throughout the game. Bangsbo et al. (1991) suggested that data pertaining to match performance should be collected over several matches in order to obtain a good set of data for each player. Additionally

> "Differences in personal style of play, individual motivation, level of competition, frequency of time-outs, foul shots and out of bounds, and a player's fitness will affect the intensity at which a particular sport is played"
>
> (McArdle et al. 1971, p.184)

Clearly it is possible to reduce some of these variables by using players of a similar standard in games of the same importance.

Any analysis of team games must therefore acknowledge that the data obtained relate to that specific match and that only general assumptions and trends can be applied to both previous and future games. Further, in order to obtain accurate information in relation to match play, the collection of data must take place in a competitive situation i.e. a "real" match (Dal Monte et al., 1989; Van Gool et al., 1988), otherwise the players will not be working under the same conditions. It is difficult to replicate the intensity of movements from a game in simulated match play and certainly not the psychological pressures (Reilly & Secher, 1990).

With reference to individual performances Franks & Goodman (1986) suggested three main areas of analysis,

1. Physiological analysis
2. Time and motion analysis
3. Technique analysis

These three types of analysis can be combined to give a complete picture of a player's physical performance. As this research is concerned with the metabolic demands in terms of energy expended and the physical work done rather than the players' contribution to the game in terms of skill or playing effectiveness, the methods of technique analysis will not be reviewed. Franks & Goodman (1986) identified physiological analysis and time and motion analysis as measuring different components of performance, in particular they suggested time-motion analysis should observe the displacement of players in relation to other players rather than being concerned only with measuring the physical workload, i.e. it should be used to monitor tactical performance. For the purpose of this study time-motion analysis will be used to assess the physiological workload on players rather than their playing effectiveness.

Although a variety of physiological parameters could be assessed, practical considerations mean that the metabolic demands of field games are usually evaluated in terms of heart rate response, energy expenditure or as distance covered or time spent in activities.

The most used method for estimating energy expenditure in team sports involves the use of the linear relationship between heart rate and oxygen uptake. A regression equation is established for heart rate and oxygen uptake at steady state workloads in the laboratory and is applied to heart rates obtained during match play. The use of heart rate to estimate energy expenditure in team sports is generally considered to overestimate the true energy cost. This is partly attributed to the psychological factors associated with competition (McArdle et al., 1971; Van Gool et al., 1988). This method assumes that the heart rate - oxygen uptake relationship during non-steady state intermittent activity will be the same as that observed during steady state exercise.

Time-motion analysis is a second non-intrusive method to estimate energy expenditure. Time spent in each activity is recorded and assigned an appropriate energy cost. This method has been used in several studies to estimate daily energy expenditure (Durnin & Passmore, 1967; Reilly & Thomas, 1979) and the energy cost of simulated basketball match play (Ballor et al., 1989). It has been suggested that this method of estimating energy expenditure will underestimate the actual value if used during match play due to the additional requirements of changing activity (Reilly & Borrie, 1992). This type of analysis can also be used to measure the amount of time which is spent in discrete movements, determine work : rest ratios, and investigate the contribution that different energy systems make to the game.

By combining the information obtained from time-motion analysis, heart rate analysis and the estimations of energy expenditure a comprehensive picture of the physiological stress on players during women's hockey match play can be obtained. This can be used to aid performance in a number of ways, firstly by the design of game-related training schedules, that is players train the energy systems required in the game. Secondly, knowledge of the rate of energy expenditure determines whether glycogen depletion contributes to end of match fatigue and as a result whether greater dietary knowledge might aid players' performance. Thirdly if inter-positional differences exist it might be that some players are placed under greater stress and as such may be subject to greater fatigue.

1.4. Research hypothesis

The main aim of this research is to estimate the metabolic demands of women's hockey. In order to achieve these aims the error in the use of both heart rate analysis and time-motion analysis as a means of estimating the energy expenditure of women's hockey needs to be established. The second aim of this research is to determine whether all players were subject to similar physiological stress both in terms of energy expenditure and the nature of the activity. In order to achieve these aims three separate studies have been devised.

Study one : **The estimation of energy expenditure from heart rate during women's hockey match play**

The aim of this study is to determine the nature of the players' heart rate response during match play and use this to estimate their energy expenditure. The heart rate response during match play will be used to set the work intensities for the third study, which is to establish the errors in the use of heart rate analysis to estimate energy expenditure.

The information obtained from study one will be used to test the following null-hypothesis :

Hypothesis 1 : In women's hockey, there is no significant difference in the energy expenditure (estimated from heart rate) in relation to position played.

As stated earlier it has been found in several studies in soccer that midfielders have a higher physiological loads than other players, the objective of this hypothesis is to determine whether the same is true in women's hockey in relation to the total energy cost.

Hypothesis 2 : In women's hockey, there is no significant difference in the total energy expenditure (estimated from heart rate) for one player over several matches.

The two objectives of this hypothesis were firstly to determine the highest total energy expenditure for each player over several games, it was felt if positional differences were observed over only one game the opposition would be a large factor in determining a player's energy expenditure. The second objective was to determine the range of energy expenditure that players were subjected to, because, it may be that some players very rarely are required to work under high physiological stress as they play for stronger teams and as a result get very little physiological training effect from most matches. Hence it was felt necessary to observe each player over a range of matches.

Study two **The estimation of energy expenditure from heart rate and time-motion analysis during women's hockey match play**

The main aim of the second study is to determine the differences between estimating energy expenditure from both heart rate and time-motion analysis, where a complete match for each player will be analysed using both techniques. This second study is to be used to establish the movement intensities and work : rest ratios for the third study on establishing the errors in the techniques of heart rate and time-motion analysis as a means of estimating energy expenditure in women's hockey. The results of the time-motion analysis will be presented to help establish the physical workload that players are under.

The following null-hypothesis have been formulated for the second study :

Hypothesis 3 : For each player, during match play there is no significant difference between the estimation of energy expenditure from heart rate and time-motion analysis.

The objective of hypothesis three was to determine the magnitude of the differences between the two techniques and whether there was a strong correlation between the two techniques i.e. despite the likely errors, were the two techniques measuring the same variable.

Hypothesis 4 : There is no significant difference between the energy expenditure (estimated from heart rate analysis) for the first and second halves.

Hypothesis 5 : There is no significant difference between the energy expenditure (estimated from time-motion analysis) for the first and second halves.

The objectives of hypothesis 4 and 5 are to determine the nature of fatigue during the second half in terms of the amount of physical work that players completed and their energy expenditure estimated from heart rate.

Hypothesis 6 : There is no correlation between a player's aerobic power and the time spent in high intensity activity.

The objectives of hypothesis 6 is to determine the relationship between aerobic power and the player's contribution to the game in terms of the amount of time spent in high intensity activity, as in soccer it has been found that there is a strong correlation between aerobic power and a) total distance covered and b) no of sprints (Reilly, 1990) in soccer. This would help determine the relevance of aerobic training in the "multiple- sprint" sports.

This study will also determine whether a player's total energy expenditure is related to the time she spends in high intensity activity or whether factors such as body weight and efficiency of movement are greater factors in the total energy expenditure.

Study 3 : The errors in the use of heart rate and time-motion analysis to estimate energy expenditure during "multiple-sprint" activity

Using the information obtained from the first two studies to determine the physiological demands of women's hockey, the aim of the third study is to examine the errors in the use of heart rate and time-motion analysis as a means of estimating energy expenditure in activity similar to women's hockey (multiple-sprint activity).

The third study will test the following null-hypothesis :

Hypothesis 7 : During intermittent activity on the treadmill, there is no significant difference between the use of heart rate to estimate energy expenditure and the measurement of energy expenditure from the direct collection of expired air.

The same methodology as used in studies one and two will be used to estimate the energy cost of non-steady state treadmill activity from heart rate and compared to the actual energy expenditure. This will establish the nature of the errors involved in using heart rate to estimate energy expenditure in non-steady state activity.

Hypothesis 8 : During intermittent activity on the treadmill, there is no significant difference between the use of time-motion analysis to estimate energy expenditure and the measurement of energy expenditure from the direct collection of expired air.

The same methodology as used in study two will be used to estimate the energy cost of intermittent treadmill activity from time-motion analysis and to determine whether time-motion analysis is a good technique for estimating energy expenditure.

By combining the information obtained in the three studies outlined above the true metabolic demands of top level women's hockey will be established. These results can then be applied to determine the nature of women's hockey in relation to other "multiple-sprint" sports and the most appropriate type of training. The accuracy of the methodologies for estimating energy expenditure may be helpful in establishing the metabolic demands in other "multiple-sprint" sports

Chapter 2

Review of Literature

2.1 Introduction

The first section of this review of literature will concentrate on the methods of analysis available for determining the physiological responses and the nature and intensity of work during "multiple-sprint" sports. The techniques for expressing the results of these physiological analysis in terms of energy expenditure will be also be discussed.

In the second section results from research into the metabolic demands in other "multiple-sprint" sports will be reviewed. By determining the physiological responses observed during "multiple-sprint" activity in both competition and simulated match play, women's hockey can be compared to other "multiple-sprint" sports such as soccer to determine whether there are similarities between the sports.

Part three of this review of literature will concern itself specifically with the previous research into the physiological nature of women's hockey, which has centred mainly on the fitness assessment of players, with limited work on the metabolic demands of the game .

Research into the physical nature of women's team sports is scarce (Alexander et al., 1988; McArdle et al., 1971; Skubic & Hodgkins, 1966) and so much of the literature pertaining to methods of analysis and the nature of "multiple-sprint" sports will be drawn from male team sports.

2.2 Physiological analysis techniques

The physiological demands of a sport can be directly assessed by two means. The first is to monitor the players' physiological responses throughout and/or after matches, the second is to assess the physical workload that players complete.

The most common parameter used to monitor the physiological demands of team games, has been heart rate (Ekblom, 1986; Gleim et al., 1981; Hahn et al., 1974; McArdle et al., 1971; McLaren et al., 1988; Rhode & Esperson, 1988; Skubic & Hodgkins, 1967; Van Gool et al., 1983; Van Gool et al., 1988). In order for heart rate to give a truer indication of the physiological load it is often expressed as a percentage of maximum heart rate (McArdle et al., 1986; Van Gool et al., 1988), as a percentage of maximum VO_2 (Ekblom, 1986; Van Gool et al., 1988); or in terms of energy expended (Ali & Farrally, 1990; McArdle et al., 1971; Skubic & Hodgkins, 1967). A second parameter available is the level of lactate produced during the game (Cochrane & Pyke, 1976; Ekblom, 1986; Gerisch et al., 1993; McLaren et al., 1988; Rhode & Esperson, 1988) which can be used to give an indication of the contribution of the anaerobic lactate energy system. Thirdly, the level of post-game glycogen stores (Ekblom, 1986) will give an indication of the energy reserves available at the end of the match.

Time-motion analysis and distance analysis both relate to the types of movements a player is engaged in during a game, and can be used to determine different aspects of these movements and the physical workload on players. Distance analysis can be used to establish, firstly, the total distance covered in all movement categories and, secondly, the most recurring distances found in each category e.g. the average length of a sprint, which can then be applied to the development of the appropriate training. In contrast an analysis based on the time spent in different activities can give a better indication of the work : rest ratios during the game and also the percentage of total time spent in high intensity activities. By applying both these methods of analysis a more accurate definition of what a player does during the game can be established.

2.2.1 Heart rate methodologies

It is only recently, with the advances in micro-computing technology that the continuous monitoring of heart rate has been both possible and practical. Consequently heart rate is becoming a common parameter in the monitoring of the physiological demands of team games. The nature of team games requires that any monitoring equipment must be light weight, robust and unobtrusive as players will only agree to being monitored during competitive matches if they suffer no inconvenience and if the monitors do not affect their play.

Two main methods of heart rate monitoring which have been developed for use in the field situation are radio telemetry and microcomputers using short range radio telemetry in the form of heart rate memory watches (Karvonen & Vuorimaa, 1988).

Studies in team sports which have used the radio telemetry method include Skubic & Hodgkins (1967), McArdle et al. (1971) and Van Gool et al. (1983; 1988). In this method a receiver is positioned by the side of the pitch where it picks up a signal from a radio transmitter worn by the player and connected to electrodes attached to the chest. For continuous recording of heart rate this method requires a radio receiver unit for each subject. The major problem with telemetry is the chance of malfunction of the electrodes through player contact, sweating where the electrodes fall off as the connections lose their stickiness or by the players accidentally disconnecting the electrodes by catching the wires connecting the electrodes to the transmitters (Ali & Farrally, 1991; Van Gool et al., 1983).

Heart rate memory watches have been used in studies in soccer by Ekblom (1986), Rhode & Esperson (1988), and Ali & Farrally (1991; 1990). This system consists of an electrode belt to which a small transmitter is attached and a watch receiver which records the players' heart rate at given intervals (5, 15 or 60 seconds). The small size of the complete system (the total weight of which is 128.5 grams) means that it can be worn by the player without any inconvenience. The heart rate data are stored for analysis through a computer system at a later date. This method allows several players to be monitored during the same match provided that they are not in close proximity. As the transmitters and watches operate on the same frequency, a signal from another player will be recorded if players come within 1.5 m of each other.

One such short range telemetry is the Polar Sport Tester PE 3000 heart rate monitor which has been found to be both valid and reliable when compared with a simultaneous ECG reading (Leger & Thivierge, 1988). The validity (r=0.95) was greater at workloads between 65-75% of maximum heart rate than at the higher workload of 85-95% of maximum heart rate (r=0.71); at this workload the standard error was ≤ 6 beats.min^{-1}. In 99 separate recordings, this monitor was found to record 0% of doubtful cases and 0.1% of unrealistic values. Three types of activity were used to validate the Sport Tester PE 3000; these were cycle ergometry, treadmill walking/running and bench stepping. The

Sport Tester PE 3000 records the actual heart rate every 5th second rather than an average over the 5 second interval

Ali & Farrally (1991) validated the use of a short range telemetry system (Sport Tester PE 3000) during simulated soccer match play against a standard electrocardiograph (ECG) telemetry technique (Hewlett Packard), it was found that between the ECG recordings and the heart rate values recorded every 5 seconds by the Sport Tester PE 3000 there was very little difference; these differences were never greater than 2 beats.min^{-1}. The short range telemetry system (Sport Tester PE 3000) was found to be the more practical method of monitoring heart rate during match play.

The Sport Tester PE 3000 heart rate monitoring system has been found to be a practical means of measuring heart rate during competitive soccer (Ali & Farrally, 1990, 1991; Rhode & Esperson, 1988). These studies, however, do not identify the percentage of data if any that might be lost using this method of heart rate monitoring in match play. In a study of the heart rate response of ringette players (ringette is a game similar to ice hockey) using a Sport Tester PE2000 heart rate monitor, Alexander et al. (1988) lost about 50% of the data they tried to collect from poor electrode contact, malfunction of the recorder or from a blow to the system. Green et al. (1976) reported a loss of approximately 40% of their data during the heart rate monitoring of ice hockey players using telemetry. Ali & Farrally (1991) suggested that due to interference from other players' transmitters, it is only possible to monitor one player per match, whereas Rhode & Esperson (1988) monitored more than one player per match.

2.2.2 The use of heart rate to estimate energy expenditure

In terms of calculating the energy expenditure during team games the direct collection and analysis of expired air would give the most accurate values of oxygen uptake. This can be done using Douglas Bags, a respirometer or the Cosmed K2 portable analyser. However, these methods would be impractical during the "real" game situation as the collecting equipment for expired air is heavy and restricts players' movements. Douglas Bags would require changing every 2-3 minutes depending on the subjects' ventilatory rate. The direct collection of expired air by using a respirometer may not in fact give a true value for oxygen uptake during the activity as the collecting equipment tends to affect heart rate, oxygen uptake and may well hamper the subject's movements. The respirometer has an approximate weight of 3.6 kg and so will increase the subjects' energy expenditure at a given work rate. Another problem with the use of respirometers during intensive physical activity where the flow rate is greater than 50 litres.min^{-1} of expired air is that at higher ventilation rates the resistance to flow begins to impose a "significant resistance to the subjects' breathing" (Durnin & Passmore, 1967 (p. 22); McArdle et al., 1986).

The Cosmed K2 portable oxygen analyser is a recent telemetric system which measures oxygen uptake and VE every 15 seconds; this system allows the subject a good range of movement and could be used under simulated match conditions. The Cosmed K2 consists of three units ; a face mask with turbine attachment, an oxygen analyser and transmitter, and a battery pack.

Expired volume is measured by an optoelectronic sensor which counts the number of revolutions of the turbine blade. The percentage oxygen in expired air is measured in a 2 ml mixing chamber by a polarographic electrode. Expired air is drawn through the mixing chamber at the same rate as the flow rate through the turbine, from just in front of the turbine. The manufacturer's claims that this system prevents the problems caused by the time lag in expired volume measurements and the analysis of the corresponding gases (Dal Monte et al., 1989).

Oxygen uptake is calculated from the percentage oxygen in the expired air and expired volume. As there is no measurement of percentage carbon dioxide in the expired air, it is assumed that expired volume equals inspired volume and that the respiratory exchange ratio equals 1. This method of calculation will cause underestimation of oxygen uptake at low workloads and an over-estimation at high workloads (close to maximal). However these differences are not statistically significant (Dal Monte et al., 1989)

The Cosmed K2 portable oxygen analyser system has been validated against the Jaeger on-line system (Dal Monte et al., 1989) for cycling using seven steady state workloads up to a maximum. There would appear to be no validation of this equipment at either non-steady state workloads or for running which is the form of locomotion in team sports. This system although less cumbersome than either the Douglas Bags or the respirometer would not allow for measurements to be made during match play, it would, however, give a better indication of the nature of the oxygen uptake response during non-steady state activity as the values are reported every 15 seconds.

Heart rate is also reported every 15 seconds using a signal from a Sport Tester PE3000 short range telemetry system which is picked up and transmitted from the Cosmed K2 transmitting unit. This heart rate is the mean of the heart rate during the 15 second collection period.

As a result another parameter must be employed which can be used to estimate oxygen uptake and which can be easily monitored during a competitive situation without inconveniencing the player. Malhotra et al. (1963) and Seliger (1968) have suggested that heart rate during physical activity can be used to estimate oxygen uptake. Astrand & Rodahl (1986) stated that heart rate may give as "good" an estimation of energy expenditure as the direct collection of expired air in the field situation.

A number of authors have used heart rate to determine oxygen uptake during team games (Ali & Farrally, 1990; McArdle et al., 1971; Skubic & Hodgkins, 1967; Van Gool et al., 1988). The use of heart rate to predict energy expenditure is based on the linear relationship which exists between heart rate and oxygen uptake during steady state activity. The equation of this line is dependent on a number factors including "posture and type of work, intensity of work, emotion, food, temperature, time of day, fatigue, previous work and physical fitness"(Acheson et al., 1980 p. 1161). This relationship must first be established in the laboratory to determine an individual's heart rate response and oxygen uptake at given steady state workloads(Mass et al., 1989). An analysis of the respiratory gases at each progressive workload determines the oxygen uptake and the respiratory exchange ratio, consequently the energy cost at each workload can be calculated. This then permits heart rate recorded during the game to be related to energy expenditure.

The mode of exercise used to establish the heart rate - oxygen uptake regression equation should relate directly to the type of exercise in the field situation i.e. the same major muscle groups should be used (MacDougal et al., 1982). Other studies have suggested that a simulation of the activity to which the heart rate - oxygen uptake regression equation is to be applied should be used to establish the equation. (Mass et al., 1989). In field games which by their very nature include a lot of running, a maximal progressive test would be carried out on the treadmill or through the collection of expired air during simulated match activity. The major problem with the use of simulated activity is establishing a steady state situation so the heart rate - oxygen uptake relationship can be determined at different workloads. The protocol used should include a maximal workload (Van Gool et al., 1983) or elicit heart rates similar to those observed in the field situation (MacDougal et al., 1982).

These studies have all assumed that the relationship between heart rate and oxygen uptake obtained at steady state workloads on the treadmill is the same during match conditions, i.e. the heart rate obtained during the game for non-steady state activities represents the same oxygen uptake as that for steady state heart rates on the treadmill. One of the problems is that the majority of activity used to establish the regression equation was aerobic in nature (except for the final workloads where the subjects would be working maximally aerobically and also providing some energy from anaerobic glycolysis), whereas during multiple sprint sports the nature of activity is short periods of maximal activity interspersed with longer periods of low intensity activity, suggesting that the immediate source of energy will be provided anaerobically through the creatine phosphate system and glycolysis. So not only is the heart rate - oxygen uptake relationship established during steady state activity applied to a fluctuating heart rate the energy systems in operation are also changing.

In studies where the energy expenditure has been calculated from the estimated oxygen uptake a constant calorific value has been assumed for each litre of oxygen used. For example, Ali & Farrally (1990) assumed an energy expenditure of 4.83 $kcal.l^{-1}$ for each litre of oxygen and Ballor et al. (1989) an energy expenditure of 5 $kcal.l^{-1}$. The heart rates observed in "multiple-sprint" sports and described in terms of percentage of maximum heart rate show that players have been found to work at a mean percentage of maximum heart rate between 72 and 91% (see section 2.3.1). These intensities would suggest that carbohydrate is the main fuel source and consequently, the energy expenditure per litre of oxygen is likely to be closer to 5 kcal rather than 4.83 kcal.

There has however been little research which validates this method of predicting energy costs in non-steady state competitive situations (McArdle et al., 1986) i.e. it has been assumed that heart rate is a valid indication of energy expenditure in the game situation. The majority of studies have assumed that heart rate will over-estimate energy expenditure as a result of psychological factors (see section 2.2.4) elevating the heart rate response, however although most studies have acknowledged the problem with using a steady state regression equation to predict energy expenditure during non-steady state activity it is unclear whether this is likely to over or under predict the true energy expenditure.

2.2.3 The validation of heart rate analysis to estimate energy expenditure

A number of studies have observed the differences in the use of heart rate to measure energy expenditure during daily activity when compared to other methods of measuring daily energy expenditure, whole-body indirect calorimetry (Ceesay et al., 1989; Dauncey & James, 1979; Spurr et al., 1988) and the doubly labelled water ($^{2}H_2\ ^{18}O$) technique (Livingstone et al., 1992). The results of these studies show that there is a wide variation in the errors caused by the use of heart rate to estimate daily energy expenditure.

The heart rate estimation method used by Ceesay et al. (1989) and validated against whole-body indirect calorimetry, involved the establishing of a FLEX heart rate value above which there was a strong relationship between heart rate and oxygen uptake and below which this relationship was not as good. The FLEX heart rate can be defined as the heart rate which discriminates between resting and exercising heart rates and is individually determined. The FLEX heart rate was determined as the mean of the highest heart rate recorded when standing and the lowest heart rate while stepping (20 steps per min / 225 mm step), and a regression equation was established for activities above the FLEX point; for heart rates below the FLEX value the same mean energy expenditure was allocated for each value. The mean FLEX heart rates were 86 ±10 beats.min^{-1} (male, n=11) and 96 ±6 beats.min^{-1} (females, n=9). During 21.5 hours in an indirect calorimeter the heart rate method underestimated total energy expenditure by a mean 1.2 ±6.2%, but the range of values (-11.4 to 10.6%) shows that there are large individual differences associated with the use of heart rate.

Within this study were four periods of 30 minute steady state exercise sessions (cycling, rowing, stepping, jogging). Individual errors in the use of heart rate to estimate the energy expenditure during these periods ranged from -39.5% to 18.6%, the mean error was -11.6 ±16.5%. The authors suggested that the underestimations were caused by the failure of the exercising heart rates in some subjects to exceed the FLEX value suggesting that the exercise intensity was too low or the FLEX value was too high. It might also have been that the choice of FLEX value was too low, giving an error in the calculation of the linear relationship.

Observation of the heart rate trace in relation to activity for two of the subjects suggests that during two of the periods of exercise there was either a problem with the short range telemetry system (Sport Tester PE 3000, heart rate monitor) in that an increase in heart rate was not observed or that the intensity of the activity did not raise the subjects' heart rate above their FLEX values. As the rate of energy expenditure doubled, this would suggest that the level of activity was enough to increase the heart rate, hence some of the errors in this study may have been caused by malfunction of the heart rate monitor.

These results are similar to those found by Spurr et al. (1988) using a similar methodology for the estimation of total daily energy expenditure, the errors in this study ranged from -15 to 20%. During the exercise periods there was a mean overestimation by heart rate of 30% of the total energy expenditure as measured by calorimetry which is contrast to the findings of Ceesay et al. (1989) who observed an underestimation of energy expenditure by heart rate during exercise. This may be partly explained by the fact that in the study of Spurr et al.

(1988) the heart rate reflected the activity which was not always the case in the study of Ceesay et al. (1989).

Dauncey & James (1979) found that the differences between actual energy expenditure determined by indirect calorimetry and the predicted values from heart rate could be reduced from means of -14% for light activity and -11% for moderate activity (the standard deviations are only reported as being "large") to 3 ±10.5% and 3 ±6.7% respectively. This was done by establishing the heart rate - energy expenditure regression equation through values obtained from indirect measurement in the calorimeter rather than the more traditional methods of establishing energy expenditure by measuring oxygen uptake at different steady state workloads.

In this study single regression equation were established using either lying and cycling, sitting and cycling or lying, sitting and standing. There was no establishment of either FLEX values (Ceesay et al., 1989; Livingstone et al., 1992; Spurr et al., 1988) or the two regression equations (Malhotra et al., 1963); this may have increased the errors due to the change in the oxygen uptake - heart rate relationship when maximum stroke volume is reached (around 120 beats.min^{-1}).

Livingstone et al. (1992) found differences ranging between -16.7% and 18.8% (n = 36) between the heart rate method and the doubly labelled water technique for calculating the daily energy expenditure. In this study the FLEX heart rate was defined as the mean of the highest heart rate during resting activities and the lowest heart rate during the low intensity walking. When the heart rate fell below the FLEX value the energy expenditure was assumed to be a constant (resting metabolic rate). James et al. (1988) in a review of the accuracy of the doubly labelled water technique reported differences in the region of ±5% under steady state conditions when compared to chamber calorimetry, and suggested that these discrepancies may be greater under free living conditions. This would suggest that the doubly labelled water technique for estimating energy expenditure is not accurate enough to be used to determine the errors in the use of heart rate to estimate energy expenditure.

Astrand & Rodahl (1986) stated that maximum stroke volume is reached between 110-120 beats.min^{-1}, it is only above maximum stroke volume that the additional oxygen uptake requirements are met by increasing heart rate and not a combination of increases in stroke volume and heart rate, consequently the heart rate oxygen uptake relationship is only linear after maximum stroke volume has been obtained. As a result the heart rate should exceed 120 beats.min^{-1} on the first workload when establishing the heart rate oxygen uptake regression equation. In the following study by Malhotra et al. (1963), two regression equations were established, the heart rates used for the determination of each regression equation were above or below 95 beats.min^{-1}; a significant difference was found between the two equations. There is no explanation as to why 95 beats.min^{-1} was selected as the point for establishing the two regression equations but this may be a source of error.

Malhotra et al. (1963) conducted a study which was to estimate the error in predicting energy costs from heart rate during various activities. The method used was firstly to establish the heart rate - oxygen uptake regression line for each individual (n =7) in the laboratory on a cycle ergometer (loads from 50 - 600 kg.m^{-1}min^{-1}), the expired air was collected using a Kofranyi Michaelis respirometer which was also used during the field tests. Heart rate was then recorded and expired air collected during a number of activities (marching, running, walking, hopping, hammering). The actual oxygen uptake from the collected gases in the respirometer was then compared to the predicted oxygen uptake from heart rate using the regression equation established on the ergometer. The average error for each subject ranged between 0.6-7% for the various tests. The problem with using this study as a means of verifying the use of heart rate as an indication of energy expenditure in team games is that the activities in this study were steady state in nature i.e. the collection of expired air was at a constant heart rate. Secondly, the highest heart rate in this study was 150 beats.min^{-1} and thus it cannot be assumed that heart rate is still a valid indication of oxygen uptake at higher workloads.

Sharkey et al. (1966) estimated the errors in the use of a heart rate - oxygen uptake regression equation which was established with subjects (n=4) walking on the treadmill at six different gradients. The energy expenditure was measured by the direct collection of expired air for four different steady state activities (walking, walking while carrying a 23lb weight, cycling a cycle ergometer and hand-cranking a cycle ergometer) and estimated from the heart rate response. In all cases the heart rate - oxygen uptake regression equation over-predicted energy expenditure, the mean percentage error for walking was 7.9%, with the weight was 21.9%, cycling 15.8% and cranking 29.8%. This study showed least error when the regression equation was applied to a similar activity from which it was obtained. This is in agreement with MacDougal et al. (1982) who stated that the mode of activity used to establish the regression equation should directly relate to the activity for which the energy expenditure is being estimated.

Mass et al. (1989) observed the error caused in using the heart rate - oxygen uptake regression equation established during steady state running and applying it to heart rates obtained during walking with different weights (dynamic/static exercise). For 8 subjects there was no significant difference between the actual and estimated energy expenditure for walking with 4, 6 and 8 kg weights, the percentage differences being -2, 8 and 19% respectively. However the energy expenditure was significantly overestimated while walking with 12 kg weights (38%). This study concluded that a dynamic activity can be used to estimate the energy expenditure in a similar activity which involves a small static component, the greater the static component the greater the error. The workloads used to establish the regression equation included standing which did not raise the heart rate response above 90 beats.min^{-1}. This is in contrast with Malhotra (1963) who established the need for two separate regression equations and other studies which have established FLEX values(Ceesay et al., 1989; Livingstone et al., 1992; Spurr et al., 1988) as the heart rate above which the regression equation is established.

Seliger (1968) attempted to validate heart rate as an index of physical load in a large range of sports from weightlifting to basketball. He found that in sports that were greater than 5 minutes in duration, heart rate was a valid indication of workload, even if the sport was of "variable intensity of movement" i.e. non-steady state activities. Seliger first established the true energy cost from the collection of expired air during simulated or actual sports if collection of expired air was possible and then correlated this with the circulation load calculated from the cumulative frequencies of heart rate during the sport. This method does not establish an individual's oxygen uptake at specific heart rates and also assumed a maximum heart rate of 200 beats.min^{-1} for all subjects, so consequently does not account for differences in fitness or maximum heart rates between individuals. The physical load was determined from the heart rates and the energy costs from indirect calorimetry by the collection of expired air, both have been used as an indication of physical stress. The work of Seliger (1968) only suggests that heart rate can be used as an indication of the physical intensity of an activity rather than as a means of estimating energy expenditure and as the individual's heart rate response is determined by his/her aerobic fitness, the physical intensity as measured by heart rate can only be applied to that individual rather than to the sport as a whole.

This study does show that it is possible to collect expired air during team games by simulating the activity to the extent that the collecting equipment will allow. However Seliger (1968) does not give exact details of the methodology used to allow for the continual collection and subsequent analysis of expired air in the activities he analysed which included basketball and football, but it was under model game situations.

Ballor et al. (1989) observed the errors in using a Caltrac, heart rate analysis and video analysis to estimate energy expenditure during simulated basketball match play when compared to the measured value from oxygen uptake. The Caltrac is a lightweight microcomputer (14 × 8 ×4 cm, 400 grams) which calculates energy expenditure from vertical acceleration measurements. The subject's age, height, weight and sex are entered into the Caltrac to estimate resting metabolic rate, this is then added to the energy expenditure estimated from vertical accelerations. A voltage is produced by a piezoceramic beam in response to vertical accelerations / decelerations. This voltage is then converted to an energy cost (Ballor, 1989).

It was found that the Caltrac system underestimated by 5.9%, the heart rate analysis overestimated by 16.3% and the video analysis underestimated by 26.7% the measured energy expenditure. Expired air was analysed continually throughout the simulated match play using an on-line system, averages being reported every minute, with volume being measured on the inspired side. The connecting tubing between the gas meter, the subject's breathing valve and the gas analysers, was long enough to allow the subject both to run on the treadmill and to perform basketball related activities alongside the treadmill.

The problem with using an on-line system to measure non-steady state activity is the time delay in measuring gas volume and the corresponding expired air entering the mixing chamber and then being passed over the analysers (Powers et al., 1987). A second problem with the study of Ballor et al. (1989) was that the mean heart rates recorded during the simulated basketball match play was 118 ±27 beats.min^{-1}, it is likely at this intensity other factors may have influenced the heart rate - oxygen uptake relationship and that the intensity of the activities used was not a good simulation of basketball match play. The heart rate - oxygen uptake regression was established using a cycle ergometer and the oxygen uptake estimated from the workload, which is likely to lead to greater errors than if treadmill activity had been used. The energy cost of each basketball-related activity was estimated from the literature for the video analysis.

Ogushi et al. (1993) found that the estimation of oxygen uptake from the heart rate - oxygen uptake regression equation overestimated the actual oxygen uptake by around 12 ml.kg^{-1}.min^{-1}. during soccer match play. In this study expired air was collected into a Douglas bag midway through the first and second half; the collection time was between 141-168 seconds, for two subjects. The heart rate was recorded during the collection period and used to estimate the oxygen uptake from the heart rate - oxygen uptake regression equation established in the laboratory (method not described) and compared with the measured value from the expired air. These results showed that the estimation from heart rate overestimated the percentage of $\dot{V}O_2$ max. that players were working at, by 30%. It is doubtful whether the collection of a 2-3 minute sample of air midway through the half can be related to heart rates which will have been affected by the level of activity prior to the gas collection. In order for this method to be valid gas collection would have to take place continually for the whole period of activity. Green et al. (1976) suggested that in order to obtain the true value of the energy expenditure during non-steady activity, expired air should be collected during the recovery period, also.

Most studies which have used heart rate to estimate energy expenditure during competitive sport have assumed that the use of heart rate over-estimates energy expenditure due to psychological factors. Several of the studies reviewed observed that heart rate overestimated energy expenditure in non-competitive situations (Ballor et al., 1989; Malhotra et al., 1962; Mass et al., 1989; Sharkey et al., 1966; Spurr et al., 1988) suggesting that the use of heart rate may overestimate energy expenditure in competitive situations to a greater extent than previously thought when combined with psychological factors.

This review of the studies observing the validation of heart rate as a method of estimating energy expenditure has shown that although heart rate has been used widely in a number of sports to estimate the energy expenditure of players, there is little validation of this method in relation to high intensity non-steady state activity. With the exception of the work of Ogushi et al. (1993), all other studies had heart rates of less than 150 beats.min^{-1} which is much lower than the values reported in team sports (see Table 2.1). Any validation study of the use of heart rate during match play must take into consideration the following :-

i) The regression equation for heart rate and oxygen uptake must be established using an activity similar to the sport i.e. for women's hockey treadmill running rather than cycle ergometry.

ii) Two regression equations should be established, one for workloads that elicit heart rates below 120 beats.min^{-1} and the other for heart rates above 120 beats.min^{-1}.

iii) The simulation must elicit heart rates within the ranges of those found during match play.

iv) All expired air during the activity period should be collected.

v) A Douglas bag system is the best method of measuring actual oxygen uptake unless a variable time-delay option is available on the on-line-system.

vi) The intensity of activity, i.e. the work : rest ratio of the simulation, should be similar to actual match play.

In this review of studies which have observed the errors in the use of heart rate to estimate energy expenditure, there was no single study which fulfilled the above criteria for the validation of heart rate as a means of estimating energy expenditure in the "multiple-sprint" sports. Consequently it remains unclear whether heart rate gives a good estimation of energy expenditure or whether it under or over predicts the actual value.

2.2.4 Problems with the use of heart rate

The problem of using heart rate as an indication of physical workload is that

> "Factors other than oxygen consumption can influence the heart rate. These include temperature, emotions, food intake, body position, the muscle groups exercised and whether the exercise is continuous or stop and go, or whether the muscles are contracting isometrically or in a more rhythmic manner."
>
> (McArdle, et al., 1986, p. 144)

Variations in heart rate can occur even under standard laboratory conditions, and can be as much as ± 5 beats.min^{-1} at the same submaximal workloads (heart rate less than 160 beats.min^{-1}) from day to day (Astrand & Rodahl, 1986; McArdle et al., 1986). At higher heart rates approaching maximum the variation in heart rate is in the region of ±3 beats.min^{-1} even under non-standardised conditions e.g. changing temperatures (Astrand & Rodahl, 1986).

The effect that emotional stress can have on a player's heart rate during the competitive situation is acknowledged by a number of authors (Hahn et al., 1974; McArdle et al., 1971; Rhode & Esperson, 1988) and as a result of these emotional factors the use of heart rate to estimate oxygen uptake will tend to over-estimate the energy cost of the game (McArdle et al., 1971; Van Gool et al., 1988). Rhode & Esperson (1988) suggested that part of the heart rate response during team games will be caused by emotional stress but that it is likely that at the high physical workloads the psychological effects will be neutralised to some degree by the physiological responses. To what extent this occurs is unclear. Astrand & Rodahl (1986) suggested that at work intensities which elicit heart rates greater than 150 beats.min^{-1} there will be a reduced effect on heart rates from psychological factors. Studies of team sports show mean heart rates exceed these values in soccer. Van Gool et al. (1983) observed mean hearts in players from 156 ±16 to 172 ±12 beats.min^{-1} and in women's hockey mean heart rates of 178 beats.min^{-1} (Skubic & Hodgkins, 1967) have been found.

Hahn et al. (1974) supported this notion of emotional factors affecting the heart rate during the game by observing higher than expected heart rates during an extended period of low activity (some minutes) for two Australian Rules players. However there is no indication given as to the type of activity in which these players had previously been engaged in or their fitness levels so part of this higher than expected heart rate may have been due to slow recovery. Environmental factors would not appear to be the cause as conditions were "cool & dry".

By relating the heart rates during the game to a movement analysis, a better indication of a player's heart rate response to the work done can be obtained. Through game simulation the movements of the game could be replicated but the psychological factors would be reduced and any discrepancies between the "match" heart rate and the simulated game heart rate could be attributed at least in part to emotional factors.

2.2.5 Distance analysis

In terms of distance analysis the studies of Brookes & Knowles (1974) and Reilly & Thomas (1976) on the distances covered by professional soccer players would appear to be the first creditable studies in this area. Both methods involved the estimations of distance covered by players using trained observers. Brooks & Knowles (1974) recorded the movements in coded form with pencil and paper in units of 5 yards.

Although this was an extensive study using twenty observers who each monitored a player during four English First Division matches, there is bound to be some error in the estimations of distance as each movement was recorded to the nearest 5 yards. This study was also limited by the fact that only three movement categories were identified, walking, jogging and running.

Reilly & Thomas (1976) adopted a more detailed methodology where each observer made a recorded commentary of a players movements based on a grid map of the ground (n=40, English First Division). During this commentary

> "Each discrete movement activity in one individual during competitive play was recorded from observation and any change in the level of behaviour constituted a new activity" (p.80)

In all 5 separate movement categories were identified plus any other movements e.g. kicking, heading, jumping. Although both the methods above rely on an observer's estimations of distance, they are easy to employ in the field as no specialised equipment is required.

With video cameras becoming more available this has become the major method of recording data. The advantage of video recordings is that they can be reanalysed by independent sources to validate techniques. Also, different analysing techniques can be applied to the same video increasing the amount of data which can be obtained from the recording of one match.

From the video recording, distances can be determined using the method developed by Withers et al. (1982) based on the assumption that there is

> "For every runner and speed an optimum stride length and frequency. The most economical stride length always lay in the region of the freely chosen one with the well trained subject."
>
> (Hogberg, 1952, in Reilly & Thomas, 1976, p.82)

By assuming that the length of the player's stride remains the same for each activity, total distances can be calculated from the number of strides. The length of a player's stride in each activity was obtained from the player travelling a given distance (18 metres) and counting the number of strides. Total distances covered during the game were calculated by counting the number of strides in each activity and multiplying by stride length.

The advantage of this method for determining distances from a video-recording is that it reduces any error which may be caused by parallax when trying to estimate distance from a video screen. The accuracy of this method was not established by Withers ey al. (1982) and does not allow for any changes in stride length which may be caused by changes of direction, acceleration / deceleration which may be magnified over short distances, or a shorter stride length caused by fatigue later in the game. Consequently this method may well tend to over-predict distances covered in a match.

The errors involved in calculating distance from both a coded commentary method and a stride length method would appear to be similar. Reilly & Thomas (1976) used stride length to validate their study, one player was followed with a video camera while an observer made a coded commentary of the distances he covered. The distances for each activity were then estimated using stride length from the video. The discrepancy between the two methods was found to be less than one percent. This, however does not validate the use of either method as there may be similar errors associated with both methods.

A more reliable method to estimate distance covered which makes no assumptions of stride length or distances has been developed by Ohashi et al. (1988) using two video cameras on tripods which were equipped with potentiometers to relay signals to a computer. The cameras were placed at either end of one touch line and a single player was followed for the whole match. By using the angles from the potentiometers it was possible to obtain X and Y co-ordinates for the player throughout the game, and as a result the exact distances and movement speeds could be determined. Ohashi et al. (1993) used this method to determine the distance covered and time spent in anaerobic / aerobic activity during match play. Anaerobic activity was defined as the speed at which the subject's blood lactate rose above the 4 mM level, this was determined individually on the treadmill

Although the method developed by Ohashi et al. (1988) would appear to be a more accurate method of determining distances than those previously described, the associated problem with this technique is that it requires sophisticated equipment linked to a computer system on the side of the pitch, and it is unlikely that more than one player could be monitored at once. Although only four players in the Japanese soccer league,were monitored by Ohashi et al. (1993) the distances covered (10,341m) are less than those obtained by Withers et al. (1982) in the Australian Phillips league,using stride length (11,527m), (n=20). By applying both methods to the same player during a match the validity of stride length could be determined.

Consequently the method used by Withers et al. (1982) of estimating distance by determining stride length would seem to be the most practical as firstly the recordings can be reanalysed using other techniques to gain additional information and secondly on limited evidence it would appear to be as valid as using other techniques.

A development of Withers and co-workers' (1982) method would be to estimate stride length from the activity during the game. If at some point a player travels a known distance during the game this could be used to determine stride length. This method was used by Reilly & Thomas (1976) on one player and they found that the mean stride length obtained before the game over 15 metres "consistently concorded with results taken from the video tape record during typical movements .... when the distances between two marked points allowed accurate estimation" (p. 83). So provided distances used to estimate stride length are similar to those found in the game then a mean stride length obtained before a game is an accurate estimation of mean stride length during the game. Alternatively the player's stride length could be determined before and after the match and an average of the two could be taken as a "better" indication of stride length during the game which would allow for the effects of fatigue which may shorten stride length.

2.2.6 Time-motion analysis

Time-motion analysis as the name suggests records the length of time spent in discrete movements (Mayhew & Wenger, 1985; McKenna et al., 1988; Otago, 1983). The main reason behind this type of analysis is that the amount of time that is spent in high and low intensity activities can be used to determine work : rest ratios and consequently the contribution that the three energy systems make to the game. McKenna et al. (1988) suggested that a time-motion analysis is preferable to a distance analysis as it is less susceptible to error as time spent in different categories of activity can be measured much more accurately than the methods of estimating distances.

It is also suggested that the total distance covered does not indicate the physical workload on a player and that it is the time spent or distance covered in high intensity activities which directly relates to physical stress (Hahn et al., 1974; Van Gool et al., 1988).

Otago (1983) in a time motion study of Netball split the movements into 8 categories which were specific to the game e.g. guard, shuffle, block. The time spent in each activity was recorded on to paper from a video using a stopwatch. The activities were then split into either the area of work or rest and then grouped to give the work to rest ratios.

Mayhew & Wenger (1985) in a time motion analysis of professional football players defined 5 distinct movement categories - standing, walking, jogging, running (included sprinting) and utility (which was all other movements). McKenna and co-workers' (1988) time motion study on Australian rules football used a similar methodology to Mayhew & Wenger (1985) although McKenna and co-workers (1988) regarded any game related activity such as ball contacts, jumps or tackles as high intensity activities and therefore classified as work.

Bangsbo et al. (1991) classified in greater detail the movement categories in soccer. The main difference between this methodology and those previously reported was that a greater range of running speeds was identified, namely, jogging (8 $km.h^{-1}$), low-speed running (12 $km.h^{-1}$), moderate-speed running (15 $km.h^{-1}$), high-speed running (18 $km.h^{-1}$) and sprinting (30 $km.h^{-1}$). Running speeds of less than 15

$km.h^{-1}$ were considered to be low intensity activity. The running speeds were determined after a match for each player by having him run over a known distance (18 yds).

In terms of using time-motion analysis to determine work : rest ratios, training programmes or the stress on the energy systems, it is unlikely that the categorisation of running into 5 speeds (Bangsbo et al., 1991) is required; jogging, cruising and sprinting would give enough detail. If the total energy expenditure was to be estimated from running speed, the greater the number of categories the better the estimation. However, as a small percentage time is spent at speeds greater than jogging (e.g. 11.3%, Mayhew & Wenger, 1985; 8.1%, Bangsbo et al., 1991) these errors will be small.

McLean (1992) in a time motion analysis of rugby union defined the work : rest ratio as work being the time the ball was in play and rest being the time that the game was stopped. It is unlikely that players were involved in high intensity activity for the total time that the ball was in play which would suggest that this method would not give a good indication of the actual work : rest ratios. It may give an indication of the physiological demands of the game.

From the above studies it can be seen that the method of time-motion analysis can be adopted to suit the movement categories which are typical of the sport being analysed and this is important, as for example, the movement categories used in Netball would not be applicable to Football. The benefit of this type of analysis is that categories of activity can be included that cannot easily be identified with distance e.g. jumps and tackles. It also allows for changes in speed or direction within a movement category. Periods of inactivity i.e. standing still, are accounted for and hence this gives a better indication of rest periods than a distance analysis.

By combining the information obtained from both a distance and a time motion analysis a more accurate definition of what a player does during the game can be obtained, for example, the total work done, the work to rest ratios, type of activities, ball contacts and number of changes of activity.

Although time-motion and distance analyses determine the type of work a player does, more information is required to determine the true physiological cost and the physical stress which a player is under during the game. For example, if two players perform exactly the same work during a game, the less fit player will be under greater stress. Consequently, it is necessary to determine the physiological load on a player as well as the work done in order to get a true indication of the nature of the game.

2.3 Results of physiological research in "multiple-sprint" sports

In section 2.2 the methods available for analysing the physiological demands during team games were reviewed. This following section will concentrate on the results of previous research into the physiological demands of the "multiple-sprint" sports. By gaining an insight into the nature of sports which appear to be similar to hockey, it can be established whether there are in fact common metabolic demands between this group of sports. If this is the case then similar training programmes could be applied to several sports.

2.3.1 Heart rate response during match play

The study of heart rate response under match play has been applied to both individual sports including Handball (Alexander & Boreskie, 1989), Squash (Montpetit et al., 1987), Tennis (Morgans et al., 1987) and team sports, Football (Ali & Farrally, 1990, 1991; Cochrane & Pyke, 1976; Ekblom, 1986; Rhode & Esperson, 1988; Van Gool et al., 1983, 1988), Ice hockey (Green et al., 1976), Indoor Football (McLaren et al., 1988), Women's Basketball (McArdle et al., 1971; Skubic & Hodgkins, 1967), Women's Hockey (Skubic & Hodgkins, 1967) and Women's Indoor Football (Miles et al., 1993). Table 2.1 shows the mean heart rates observed in these studies. In some of these studies heart rates have been used to express the workload in terms of percentage of maximum heart rate allowing for several players to be directly compared.

In terms of heart rate, Cochrane & Pyke(1976) (n= 2) suggested that on average a football player works at 86% of his maximum heart rate; this is supported by Van Gool et al. (1988) (n=7) who has established similar work rates. The only study to record workloads greater than this was McArdle et al. (1971) in women's basketball where the mean work rate was 91% and ranged from between 81-95% of maximum heart rate for each subject. This is comparable to the range of percentage maximum heart rate reported for footballers 82-93% (Van Gool et al., 1988)

Table 2.1 **Heart rate response during "multiple-sprint" sports**

Sport	N	Sex	mean heart rate (beats.min^{-1})	% max. heart rate	Author
Handball	2	M	156 ±10	84	Alexander et al. (1989)
Squash	16	M	147 ±18	72	Montpetit et al. (1987)
Tennis	17	M	154 ±17	82	Morgans et al. (1987)
Ice hockey	8	M	170-174		Green et al. (1976)
Football		M	175		Agnevik (1970)*
	2	M	165	86	Cochrane & Pyke (1976)
	4	M	163 ±9		Van Gool et al. (1983)
		M	157		Reilly (1986)*
	7	M	167 ±7	86	Van Gool et al. (1988)
	27	M	169 ±6		Ali & Farrally (1991)
Indoor Football	3	M	172		McLaren et al. (1988)
	10	F	171 ±11	86	Miles et al. (1992)
Basketball	6	F	159 ±22	76	Skubic & Hodgkins (1967)
	6	F	179 ± 14	91	McArdle et al. (1971)
Hockey	2	F	180	83	Skubic & Hodgkins (1967)

*Values reported in Reilly et al. (1990)

The heart rate measurements can only be used to give an indication of the physiological demands of the sport; for example the 20 beat difference observed in women's basketball in the studies of Skubic & Hodgkins(1967) and McArdle et al. (1971) may have been caused by the game monitored by Skubic & Hodgkins (1967) being played at a lower intensity. Alternatively the players observed by McArdle et al. (1971)

may have had a lower aerobic power than those studied by Skubic & Hodgkins (1967).

McArdle et al. (1971) observed two extremes of heart rate response in women's basketball. One subject demonstrated a high mean heart rate (195 beats.min^{-1}) but with a small standard deviation (±9 beats.min^{-1}) whereas a second subject recorded a mean heart rate of 163 beats.min^{-1} with a standard deviation of 23 beats.min^{-1}, suggesting that the nature of the heart rate response is not the same for all subjects. The other subjects fell between these two extremes.

Cibich (1991) analysed the physiological requirements of men's hockey recording heart rates for four players during Division 1 matches. He found that players spent at least 80% of the match at heart rates greater than 75% of their heart rate maximum. This percentage is likely to be greater for actual match play as the heart rate recorded at half-time and during the warm-up were included in the results. All players also spent at least 20% of the time at heart rates greater than 92% of their maximum heart rate, demonstrating the high peak heart rates found during match play. When compared to heart rates monitored during skills training sessions, player were found to record much lower heart rates with only 41% of the time being spent above 75% of maximum heart rate, suggesting that skills sessions are unlikely to reflect the intensities of match play and that additional fitness training will be required in a player's preparation for the competitive situation.

Presenting heart rates in terms of percentage of maximum heart rate again does not account for differing fitness levels but does give an indication of the physiological strain a player is under. In order to standardise the values so players from different sports can be compared, it is necessary to determine the physiological strain in terms of oxygen uptake or energy expenditure.

2.3.2 The estimation of oxygen uptake from heart rate during match play

Using heart rate to estimate oxygen uptake, Ekblom (1986) suggested that the average oxygen consumption throughout a football match is about 80% of a players maximum $\dot{V}O_2$, regardless of the fitness level of the player or the standard of competition (professional or recreational). Hence it could be suggested that there is a maximum work rate which players can maintain for the length of the game. Van Gool et al. (1988) suggested that this work rate is in the region of 75 % of a player's maximum $\dot{V}O_2$.

Similar work rates to those found in soccer have been reported for ice hockey (Green, et al., 1976) where players were found to maintain work rates of between 70-80% of their maximum $\dot{V}O_2$. The heart rates recorded were higher than the skating speeds observed would suggest, Green et al. (1976) stated that this is caused by the additional energy requirements of changing direction, accelerating/decelerating and ice hockey related activities.

Miles et al. (1993) analysed the physiological demands of women's 4-a-side soccer under practice match conditions (n=10). The mean heart rates were resting 88 ±12 beats.min^{-1}, goalkeeping 147 ±17 beats.min^{-1} mixed outfield 169 ±13 beats.min^{-1} (84.8% of maximum heart rate) and female only outfield 171 ±11 beats.min^{-1} (85.7% of maximum heart rate). Miles et al. (1993) suggested that the heart rates observed while playing in goal were partly caused by the anxiety of playing in that position and so were not purely a physiological response. Each subject played for 1 hour on two single occasions, during each hour the subjects playing alternated every 5 minutes between the following conditions female only outfield, a mixed outfield (2 men/2 women), goalkeeping and resting. During the outfield periods, players were working at 70.7% (mixed) and 73.6% (female only) of their $\dot{V}O_2$ max. It is doubtful whether these short periods of play can be related to matches of longer duration as players may work at a higher intensity if they know it is only for 10 minutes (female/mixed outfield).

Although the afore-mentioned studies have determined the heart rates for a number of subjects, in no study has one player been monitored over several matches to determine whether the work rate is similar for each match or whether it is determined to a greater extent by other variables e.g. weather, result, opposition. What these studies do establish is the high stress placed on the aerobic system during the "multiple-sprint" sports.

Van Gool et al. (1983) (n=6) found a significant difference in heart rate between the first and second halves, although this has not been supported in subsequent studies (Ali & Farrally, 1990; Van Gool et al., 1988). It is not substantiated whether players do in fact have a lower work rate during the second half with the onset of fatigue or due to other factors. This is perhaps better answered through motion analysis as a player's work rate for each half can be examined in detail.

2.3.3 The estimation of energy expenditure from heart rate during match play

Skubic & Hodgkins (1967) used heart rate to estimate energy expenditure in a range of women's sports, two of which were team games. Heart rate was recorded using telemetry for the first two minutes of every game and then for the last 30 seconds of every 2nd minute. The regression equation was established from the collection of expired air while sitting at rest (72 beats.min^{-1}), and on the treadmill at workloads which obtained heart rates in the region of 120, 145 and 185 beats.min^{-1} although there is no mention of how these were obtained, if treadmill speed or incline was increased. An $r^2 \geq 0.89$ was obtained for the regression equations. In sports with fluctuating heart rates it is questionable whether the recording of heart rate for 30 seconds every 2 minutes gives enough data to estimate the energy expenditure accurately. Van Gool et al. (1983) in a study on soccer players observed that the heart rate recorded during a 15 second period was not significantly different to the following 75 second period, and consequently the recording of heart rate for 15 seconds during every 90 second period gave a heart rate representative of the 90 second period. Hence the method used by Skubic & Hodgkins (1967) to record heart rates is likely to be representative of the whole match.

In this study of Skubic & Hodgkins (1967) energy expenditures of 34.2 $kJ.min^{-1}$ to 40.4 $kJ.min^{-1}$ were estimated for women's hockey (n=2) and 23.1 $kJ.min^{-1}$ to 39.3 $kJ.min^{-1}$ for women's basketball (n=2, 6 matches) (based on 5 $kcal.min^{-1}$ per litre of oxygen). The values of energy expenditure estimated in this study seem low despite suggestions by Skubic & Hodgkins (1967) that the $\dot{V}O_2$ max of the subjects was 43.4 and 49.5 $ml.kg^{-1}.min^{-1}$, based on the extrapolation of the regression equation to the maximum heart rates observed in the matches, 228 and 218 $beats.min^{-1}$ respectively. It is more likely that these subjects have $\dot{V}O_2$ max values closer to those observed on the treadmill (35.3 $ml.kg^{-1}.min^{-1}$ / 188 $beats.min^{-1}$ and 38.5 $ml.kg^{-1}.min^{-1}$ / 184 $beats.min^{-1}$) as this would explain the low energy expenditures in relation to the high mean heart rates observed during match play. Alternatively the method of determining the regression equation using sitting, walking and running values may under-predict energy expenditure.

Skubic & Hodgkins (1967) also observed that 10 minutes after the end of the basketball and hockey matches, the subjects' heart rates were still elevated by 45 ±15 $beats.min^{-1}$, showing that there will be some oxygen debt at the cessation of "multiple-sprint" sports.

McArdle et al. (1971) estimated the energy expenditure in women's basketball (n=6). The energy expenditure was estimated as ranging between 29.7 and 49.3 $kJ.min^{-1}$. Each player was monitored using telemetry for at least one quarter of the match. The problem with monitoring basketball during the competitive situation is that players can be substituted at any point which makes the collection of a complete set of data difficult. The heart rate - oxygen uptake regression equation was established on the treadmill using a walking protocol (5.6 $km.h^{-1}$) with an increasing gradient, at least 5 workloads up to a maximum were used, expired air was collected at the initial workload and then every third minute. This was used to establish a single regression equation for each subject. This protocol, however, does not replicate the movement speeds of the game as 5.6 $km.h^{-1}$ represents a walk or slow jog so a better protocol would include running speeds similar to those found during the game. The average oxygen consumption was 30.6 $ml.kg^{-1}.min^{-1}$ for all positions during a basketball match which is comparable to the values estimated by Skubic & Hodgkins (1967) of 28.3 $ml.kg^{-1}.min^{-1}$.

The $\dot{V}O_2$ max of the subjects used by McArdle et al. (1971) was 35.1 ±4.1 $ml.kg^{-1}.min^{-1}$ which is low for women competing in competitive sport, other studies have reported $\dot{V}O_2$ max values ranging from 38.7-57.2 $ml.kg^{-1}.min^{-1}$ for women basketball players at collegiate and international level (McLaren, 1990). As a result of the low aerobic capacity of the subjects in this study, it is likely that the energy expenditure in top level women's basketball is greater than these values.

A more extensive study on the heart rate of soccer players was by Ali & Farrally (1990) where the heart rate response of 27 players (9 semi-professional, 9 university, 9 recreational) was examined and related to position played. Energy expenditure was estimated from the regression line for heart rate against oxygen uptake. This relationship was determined from the Leger test (Leger & Lambert, 1982), which is a multistage progressive shuttle run test. This method was used to predict the relationship between heart rate and oxygen uptake as it was felt by the author that this test related more to the type of movements found on the football pitch e.g. turns and periods of acceleration / deceleration, than any protocol on the treadmill. It also meant that oxygen uptake was established at non-steady state workloads, although there were no recovery periods as found during the game. Ali & Farrally (1990) assumed the respiratory exchange ratio to be 0.83 with a corresponding energy cost of 4.83 kcal per litre of oxygen consumed, which although not an exact value is an acceptable error (4%., McArdle et al., 1986). The study found that at all levels midfield players expended more energy (4384 kJ) than forwards (3986 kJ) or defenders (3983 kJ). These values of energy expenditure are much lower than those estimated by Reilly & Thomas (1979) from heart rates during a simulated game which when related to the heart rate - oxygen uptake regression line (established on the treadmill) and extrapolated to a full game to give a value of 6552 kJ which is approximately a third more than in Ali & Farrally's (1990) study for midfield players. However, the values of Reilly & Thomas (1979) are for full professional players so it might be that at a higher standard, the game requires more energy.

With the exception of the work of Skubic & Hodgkins (1967) these studies cannot be directly related to women's hockey though they do give an indication of the nature of heart rate response and the energy costs of similar "multiple-sprint" sports.

2.3.4 Distance analysis studies

A number of studies have reported the total distances covered by soccer players during match play. Reilly & Thomas (1976) found using a coded commentary that on average players (n=40, English 1st Division) covered 8680 ±1011 m with a range of 7069-10921 m. Using stride length to estimate distance, Withers et al. (1982) observed a greater mean distance of 11,527 ±1796 m for Australian professional soccer players (n=20). Between these two extremes, Ohashi et al. (1988) measured a mean distance of 10,341 m for Japanese soccer players (n=4), Van Gool et al. (1988) observed similar mean distances of 10,255 ±580 m for Belgian University players (n=7) and Bangsbo et al. (1991) a mean distance of 10,800 m (range 9490-12,930 m) for Danish professional and semi-professional players. The methods used by Ohashi et al. (1988) (video cameras linked to potentiometers and computer) and Van Gool et al. (1988) (film digitisation) are valid techniques as the actual distances are measured using x-y co-ordinates. The variation in total distance measured by the above studies could be attributed firstly to errors in the measurement technique. It is likely that stride length will tend to overestimate total distance (see section 2.2.5). Alternatively, as these studies observed different nationalities, there is likely to be differences in playing style which will influence the distances covered.

Although Withers et al. (1982) observed a greater total distance than Reilly & Thomas (1976), the total distance covered in high intensity activity was less, 2172 m and 2784 m respectively. This represented 18.8% of the total distance in the study of Withers et al. (1982) in comparison to 31.7% of the total distance in the study of Reilly & Thomas (1976). In comparison Van Gool et al. (1988) observed that players were involved in high intensity activity for only 7.5% of the total distance or 771 m. The differences in the findings of this study in comparison with the studies of Withers et al. (1982) and Reilly & Thomas (1976) may have been caused by the definition of jogging

(2.04-4.89 m s^{-1}) which represents a top speed of 17.6 $km.h^{-1}$ and is likely to have been considered as high intensity activity in other studies. This is supported by Ohashi et al. (1993) who found that speeds of 12.3-14.0 $km.h^{-1}$ represented the 4 mM lactate level for soccer players (n=3), and Bangsbo et al. (1991) who defined low intensity running speeds as between 8-12 $km.h^{-1}$. Hence it is likely that Van Gool et al. (1988) overestimated the speed of low intensity activity and hence underestimated the distances covered in high intensity activity. The differences in distances covered in high intensity activity between the estimations by Reilly & Thomas (1976) and by Withers and co-workers (1982) show that the measurement of the total distance covered is not necessarily a good indication of the physiological demands on players.

Reilly & Thomas (1976), Withers et al. (1982) and Bangsbo et al. (1991) all observed that midfielders covered a greater distance than other positions. However when high intensity activity was considered, Withers et al. (1982)and Bangsbo et al. (1991) found no significant differences between positions. In comparison Reilly & Thomas (1976) found that midfielders and strikers sprinted significantly ($p<0.05$) greater distances than the backs. Withers et al. (1982) and Bangsbo et al. (1991) suggested that the greater distances covered in low intensity activity by midfielders are as a result of the dual role of the position i.e. players are expected to be involved in both attack and defence.

The distances covered in men's hockey have been estimated by Wein (1981) during a single match in the 1973 men's World Cup as being 5.61 km, and similar to soccer, midfielders were observed to cover the greatest distances (6.36 km) and the maximum distance covered by a player was 8.82 km The accuracy of these estimations cannot be commented on as the methodology used is not stated. Due to the fact that a hockey match lasts 20 minutes less than a soccer match the distances can only be compared in terms of metres per minute. For soccer the range is in the region of 77.8-144.4 $m.min^{-1}$ and for hockey a value between 80.1 $m.min^{-1}$ and 126 $m.min^{-1}$ (Wein, 1981). The limited data available on men's hockey would suggest a mean work rate towards the lower end of the range found in professional soccer.

In soccer, the total distance covered running (jogging, cruising and sprinting) during the second half has been found to be significantly less than the first half (Reilly & Thomas, 1976 ($p<0.05$)), Withers et al. (1982) observed a small drop in the distance covered during the second half but this was not statistically significant. Reilly & Thomas (1976) observed that in 32 of 44 matches analysed , soccer players covered a greater distance running in the first half as compared to the second half. The work of Reilly & Thomas (1976) shows that factors other than fatigue may influence a player's work rate during the second half, the importance of the match and the score in the second half will influence a player's contribution, in a one-sided game both teams are likely to work less hard towards the end of the match as the result has been "decided". Consequently, players need not cover less distance during the second half, obviously their work rate will be related to their pre-game glycogen levels (see section 2.3.7) and the intensity of the first half.

The only research group which has compared distance covered by the same player in different matches is Bangsbo et al. (1991). Each of 14 players was observed in at least 2 matches each. The differences in the total distances covered between matches ranged from 0.6-16.4% with a mean of 8.5%. However there was no significant difference in the time spent in high intensity activity for the player with the greatest difference in high intensity activity. It may be that more than 2 matches per player need to be analysed in order to identify the true range of the physical workload on players over a season.

2.3.5 Time-motion analysis

In soccer, Mayhew & Wenger (1985) analysed 4 matches recording the movements of two players alternately every seven minutes. Three different players were observed over the four matches. The mean percentage of total time spent in high intensity activity was found to be 12% and the mean length of each period of high intensity activity (running / sprinting) was found to be 4.4 seconds, with a work : rest ratio of 1:7.

In Australian Rules football, McKenna et al. (1988) found that 80% of high intensity activities lasted less than 6.0 seconds (the maximum duration of a high intensity activity was 21.7 seconds) with a change of activity on average every 7.3 seconds. This is similar to football in that Mayhew & Wenger (1985) found that the type of activity changed every 6.1 seconds.

Brodowicz et al. (1990) extended the work of Mayhew & Wenger (1985) by comparing the time spent in different activities when compared to position, 17 players (American semi-professional) were videoed for 10 minute periods during match play. It was found that forwards spent more time walking and sprinting than the midfielders and defenders; midfielders were found to spent more time jogging than the other two positions. The mean duration of each sprint was found to be 3.4 seconds (forwards), 1.5 seconds (midfielders) and 0.7 seconds (defenders), with forwards also sprinting most frequently. This study demonstrates the different physiological demands placed on soccer players in different positions. As sprinting was the only high intensity activity defined, then this study suggests that the mean length of each period of high intensity activity is less than previously reported, especially in the case of defenders. For all players less than 1.5% of the time was spent sprinting or in "other" activities (other activities were actions that could not be defined as standing, walking, jogging or sprinting), the mean time spent in high intensity activity for all players was 0.4%

Bangsbo et al. (1991) observed that during soccer matches 8.1% of the total time was spent in high intensity activity and Ohashi et al. (1993) found mean percentage time spent above the 4.4 mM work intensity (established on the treadmill) was 10.4%. Mayhew & Wenger (1985), Bangsbo et al. (1991) and Ohashi et al. (1993) found considerably greater time spent in high intensity activities than did Brodowicz et al. (1990). This may be partly explained in the classification of activities by Brodowicz et al. (1990) as there were only two running categories, jogging and sprinting, so some of the cruising speeds classified as high intensity in other studies may have been classified as jogging. It may also be that 10 minute periods used by Brodowicz et al. (1990) were not a good indication of a player's work rate for a complete match.

McLean (1992) in a time-motion analysis of rugby union defined the work : rest ratio as work being the time the ball was in play and rest being the time that the game was stopped. He found that the mean duration of work periods was 19 seconds and the most frequent work rest ratios were in the range of 1:1 and 1:1.9. It is unlikely that players were involved in high intensity activity for the total time that the ball was in play which would explain the large difference between work : rest ratios in this study and those found in soccer and Australian rules football.

The number of changes of activity during soccer matches has ranged from mean values of 900 plus (Reilly & Thomas, 1976) to 1179 (Bangsbo et al., 1991). Obviously the number of movement categories identified in the movement analysis will to some extent determine the number of changes of activity. Reilly & Thomas (1976) identified 6 separate movement activities plus categories for jumping, shooting and lying on the ground, whereas Bangsbo et al. (1991), identified 9 movement categories and one "other" category for heading and tackling. These different methods of categorising activities explain some of the differences between the two studies.

Ohashi et al. (1993) compared the work intensity observed from both distance analysis and time-motion analysis. The percentage time spent in high intensity activity was 10.4% whereas when calculated as a percentage of the total distance, high intensity activity accounted for 27.8% of the total distance. The ratio of anaerobic : aerobic work was found to be 3:7 in terms of total distance and 1:9 in terms of total time. This shows the necessity to present work : rest ratios in terms of time rather than distance as in a distance analysis the periods of standing are not accounted for and the true nature of the work : rest ratio in terms of recovery time is unclear.

Ekblom (1986) found that players of lower divisions spent less time (both in terms of mean duration and frequency) in high intensity activity than those players in higher divisions, suggesting that the results of movement analysis should only be applied to the level of competition from which it was obtained. This is in contrast to Yamanaka et al. (1988) who found that college and amateur players sprinted more frequently than professional soccer players. From this they suggested that professional players were more tactically aware and played more efficiently. However without knowing the aerobic capacity of the subjects, it is unclear whether the differences in high intensity activity were tactical or related to fitness.

2.3.6 Energy Systems

The short duration of high intensity activities linked with a low work : rest ratio in the studies on soccer would suggest that the predominant anaerobic system in football is the alactic creatine phosphate system with the occasional longer periods of high intensity stressing the lactic acid system (Mayhew & Wenger, 1985; McKenna et al., 1988). The relative contribution of these two energy systems in these types of "multiple-sprint" sports is not known and may vary between sports depending on the game characteristics. Indeed the involvement of anaerobic glycolysis in short duration events is still doubtful. The following section will review studies which have analysed the nature of "multiple-sprint" activity using movement intensities similar to match play under controlled conditions in the laboratory.

2.3.6.1 Simulated "multiple-sprint" activity

Astrand et al. (1960) in Astrand & Rodahl (1986) stated that for short duration high intensity activity lasting less than 10 seconds there will be no accumulation of blood lactate. This was established in a study where the subject exercised (at a rate at which he would be exhausted after 3 minutes) for 10 seconds and then had 20 seconds recovery. It was found that the subject could continue without fatigue for 30 minutes at this rate, blood lactate did not exceed 2 mM. Astrand & Rodahl (1986) concluded that the ATP and creatine phosphate stores decreased during the exercise but were restored aerobically during rest.

A study was conducted by Holmyard et al. (1988) where 10 rugby players performed 2 tests of 10 maximal 6 second sprints on a non-motorised treadmill. The protocol for the first test was that each sprint was followed by 30 seconds recovery; during the second test the recovery was 60 seconds between sprints. The test order was randomised. They found an increase in blood lactate from 2-3 mM after the warm up to 17.83 ±2.06 mM and 17.52 ±2.29 mM for the 30 second and 60 second recovery protocols respectively. The blood lactate levels in this study would suggest that anaerobic glycolysis is a significant energy system in short duration maximal activity.

The contribution of the anaerobic glycolysis system during short maximal activity is further supported by Tumilty et al. (1988) who measured the lactate levels in 16 soccer players after 6 sets of 3 × 20 metre sprints; 20 seconds rest was given between sprints and 60 seconds between sets. The mean time for the sprints ranged from 3.04 seconds for set 1 to 3.26 seconds for set 6; this was significantly slower. Blood lactates were measured during the recovery period for each set and ranged from 5.0 mM after set 1 to 9.7 mM after set 6. These results would suggest that anaerobic glycolysis is present during very short bursts of high intensity activity with limited recovery.

Boobis (1987) showed the contribution of glycogenolysis in a single six second sprint where the blood lactate increased from a resting value of 1.39 mM at rest to 5.01 mM, measured 5 minutes after the sprint. Boobis (1987) suggests that both the creatine phosphate system and glycolysis provide energy simultaneously during maximal effort and that there will also be some contribution from the aerobic system although to what extent is unclear.

The differences in the conclusions of Astrand & Rodahl (1986) and these other studies in relation to the levels of blood lactate may have been caused by the intensity of the exercise, in the study performed by Astrand and co-workers (1960) the exercise was high rather than maximal intensity. It may be in "multiple-sprint" sports, the intensity of activity determines the rate of lactate accumulation.

One of the main physiological requirements in "multiple-sprint" sports is the ability to reproduce short periods of maximal running (Holmyard et al., 1988). In order to address the nature of fatigue in "multiple-sprint" sports, Bangsbo et al. (1993) studied the effects of previous intense exercise and active recovery on the subsequent anaerobic energy production in high intensity exercise, the mode of exercise was single knee extension. Maximum anaerobic performance was compared before and after a period of high intensity intermittent exercise following either a low intensity active recovery and passive recovery protocol. It was concluded that the impaired performance in the post-exercise test was not caused by a lack of ATP and that the activity was stopped before the anaerobic capacity was fully utilised. It was found that performance decreased less following the active recovery protocol. Bangsbo et al. (1993) suggested that soccer players should be encouraged to walk or jog between periods of high intensity activity as this reduces the decline in performance in subsequent bouts of high intensity activity. Active recovery also speeds up lactate removal but this study suggests that this was not the limiting factor in performance.

In the study of Holmyard et al. (1988) , described earlier, the effect of recovery time on performance during multiple treadmill sprinting was observed. With the 30 second recovery there was a reduction in peak power of 13.2% and mean power of 21.4%, whereas with the 60 second recovery there was a reduction in peak power of 3.0% and mean power of 4.2%. In the 60 second recovery protocol there was no reduction in total distance covered (38 m) whereas in the 30 second recovery protocol the mean distance was reduced from 38.2 ±3.4 m to 35.7 ±1.8 m. The highest heart rates were recorded during sprint 5, during both protocols and were 188 ±18 beats.min^{-1} (30 s recovery) and 180 ±14 beats.min^{-1} (60 s recovery). During the recovery heart rate dropped by about 10 beats.min^{-1} from the peak value in the sprint. The heart rates during the 30 second recovery protocol were found to be generally higher than those recorded during the 60 second protocol but these differences were not significant ($p>0.05$). This study shows that the major effect of fatigue was a drop in power output which was greater than the decrease in distance covered, while a reduction of 3 m in 40 m might significantly affect a player's contribution to the game, in "multiple-sprint" sports where power is also a requirement it is likely that performance will be further impaired.

Holmyard et al. (1988) suggested that the differences in power output between the 30 second and 60 second recovery protocols are due firstly to the fact that during the 60 second recovery period there will be greater resynthesis of creatine phosphate and secondly there will be a greater diffusion of H^+ ions (which are thought to inhibit the activity of phosphofructokinase and the contractile properties of the muscle) out of the muscle cell into the blood. This would allow for greater energy production from both the alactic creatine phosphate system and from anaerobic glycolysis.

In order to determine the relationship between fitness parameters and performance, Tumilty (1993) conducted a study on 16 junior soccer players during a simulated soccer match. The ratio between high intensity and low intensity during the simulation was 1 : 4.87. The mean heart rate for four five-minute periods of simulation was 173 beats.min^{-1} which was 87% of maximum heart rate. The 1st and 4th segments were identical and were of a higher intensity than the 2nd and 3rd segments. The mean heart rate for the first segment was 170 ±7 beats.min^{-1} whereas for the fourth segment the mean heart rate was 181 ±6 beats.min^{-1}, showing that despite engaging in exactly the same activity there was a significant difference ($p<0.05$) in the heart rate response, although the lactate levels at the end of the first segment were higher (6.7 ±1.7 mM) than at the end of the fourth segment (5.9 ±1.2 mM). Tumilty suggested that the low heart rate response and higher lactates during the first segment are a result of the stress placed on the anaerobic system before the aerobic system becomes fully activated.

The decrement in sprinting performance during the simulation was compared to performance in maximal anaerobic tests and maximal aerobic power. It was found that the better the performance in the anaerobic power tests the greater the decline in sprinting performance whereas there was a negative correlation between maximum oxygen uptake and decrement in sprinting performance. It was concluded that the fastest players had no advantage in "multiple-sprint" sports unless they had the aerobic capacity to be able to maintain this speed over a large number of repetitions. This is in agreement with studies during match play where it was found that VO_2 max was related to total distance covered (Reilly & Thomas, 1976) and the number of sprints during a match (Smoras, 1980 in Reilly et al. 1990)

The above studies suggest that a demand will be placed on both the anaerobic (creatine phosphate and glycolysis) and the aerobic energy systems during "multiple-sprint" activity and that these systems work interdependently. Hence it is important that players involved in "multiple-sprint" sports train to develop all aspects of energy metabolism.

2.3.6.2 Lactate levels in "multiple-sprint" sports

In order to obtain further information on the contribution of anaerobic glycolysis energy system in multiple-sprint sports, several studies have measured blood lactate levels during match play. A range of blood lactate levels has been reported during soccer match play at half-time and full time from 2.4 mM (Tumilty et al., 1988), 4.4 mM (Bangsbo et al., 1991), 4-9.5 mM (Ekblom, 1986). Ekblom has reported peak values of 12 mM. In Rugby Union, McLean (1992) found a range of lactates from 5.8-9.8 mM for six players with samples taken during the game. In women's indoor soccer Miles et al. (1993) reported values of 4.1 ±1.4 mM.

The problems of measuring blood lactate levels during match play are firstly, that they are only representative of the activity prior to the sample being taken (in most studies the blood sample has been taken at half-time and at the end of the match) and secondly, there will be some resynthesis of lactate during recovery periods. Bangsbo et al. (1991) suggested that any measurement of blood lactates during match play underestimates actual levels and so perhaps are not a true reflection of levels during the game, as the removal of lactic acid is aided by continuous movement at a lower work load, so the lactate level at the end of the game may well reflect the last period of anaerobic effort (Cochrane & Pyke, 1976) and will not reflect peak values (Ekblom, 1986).

To obtain a more complete picture of lactate levels during soccer match play Smith et al. (1993) obtained approximately 12 blood samples from each of subject (n=6) during a competitive match. The samples were taken at any point during the match where there was a break in play. The lactate values recorded ranged from 1.84 mM to 11.63 mM, with a mean of 5.23 mM; all subjects showed a fluctuating lactate response throughout the game, which at times changed rapidly. This shows that single measurements of lactate cannot be used to predict lactate levels throughout the match.

2.3.7 Glycogen levels in "multiple-sprint" sports

The measurement of energy expenditure during match play gives an insight into the demands placed on the pre-game glycogen stores. Reilly & Borrie (1992) suggested that the activity demands of hockey would not lead to depleted glycogen stores by the end of a match with the exception of tournaments where there are frequent matches. This is in contrast to football where several studies have reported glycogen depletion to be a contributing factor to performance during the second half .

In order to determine the effects of low glycogen levels in soccer, Saltin (1973) observed the distance covered and the intensity of movement during a match for nine players, each player being filmed individually. Four of the players were asked to take part in a hard exercise session the day before the match and then had their diet restricted. Muscle glycogen levels were measured in all subjects prior to the match. The "exercisers" had half the muscle glycogen of the control group (45 and 96 mmoles $\times$ kg^{-1} respectively), and by half-time they had almost no glycogen left (6 and 32 mmoles $\times$ kg^{-1} respectively). Both groups covered less distance in the second half, but the "exercisers" covered 25% less distance than the control group. The "exercisers" covered 50% of the distance walking whereas walking only accounted for 27% of the total distance for the control group. An analysis of the distance covered sprinting showed that the control group covered 2880 m and the "exercisers" group covered 1455 m almost half the distance. The results of this study have implications for tournament situations where teams might be expected to play on consecutive days sometimes playing teams who have had a rest day.

Kirkendall et al. (1988) studied the effect of drinking a glucose polymer drink (62.5 g of carbohydrate in 400 ml of water) just before the start of the match and at half-time. Ten subjects played two soccer matches and prior to each were given a placebo or the glucose polymer drink. Two video recorders taped three five minute segments for each half (82.7% of the pitch was covered) and the distance covered for each player (walking, jogging, cruising and sprinting) was extrapolated to 90 minutes. Kirkendall et al. (1988) found that there was no significant difference in the distance ratios for low intensity activity; there was, however, a significant difference (40%) in the distance ratio for high intensity activity during the second half between the two trials. This study suggests that the ingestion of a glucose polymer drink at the start of the match and at half-time will result in significantly greater distances being covered during the second half in high intensity activity than if no carbohydrate had been ingested. Whether the taping of six, five minute segments and extrapolating to 90 minutes will give an accurate distance for all subjects is debatable. The measuring of pre-match muscle glycogen levels would have established whether the subjects had similar initial glycogen levels during the two trials.

Nevill et al. (1993) observed the effect of a high carbohydrate diet on intermittent sprint exercise. In the first test the subjects (n=18) completed the following protocol; jog for 60 seconds, sprint for 6 seconds and walk for 54 seconds. This was repeated 30 times on a non-motorised treadmill. The subjects then followed a high (79±3%), normal (47±8%) and low (12±1%) carbohydrate diet for the 24 hours following the sprint test and then repeated the intermittent sprint test. In test one the mean power dropped from 653 ±131 watts (sprints 1-3) to 600 ±158 Watts (sprints 28-30), a decline in performance of 8.8%. In the second test the metabolic response and performance were down for all three groups, the group following the high carbohydrate (CHO) diet had a lower mean power output of 0.2%, the normal diet 0.5 % and the low CHO diet 5.0%. The blood lactate levels were lower for all three groups between tests 1 and 2 (4.5, 13.8 and 29.0% respectively) as were glucose levels (14.9, 11.3 and 35.8%). Nevill et al. (1993) suggested that a low carbohydrate diet does reduce performance during multiple-sprint activity but that the availability of creatine phosphate is the greater factor in limiting performance.

These studies have implications not only for the dietary requirements of "multiple-sprint" athletes but also for studies which are observing the work rates of players, as pre-match glycogen levels will affect the distances and intensity of work.

2.4 Research related to hockey

2.4.1 Physiological profiles

The major area of research in women's hockey has been in the assessment of the physiological profiles of players, some of which have evaluated the effect that a training programme has had on the various components of physical fitness. It can be assumed that there will be a relationship between the physiological demands of the game and the physical attributes demonstrated by the players, and that the higher the level of participation the more distinct this will become as the requirements for the game are developed partly through training and partly through natural selection. Consequently by reviewing the literature concerning the fitness profiles of women hockey players, some insight can be obtained into the physical nature of the game.

Bale & McNaught-Davis (1982) carried out an investigation into the physiques, strength and aerobic power of women hockey players aged 18-22 (n=32). The results of this battery of tests was then related to the position each subject played. It was concluded that "those players most involved in goal attack were lighter, less fat and fitter than those players concerned with goal defence." (p. 37)

These findings are in agreement with Cooke (1985). However Bale & McNaught-Davis (1982) suggested that due to the recent changes in the rules, styles of play and surfaces, future studies will find that there will be a narrowing of the physiological differences between positions. This is supported by Burke (1982) who suggested that positional variations in fitness components will become indistinguishable as players are now expected to be involved in both defence and attack.

The belief that interpositional variation in fitness no longer exists is supported by Reilly & Bretherton (1986), who carried out a "Multivariate Analysis of Fitness" on 2 groups of English players, an elite group who attended a "Centre of Excellence", and a group of county players. The authors were unable to find any fitness component which was related to position played. This confirms previous predictions that in terms of the level of "fitness" required, position is not a contributing factor. Reilly & Bretherton (1986) suggested that rather the physiological profiles are related to the standard at which the players are competing. The elite players were found to have a mean $\dot{V}O_2$ max of 45.7 $ml.kg^{-1}.min^{-1}$ whereas for the county players this was 40.6 $ml.kg^{-1}.min^{-1}$. These data suggest that the higher the level of competition, the more emphasis that is placed on the aerobic system.

Other studies have concerned themselves with the changes in the physical attributes of women hockey players after a specific training programme. Rate & Pyke (1978) studied the West Australian women's squad during a training programme which was designed to improve their aerobic and anaerobic fitness using interval running and skills drills. Before training the mean $\dot{V}O_2$ max was 46.7 $ml.kg^{-1}.min^{-1}$; however after 6 weeks training this had improved to 50.6 $ml.kg^{-1}.min^{-1}$ with a range of 42.2-50.6 $ml.kg^{-1}.min^{-1}$ for a forward and goalkeeper respectively.

The Canadian women's hockey team's preparations for the 1984 Olympics were assessed by Ready & van der Merwe (1986/87). The players $\dot{V}O_2$ max was measured on the treadmill and a mean value of 59.3 $ml.kg^{-1}.min^{-1}$ (including 2 goalkeepers)was reached, which indicates the emphasis placed on the aerobic energy system at international level. During the 18 months there was no change in the mean anaerobic power (954 watts), using a modified Margaria-Kalamen step test which suggests that either the players had reached the required level of anaerobic fitness for performance or that not enough emphasis had been placed on the development of this energy system during training or that the test failed to detect any changes.

One study which has analysed the physiological responses of women hockey players using movement analysis (five backs and seven halves of good club standard) found that the halves spent significantly ($p<0.01$) more time jogging whereas the backs spent more time standing, walking and sprinting (Cooke, 1985). A significant correlation was found between scores on a $\dot{V}O_2$ max cycle ergometer test and the distance covered walking and jogging in the match. A correlation of 0.43 was found between scores in anaerobic tests (Margaria-Kalamen test and vertical jump on a force platform) and the distance covered sprinting; no correlations were given between the distance covered sprinting and $\dot{V}O_2$ max. Cooke (1985) suggested that the differences in performance between positions in the fitness tests are directly related to the game requirements, halves obtaining higher values in the $\dot{V}O_2$ max test and backs measuring better on the anaerobic tests. It could equally be argued that the players' performance during match play was as a result of their fitness levels rather than the differences in their fitness levels being caused by the demands of the game. Cooke (1985) suggested that players should follow individual training programmes tailored to meet their positional requirements.

Aitken & Thompson (1988) suggested that the sweeper and the forwards should concentrate on anaerobic training as they are required to make short, fast movements whereas the defenders and midfielders should emphasise the training of the aerobic system as they are required to perform more continuous activity. This recommendation is based on the actual $\dot{V}O_2$ measurements of the Scottish Men's Hockey Squad. As no measure was made of anaerobic performance, it may be that the fitter players were selected to midfield/defending roles rather than being fitter through playing these positions

2.4.2 Estimated energy expenditure in hockey

Reilly & Seaton (1990) analysed the physiological costs of dribbling a hockey ball at two running speeds on the treadmill (8 and 10 $km.h^{-1}$). Heart rate, oxygen uptake and perceived exertion were measured for each subject (n=7) for running and for dribbling a hockey ball at both workloads; each activity was continuous for a 5 minute period. The energy cost of dribbling a hockey ball was found to be 60.8 ± 6.2 $kJ.min^{-1}$ at 8 $km.h^{-1}$ and 68.6 ± 17.0 $kJ.min^{-1}$ at 10 $km.h^{-1}$. This represents an increase in energy expenditure of 15-16 kJ above the cost of running at these speeds. There was also a significant increase in the heart rates observed for dribbling when compared to running at the same speeds (+27 $beats.min^{-1}$ (8 $km.h^{-1}$) and +23 $beats.min^{-1}$ (10 $km.h^{-1}$)). The perceived exertion rate also increased when dribbling. Players spend very short periods of time in possession of the ball in a game. Wein(1981) observed that 61% of players contact with the ball lasted less than two seconds, compared to the five minute periods observed in this study. Additionally players are likely to be dribbling at greater speeds than observed in this study. Reilly & Seaton (1990) suggested that players "may spend appreciable amounts of time running in a seem-crouched position following the ball and contesting possession" (p.145). Consequently this will increase the energy expenditure at a given speed when compared to upright running.

In order to determine the changes that artificial pitches have made to the women's game, Hughes & Cuncliffe (1987) conducted a match analysis on three international matches on grass and three international matches on an artificial surface. It was found that there were more touches per possession and that players dribbled with the ball more often on the artificial surface.

Malhotra et al. (1983) compared the differences between running speed, acceleration with changes of direction and the oxygen cost of playing hockey on a grass pitch as compared to an artificial surface. Running speed was measured by 20, 30 and 50 yard sprints, acceleration with changes of direction was measured by a shuttle run. The oxygen cost was determined for each subject (n=12) during a 6 a-side game on a half pitch for a 15 minute period. Oxygen uptake was measured by a Kofranyi-Michaelis Meter which measured the volume of expired air and collected a sample of air for analysis. The running speeds were faster in all sprints on the Astroturf surface both with and without a ball. These differences were only significant at the 50 yd distance ($p<0.05$). The subjects were slightly slower on the shuttle run on the Astroturf pitch although this was not significant. The oxygen cost of playing on the Astroturf pitch ($p<0.01$) was significantly higher than on the grass pitch, 2.26 $l.min^{-1}$ compared to 1.91 $l.min^{-1}$. Although these values are for a six-a-side game, and the subjects' involvement was likely to be restricted due to the Kofranyi-Michaelis Meter, they do give an indication of the differences in physiological demands between grass and Astroturf. This study supports the suggestion that the game on Astroturf is faster and requires a greater rate of energy expenditure, it also shows that turning on an Astroturf pitch is performed more slowly than on grass.

Various exercise physiologists have estimated energy expenditure for hockey. However, the methods used to calculate these values are not often clear (see Table 2.2).

The values estimated by Durnin & Passmore (1967) were obtained through the collection of expired air using a Max-Planck respirometer during a simulated game . These values are much lower than those predicted by Skubic & Hodgkins (1967) for females of 2537 kJ per match probably due to the restricted movement caused by the wearing of a respirometer. In the estimations of Durnin & Passmore (1967) there is no detail of the level of the game or the number of subjects. Even if the values obtained by Skubic & Hodgkins (1967) were a valid indication of energy expenditure during women's hockey in the 1990's, this would equal an energy cost of 36.2 $kJ.min^{-1}$ which according to McArdle et al., (1986) would classify the sport as "very heavy work" when related to their five level classification system for physical activity. In relation to Reilly & Secher's (1990) categorisation for men's sports, women's hockey would be classified as moderate activity along with sports such as baseball, fencing and gymnastics. However, it is doubtful whether the rate of energy expenditure for women and men's sports can be compared without taking body weight into account.

Jakeman et al. (1994) stated that when comparing different groups of performers, physiological parameters should be scaled to accommodate for differences in body size and allow direct comparison between groups. This has usually been done by dividing the variable by the subjects body weight (kg). Tanner (1949) suggested that this was misleading as the true relationship between body weight and other physiological variables does not pass through the origin. The equation formed when dividing by body weight suggests that the linear regression equation does pass through the origin. Nevill et al. (1992) stated that a more appropriate method was the use of a power function relationship to allow inter-group comparisons. They found that the physiological variable should be divided by body weight ($kg^{2/3}$).

Table 2.2 **The estimated energy expenditure of hockey**

Sex	Weight	$kJ.match^{-1}$	$kJ.kg^{-2/3}.min^{-1}$	Author
F	55	1176-1764	1.16-1.74	Durnin & Passmore (1967)
M	65	1470-2205	1.30-1.95	
F	53	2537*	2.57	Skubic & Hodgkins (1967)
M	50	2054	2.16	Brooks & Fahey (1984)
M	56	2205	2.15	
M	65	2558	2.26	
M	55	1848	1.82	Lamb (1984)
M	65	2184	1.93	
M	66.2	3290*	2.87	Malhotra et al. (1983)
M		2520-3500		Reilly & Secher (1990)

* These values have been estimated assuming an energy cost of 20.91 kJ per litre of oxygen uptake.

2.5 Conclusions

A number of parameters have been examined which can be used to determine the metabolic load on players under match conditions. The majority of studies reviewed have concentrated on one parameter in relationship to a number of subjects. Only the distance/time motion study by Bangsbo et al. (1991) compared the differences in physiological performance for individual players over two or more matches. Consequently there is a need to identify the range of workloads that players are subjected too.

This review of literature has found that there is a lack of quality research in to the energy expenditure of all "multiple-sprint" sports, with the technique of estimating energy expenditure from heart rate requiring validation. There is also a need to identify the relationship between the different physiological parameters in the "multiple-sprint" sports, for example how closely does the total distance covered relate to the total energy expenditure (Reilly & Thomas, 1976).

The studies in soccer identified midfielders as covering a greater distance than other positions, mainly in low intensity activities. Wein (1981), from limited data suggested that midfielders in hockey also covered greater distances than other positions. Whether changes in the game since 1973, including teams playing as single units in attack and defence, mean that these differences in workload remain is unclear.

In conclusion, the majority of research into the physiological demands of the "multiple-sprint" sports has been concerned with time-motion and distance-motion studies in soccer. Recent research is now using these data to identify performance variables e.g. fatigue in repeated sprints, both in the laboratory and simulated match setting. The only studies investigating the energy expenditure in "multiple-sprint" sports have either used the heart rate technique which is thought to overestimate energy expenditure or have collected expired air under simulated match conditions, which is likely to be at an intensity less than actual match play due to the restrictions of the collecting equipment. Consequently, there is a need to both validate the techniques used to assess the metabolic demands of the "multiple-sprint" sports and to apply these techniques to women's hockey, a sport in which there is a lack of research into all physiological aspects of the game. The results of these studies could then be used to gain a greater insight into the physiological stress on players and be applied firstly, to the preparation of players for competition in terms of fitness training and dietary requirements and secondly to management of teams in terms of substitutions and positional roles.

Chapter 3

The monitoring of heart rate during women's hockey

3.1 Introduction to heart rate during match play

In women's hockey mean heart rates of 180 beats.min^{-1} (n=2) have been recorded by Skubic & Hodgkins (1967) using radio telemetry for one complete match. The heart rates recorded ranged from 102-218 beats.min^{-1}. In women's 4-a-side indoor soccer Miles et al. (1993) reported mean heart rates of 171 beats.min^{-1}, however these results were obtained for five minute segments of play which may not be representative of a complete match.

Mean heart rates found during soccer matches have ranged from 157 beats.min^{-1} (Reilly, 1986 in Reilly et al., 1990) in a friendly match for English league footballers to 175 beats.min^{-1} (Agnevik, 1970 in Reilly et al., 1990) during a top Swedish competitive match. Heart rates recorded during friendly match play range from 118-185 beats.min^{-1} (Van Gool et al., 1983). Reilly (1986 in Reilly et al., 1990) found that due to the short recovery periods found in soccer the heart rate stayed raised and close to steady state values with small fluctuations, the coefficient of variation being less than 5%.

Heart rate can be presented as a percentage of maximum heart rate to give a better indication of the intensity of the stress that players are working at. Cochrane & Pyke (1976) suggested that on average soccer players work at 86% of their maximum heart rate; this is in agreement with Van Gool et al. (1988) who found a work rate of 85.5% of maximum heart rate. Reilly (1986 in Reilly et al., 1990) found a slightly lower work intensity of 80% of maximum heart rate. In women's 4-a-side soccer Miles et al. (1993) found a mean work rate of 85.7% of maximum heart rate for five minute periods.

The aim of this study was to observe the nature of players' heart rate response during women's hockey, to establish whether a player had a similar heart rate response over a number of games and to determine whether this heart rate response was similar to other multiple-sprint sports. The pilot studies used to establish the methodology for heart rate monitoring are described in Appendix 1.

3.2 Methodology

3.2.1 Subjects

Twelve players were selected from 4 National League (Division 1 & 2) teams using the following criteria :-

(i) They were currently in the National full squad or under 21 training pool.

(ii) They were easily classified by position i.e. they played predominately in defence, midfield or attack.

The twelve subjects consisted of four defenders (D), four midfielders (M) and four strikers (S). Details of these subjects are displayed in Table 3.1.

Table 3.1 Details of subjects

Subject	Club	Age	Weight (kg)	$\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$)	Position
A	1	22	68.0	53.4	M
B	1	29	62.0	53.1	D
C	1	25	54.0	61.0	S
D	2	21	60.0	44.8	D
E	2	19	62.5	47.3	M
F	2	22	65.0	48.2	S
G	3	19	56.5	49.6	D
H	3	20	65.5	52.4	M
I	3	19	65.5	47.6	D
J	4	20	65.0	44.6	S
K	4	20	51.0	47.9	M
L	4	19	59.0	48.5	S
Mean		21.3 ±3.0	61.2 ±5.2	49.9 ±4.5	

From table 3.1 it can be seen that the mean $\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$) of the subjects fell within the range for elite female hockey players reported in the literature of 45-59 $ml.kg^{-1}.min^{-1}$ (Reilly & Secher, 1990). The range of $\dot{V}O_2$ max values 44.6 - 61.0 $ml.kg^{-1}.min^{-1}$ shows that there is a variation in aerobic fitness despite these players competing at a similar level. The players' weight also fell within the mean range for top female hockey players reported by Reilly & Secher (1990) of 58.0-62.9 kg.

The subjects' maximum heart rate was taken to be the highest recorded heart rate either during match play or during a progressive maximal $\dot{V}O_2$ test performed on a treadmill. (protocol, see section 4.2.2)

3.2.2 Methodology for monitoring heart rate

Heart rate was measured using a short range telemetry system (Sport Tester PE3000 heart rate monitor). The receiver watch was switched on as near as possible to the start of the game to allow for the heart rates of the whole game to be recorded in the memory as the maximum recording time is 85 minutes. The watch was kept in the pocket of the player's skirt where it was least likely to be damaged. The print outs of heart rate from the pilot studies showed that the exact start, half-time and the end of the match could not be identified. It was necessary to start a stopwatch in conjunction with the heart rate monitors prior to the start, in order that the time difference between the start of the recording and the start of the match could be measured.

Once the receiver of the short range telemetry system had been switched on the there was no contact with the player until the end of the match. This was both to minimise the interference with the player and to avoid reminding her of the monitor.

All subjects were familiarised with the Sport Tester PE3000 system at either a friendly game or a training session, and then agreed to being monitored during competitive matches.

3.2.3 Editing heart rate data

The stored data were spooled from the Sport Tester PE3000 watch receiver into a BBC micro-computer. From this it was transferred across to an IBM computer (Appendix 2) which had a Minitab statistical programme. In Minitab the data were cleaned by editing any data which had been stored prior to the start of the match and after the end of the match. The data were then split into first and second half data and the half-time values removed for separate analysis. Any corrupt data were removed e.g. a zero heart rate where there was a brief loss of contact between the electrode and the skin, or an unusually high heart rate. An appropriate value was substituted which was midway between the existing values. If there were any more than eight corrupt data points then the data set was discarded i.e. 1.9% of the data.

3.2.4 Games monitored

In order to try and control the standard of play and the importance of the game, the matches monitored were all either first or second division National League or Cup games played on artificial grass.

Each subjected was monitored until at least 4 sets of complete match data had been obtained one of which was representative of a highly competitive game for each subject. A set of data was considered incomplete if more than 2% of the data points were corrupt or the short range telemetry system ran out of memory before the end of the game. Any stoppage time due to injury was included as it was felt that any recovery during this period would directly influence a player's subsequent movements.

3.2.5 Treatment of data

The data collected during match play were assumed to be non-parametric. It was felt that the variables inherent in team sports such as the opposition, players' fitness levels and differing tactical strategies, combined with the small sample size meant that the data did not meet the requirements of parametric testing. The test used to determine the differences between two sets of data for individual subjects was the Wilcoxon signed rank test for paired data. The test used to determine positional differences was the Kruskal-Wallis test (H test) for grouped data. The level of significance used to determine a significant difference was in all cases was $p<0.01$. Correlation's were determined using Spearman's rank-correlation coefficient for non-parametric data.

3.3.1 Results of measurement techniques

Throughout the 1990-91 season data were collected from a total of 26 matches, from Table 3.2, it can be seen that from a total of 71 individual heart rate recordings, 55 sets of data could be used, 19.7% of the individual data sets were lost due to problems with the Polar Sports

Tester PE3000 and 2.8% from the substitution and injury of players.

The initial selection of subjects was based on their playing position, three data sets were discarded as the player did not play in her selected position. Although these data are not included in this study the mean heart rates of these matches fell within the mean heart rate ranges for these subjects suggesting that individuals and level of opposition may determine heart rate response rather than position played.

The most physiologically demanding game for each player was assumed to be that match in which the highest mean heart rate was recorded. Similarly the least demanding game was assumed to be that with the lowest mean heart rate.

Table 3.2 **Details of all matches monitored**

Subject	No. of games monitored	No.. of good sets of data	Problems
A	7	6*	4
B	8	5	1,3,4
C	7	6	4
D	5	4	2
E	6	5	6
F	6	4	1,1
G	5	5*	
H	5	4	1
I	6	4	3,5
J	5	4	1
K	6	4	2,2
L	5	4	1
Totals	71	55	16

Problems :
1 watch did not record all data
2 corrupt data
3 transmitter disconnected
4 watch ran over memory span
5 player substituted
6 player injured
* 1 data set for other than selected position

3.3.2 Evaluation of measurement techniques

This study has shown that in field research of this nature in the region of 20% of the data sets can be lost due to malfunction of the short range telemetry system. One of the main problems with the short range telemetry system was the fact that there was no way of checking whether the watch was actually recording and in five cases the watch was accidentally switched off at some point during the game. The other main problem was either a loss of or incomplete contact between the skin and the electrodes which resulted in the collection of corrupt data. The nature of team sports dictates that even if the researcher was aware that there was a problem with the system it is unlikely that the game could be stopped to correct it. In one match there was a serious injury which stopped play for 10 minutes which meant that the short range telemetry system ran out of memory space. The only other problem with the use of the short range telemetry system was that two players dislodged the transmitter from the electrode belt through diving on the ground. Despite these problems it is felt that this particular short range telemetry system, the Sport Tester PE3000, gives a good measure of heart rate in the field situation.

Collecting match data during competitive match play will always be problematic, as the researcher has no control over the initial team selection and any subsequent substitutions. In this study this variable was reduced by selecting subjects of national squad standard and who could be easily classified by position; they were fairly certain of being included in the starting team and were less likely to be substituted than other players. Data were lost through players being selected in an alternative position in three cases and through a substitution in one case. Recent changes in the substitution rules (Hockey Rules Board, 1992) which allow for multiple substitutions mean that this variable is now much more difficult to control.

It has been found that heart rate can be monitored successfully during competitive women's hockey using the Sport Tester PE3000, but it can be expected that there will be a loss of data in approximately 20% of the games monitored. This is less than the loss of data reported by Green et al. (1976) for ice hockey and Alexander et al. (1988) for ringette of 40% and 50% respectively. The greater loss of data in these studies is likely to be caused by two factors, firstly in ice hockey and ringette there is greater player contact than in hockey resulting in the heart rate monitoring system malfunctioning. Secondly, recent improvements to the Sport Tester PE 3000 mean that there is a better contact between the electrodes and the skin reducing the problems found in earlier studies caused by poor electrode contact especially during heavy sweating.

3.4 Results of heart rate monitoring during match play

From graphing heart rate against time, it was clear that a similar pattern for all players emerged. This was a fluctuating graph showing periods of high intensity followed by a short recovery. The range of these fluctuations varyied between players and for all but one player the majority of the data fell within a 15 beats.min^{-1} range.

From Table 3.3 it can be seen that the mean heart rate for all matches was 172 ±9 beats.min^{-1}, the lowest mean heart rate found during any match was 156 beats.min^{-1} and the highest mean heart rate was 188 beats.min^{-1}. The largest difference found between the mean heart rate from two matches for an individual was 21 beats.min^{-1} (subject H), the smallest difference was 3 beats.min^{-1} (subject A). The match heart rate traces for these subjects are shown in Figure 3.1. It can be seen from Figure 3.1 (iv) that for subject H there was a large variation around the mean, with a coefficient of variation of 9.84%, whereas in Figure 3.1 (i) player A shows much less fluctuation around the mean, with a coefficient of variation of 5.21%.

Figure 3.2 shows the heart rate distribution for players A and C. The data for player A are the same as that in Figure 3.1 (i), and show a narrow range of heart rates; this match had the lowest coefficient of variation (5.21%). Player C showed a much greater range of heart rates and had the highest coefficient of variation (13.36%), this was the least demanding match for player C.

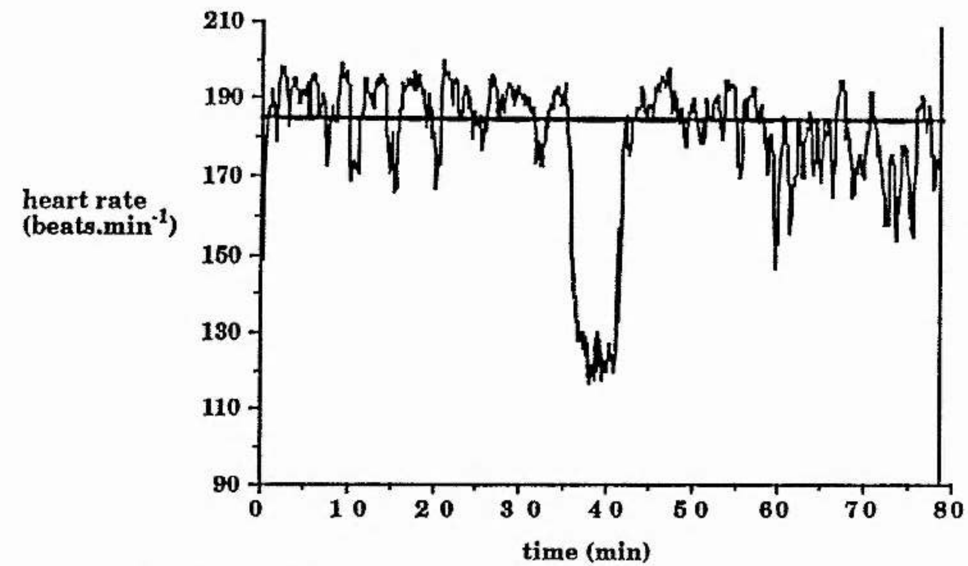
Table 3.3 **Mean, standard deviation and range of mean heart rates from all games analysed for each subject.**

Subject	Mean	Range
A	182 ± 1	181 - 184
B	175 ± 6	165 - 180
C	162 ± 5	156 - 168
D	170 ± 4	164 - 173
E	166 ± 4	163 - 174
F	164 ± 7	157 - 171
G	175 ± 6	170 - 183.
H	169 ± 9	158 - 179
I	165 ± 3	161 - 168
J	167 ± 7	157 - 172
K	185 ± 2	183 - 188
L	181 ± 5	175 - 186
for all subjects	172 ± 9	156 - 188

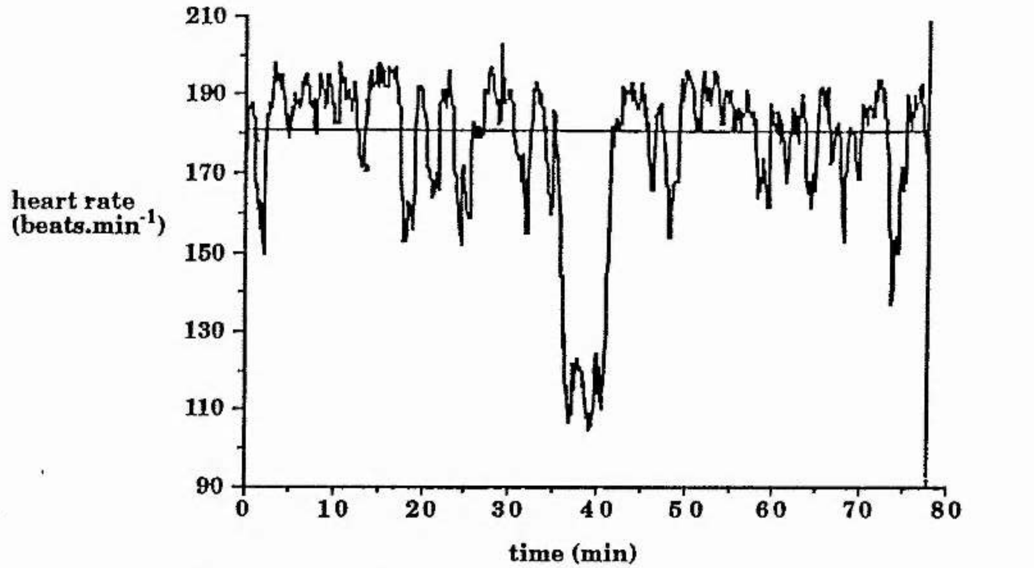
The mean coefficient of variation for the most demanding games was 6.5% whereas for the least demanding games the mean coefficient of variation was 8.6%. There was a significant difference ($p<0.01$) between the coefficient of variation between a player,s least and most demanding game, suggesting that in a less demanding game not only is the mean heart rate lower, but there is greater fluctuation around this mean when compared to a more physically demanding game.

Players worked at a mean rate which represented 86.4 ±3.5% of their maximum heart rate. This ranged from 78.8% to 89.8% for all matches.

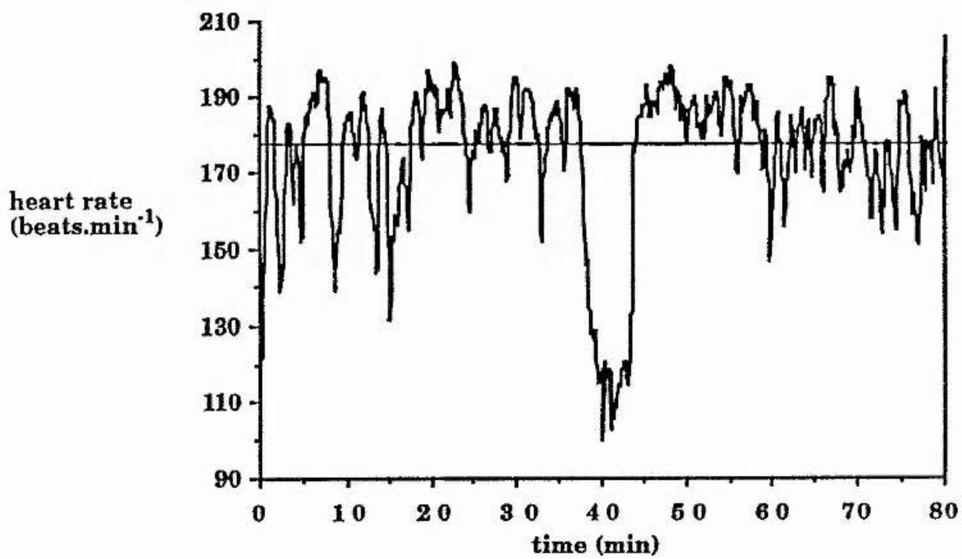
The players' maximum heart rates recorded during match play and during a maximum $\dot{V}O_2$ test are shown in Table 3.4. It can be seen that for 7 subjects a greater maximal heart rate was recorded during match play than during the maximum $\dot{V}O_2$ test.



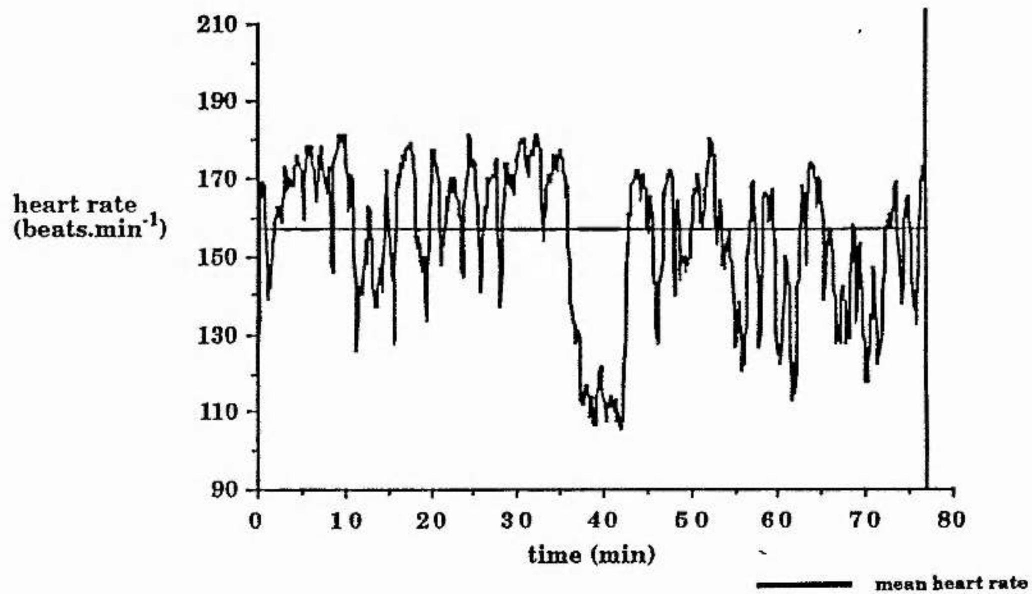
(i) Subject A (most demanding match)



(ii) Subject A (least demanding match)

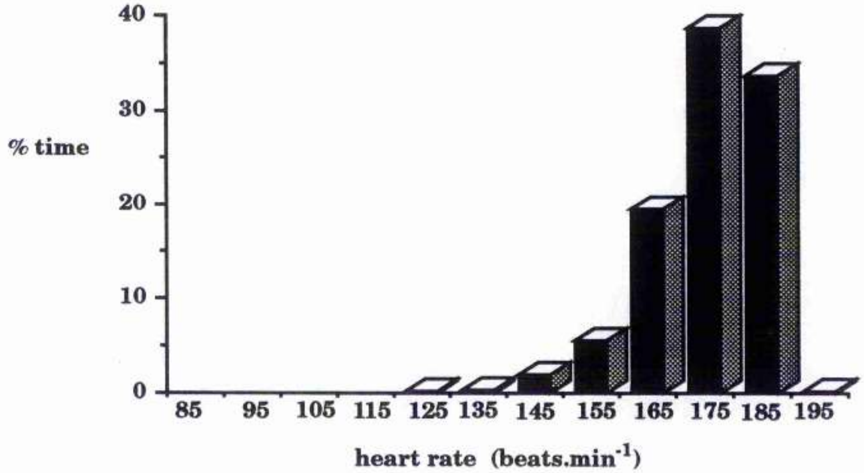


(iii) Subject H (most demanding match)

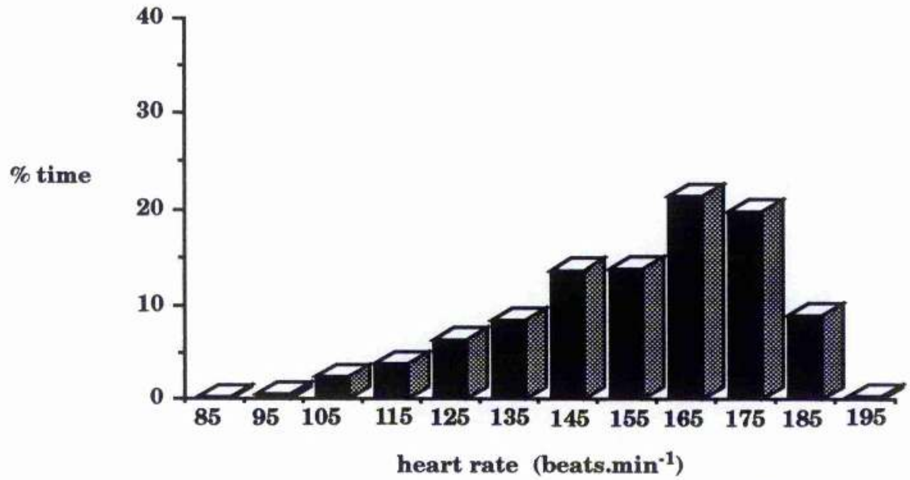


(iv) Subject H (least demanding match)

Figure 3.1 Graph of heart rate during the most and least demanding matches for subjects A & H



Subject A



Subject C

Figure 3.2 **Bar chart of heart rate distribution for subject A's most demanding match and subject C's least demanding match**

The mean heart rates during the second half were significantly less ($p<0.01$) between the second and first halves, although in 36.5% of the matches a higher heart was recorded during the second half suggesting that there will be some matches where players will be required to work at a greater intensity during the second half.

The mean heart rate for all subjects during the half-time break for the most demanding match was 135 ± 7 beats.min^{-1} compared with 126 ± 10 beats.min^{-1}. for the least demanding matches. There was not a significant difference ($p>0.01$) between the mean half-time heart rates for the most and least demanding matches. The mean heart rates recorded during the half time break ranged from 115 ±18-147 ±13. Examples of the nature of the heart rate response recorded during the half-time break are shown in Figure 3.1. The steep decline at the end of the half and the rapid increase at the start of the second half can be observed.

Table 3.4 **Maximum heart rate recorded during a maximal VO_2 treadmill test and during match play in beats.min^{-1}.**

Subjects	Maximum heart rate on treadmill (beats.min^{-1})	Maximum heart rate from all matches (beats.min^{-1})	Difference between treadmill & match (beats.min^{-1})
A	198	203	+5
B	194	197	+3
C	197	192	-5
D	189	193	+4
E	183	189	+5
F	183	190	+7
G	202	200	-2
H	200	199	-1
I	202	193	-9
J	192	190	-2
K	207	209	+2
L	200	207	+7

Observation of the heart rates showed that there was no specific pattern in relation to position played. Figure 3.3 shows the heart rate response for the most demanding game for a defender (D), a midfielder (E), and a striker (F). It can be seen that there is very little difference between the three traces.

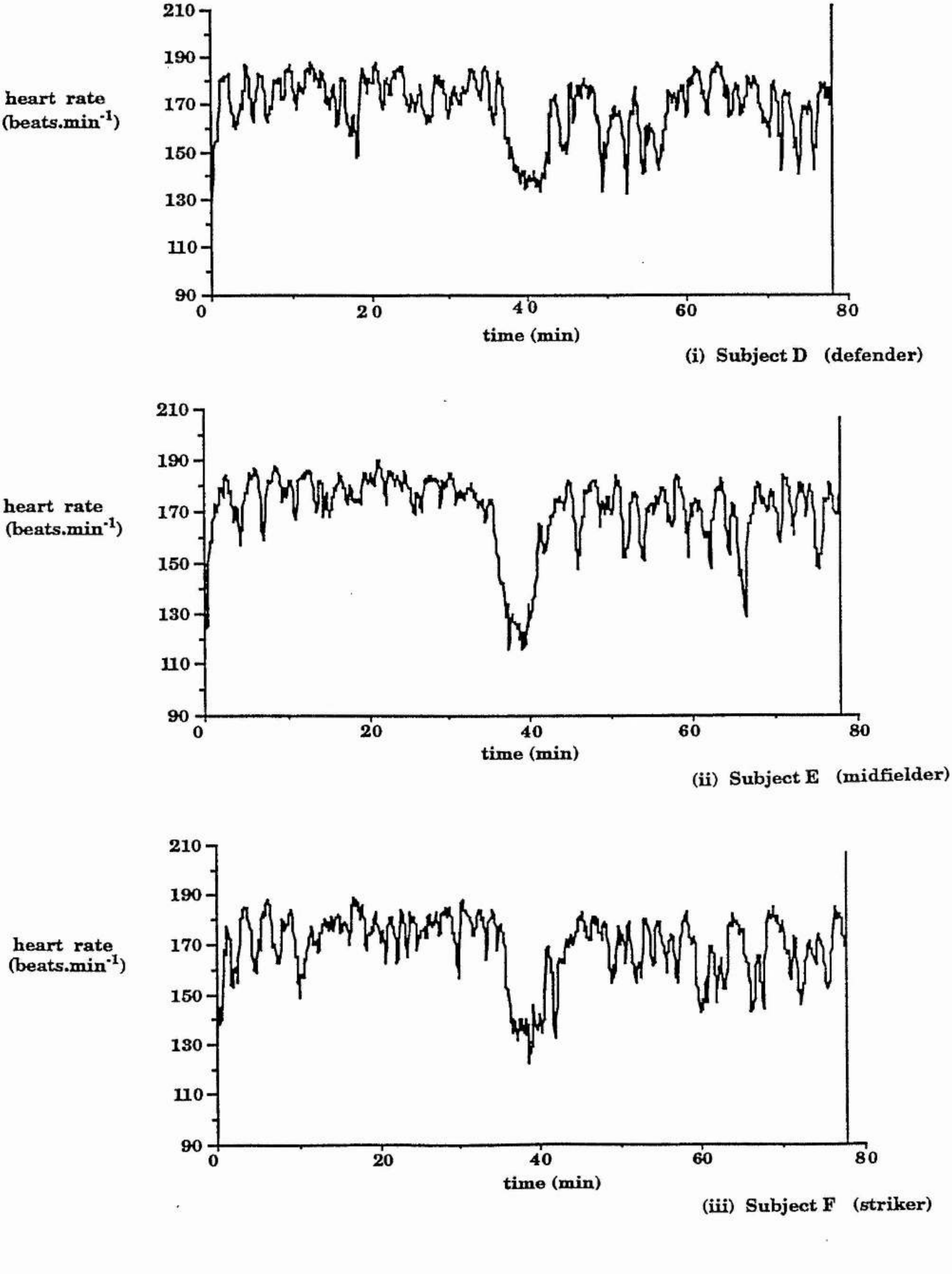


Figure 3.3 Graph of heart rate response for the most demanding game for a defender (D), a midfielder (E) and a striker (F).

3.5 Discussion of heart rate results

The heart rates recorded during match play represented between 78.8% and 89.8% of maximum heart rates. Leger & Thiverge (1988), found that above 85% of maximum heart rate, the validity of the Sport Tester PE3000 was reduced to r=0.71 from r=0.95 at 65-75% of maximum heart rate. Steady state exercise was used by Leger & Thiverge (1988) to validate the Sport Tester PE 3000; whether this validity will be as great during non-steady state exercise is unclear. The recording of heart rate every 5 seconds was felt to be sensitive enough to give a true picture of the actual match heart rates as the rate of change of heart rate every 5th second was not great enough to suggest that additional heart rate information had been lost.

The mean heart rate recorded for all matches of 172 ± 9 beats.min^{-1} was lower than that obtained in women's hockey by Skubic & Hodgkins (1967) of 180 beats.min^{-1}, although in this study during some matches some players had a greater mean value than 180 beats.min^{-1}, suggesting that heart rate response is based on a number of factors, including fitness and level of opposition. The mean heart rate recorded for all matches was higher than that found in friendly soccer matches by Reilly (1986 in Reilly et al., 1990) but lower than that found in a top Swedish soccer player of 175 beats.min^{-1} (Agnevik, 1970 in Reilly et al., 1990). Without relating these heart rate values to a player's oxygen uptake, heart rate alone cannot be used to suggest whether women's hockey requires a similar amount of work as soccer.

There was slightly greater variation in the heart rates recorded in this study on women's hockey than that reported by Reilly (1986 in Reilly et al., 1990) for soccer, suggesting that either the periods of recovery are greater in women's hockey or that the hockey players are fitter which gives them a faster drop in recovery heart rate. There was no correlation in this study between the coefficient of variation and a players $\dot{V}O_2$ max (ml.kg^{-1}.min^{-1}), suggesting that factors other than aerobic fitness affect the heart rate range. However the most extreme coefficient of variation in both the least and most demanding games was displayed by player C who also had the highest $\dot{V}O_2$ max suggesting that above a certain level $\dot{V}O_2$ max has a greater influence on recovery heart rate than other match demands.

In comparison with soccer the players in this study worked at a similar percentage of their maximum heart rate. The mean rate of 86% is in agreement with values found in soccer by Cochrane & Pyke (1976) and Van Gool et al. (1988). It is suggested that 86% of maximum heart rate is the intensity which the majority of players can maintain in the non-steady state situation. Some players may be able to sustain a greater work rate than this. In this study 89.9% was the greatest mean percentage of maximum heart rate recorded. During the least demanding game, a player was still required to maintain a work rate of 78.8% of heart rate maximum, showing that less demanding games still place a high level of physical stress on players.

The fact that 7 players recorded a greater maximum heart rate during match play when compared to a $\dot{V}O_2$ max test shows that at times a maximal stress is placed on players which shows that the heart rate response during intermittent maximal anaerobic work may be greater than the response during continuous maximal aerobic activity. This is in agreement with Gleim et al. (1981) who recorded greater heart rates during an American Football match for 4 out of 6 subjects in comparison to a $\dot{V}O_2$ max test on a treadmill.

All except two subjects had met at least two of the criteria for attaining $\dot{V}O_2$ max. The majority of subjects did not show a levelling off in the graph of oxygen uptake against workload. It was felt that this was due to the 2 $km.h^{-1}$ increments in the protocol which was necessary to obtain enough data points for establishing the linear regression equation.

The range of heart rate responses for each subject shows that despite selecting matches of a similar competitive standard throughout the season, there may be a difference of 21 $beats.min^{-1}$ in the mean heart rate for a subject between games. This identifies the problems with the analysis of match play in that each match will have its own physiological requirements which may vary greatly despite these games being of a similar competitive level.

The similar pattern of heart rate found in the most demanding game for all players (Figure 3.3) suggests that players are under similar physiological stress. This is in contrast to studies in football which have suggested that the midfield role is more aerobically demanding (Reilly & Borrie, 1992). If this was the case in women's hockey there would have been a difference in the heart rate response, with midfielders showing less fluctuation around a higher mean heart rate than both strikers and defenders. Figure 3.1 (i) shows the type of response that might be expected for a midfield player. This was only observed during the most demanding matches as Figure 3.1 (iv) shows the heart rate trace for a midfielder during a less demanding game. This is similar to results found in ringette where when the zones were removed all players demonstrated similar heart rate responses (Alexander et al., 1988).

The heart rates recorded during the half-time break show that although the players were sitting / standing for around five minutes the mean heart rates remained elevated above resting values. Whether this is caused by psychological factors or by an increased metabolic rate caused by the preceding activity is unclear.

In conclusion, the heart rate response during women's hockey is continually fluctuating, reflecting the intermittent nature of the sport. In the majority of instances the rest periods are not long enough to allow for a large drop in the heart rate before the next period of high intensity exercise. As a result of this the fluctuations are fairly small around an already elevated mean heart rate.

Chapter 4

The estimation of the energy cost of women's hockey from heart rate analysis.

4.1 Introduction

The study in Chapter 3 on heart rate response during women's hockey match play showed a large range of mean heart rates of 162 - 184 beats.min^{-1} for each subject over 4 matches, which might suggest that players were required to work at differing intensities. Although heart rate can give an indication of the nature and intensity of the game, it can only be used to compare the physiological strain on an individual player over several matches. The monitoring of heart rate does not allow for a comparison of the physiological load imposed on individuals in the same or different match situations as a player's heart rate response will be dependant on her fitness level. Also during match play the physical workload on each player will be dependant on the requirements of the game. Hence differing heart rates between individuals cannot be attributed solely to either differing work rates or differing fitness levels.

In order to use heart rate to compare the differences in workload between players, heart rate must be related to oxygen uptake in order to predict energy expenditure. For each individual the oxygen uptake at a specific heart rate will be dependent on a number of variables which include fitness and genetic factors.

The purpose of the following study was to determine the energy demands of women's hockey using the heart rate - oxygen uptake relationship. Further aims were to observe the variation in energy cost for players over several games, to observe the relationship between energy cost and position played and to observe the differences in energy expenditure between the first and second halves.

4.2 Methodology

4.2.1 Subjects

The subjects and the games monitored are the same as those described in Chapter 3 (Tables 3.1 & 3.2).

4.2.2 Calculation of the heart rate - oxygen uptake linear regression equation

In hockey much of the movement is in a stooped position and not necessarily forwards. However in order to collect expired air at steady state conditions it was assumed that a maximum progressive test on a treadmill with no incline would give a similar heart rate - oxygen uptake relationship as found in the game. A continuous level protocol was used with a starting speed on the treadmill of 4 $km.h^{-1}$. The speed was increased by 2 $km.h^{-1}$ every three minutes until the subject reached exhaustion. In some cases the final increment was 1 $km.h^{-1}$ when it was felt that the subject would be unable to cope with a 2 $km.h^{-1}$ increase. It was found in pilot work that increments of less than 2 $km.h^{-1}$ at the initial workloads made the protocol too long and it was felt that the subjects were likely to fatigue before reaching their VO_2 max.

The expired air was collected into Douglas Bags, the collection time was over the last part of each workload and was started in time to collect approximately 60 litres (collection time 120-40 seconds, see Table A4.1 for collection times for subject A). This expired air was analysed using a Servomex OA250 oxygen analyser and a Servomex PA40 carbon dioxide analyser which were calibrated with known gases. The volume of expired air was measured using a Harvard dry gas meter which had a thermometer inserted in the outlet pipe to measure the temperature of the expired air and was calibrated by drawing a known volume of air through the meter.

The heart rate at each workload was the mean of the heart rates recorded every five seconds during the collection period using a short range telemetry system (Sport Tester PE3000).

It was found during pilot studies that the three minute protocol allowed for the subjects to reach steady state during the collection period. Appendix 3 shows the heart rate trace for subject B during this protocol. It can be seen that there was no increase in heart rate during the collection period.

Oxygen uptake ($l.min^{-1}$) was regressed against heart rate to give two linear equations, the data and linear regression equations for subject A are shown in Appendix 4 (Fig A4.1). The first equation was for walking (4 & 6 $km.h^{-1}$) and the second for running (8 $km.h^{-1}$ to the final workload). These linear equations were then applied to the heart rate data recorded during match play, to give an oxygen uptake in $litres.min^{-1}$ for each heart rate; by dividing these values by 12 the oxygen uptake in litres could be obtained for each five second period (which was the period of time each heart rate represented). Summing these values gave the total oxygen cost in litres for the match.

4.2.3 Oxygen uptake to energy cost

The Respiratory Exchange Ratio (RER) values obtained on the treadmill were plotted against oxygen uptake ($l.min^{-1}$), omitting any unusual values and only using data up to the first oxygen uptake point to have a corresponding RER value greater than 1, which removed any error due to hyperventilation (see Figure A4.2).

From these graphs the plot of RER against oxygen uptake showed a linear relationship and a linear regression equation was calculated ($r^2 = 0.61\text{-}0.99$) for each subject to estimate the RER for any given oxygen uptake. This was applied to the oxygen uptake estimate during the game to calculate the energy cost. Where the RER value was calculated as being greater than 1, it was assumed to be 1.

In the case of subjects being monitored during matches before and after the Christmas break, the linear regression equation was established during both periods, so that any changes in fitness level during the mid-season break could be accounted for. Seven subjects completed the heart rate - oxygen uptake linear regression equation on two different occasions.

4.3 Results

Although to some extent the intensity of the matches monitored was controlled by using games of a similar standard there is no way of controlling the involvement of the individual players, and the strength of the opposition will to some extent dictate the players' workload. In order to minimise this problem, the match chosen for analysis for each subject was the one with the maximum demands, i.e. in order to try and standardise the energy expenditure of each player so that players could be compared. This also allowed for comparisons to be made positionally in that the maximal energy requirements of each position could be examined.

The game with maximum demands was also used to examine fatigue during the second half. It was felt if any differences in energy expenditure between the first and second halves were caused by fatigue, they would be more identifiable after a demanding first half. Secondly, if all the matches were used the result would be heavily influenced by one-sided games where players worked less hard in the second half due to the score at half time i.e. any drop in energy expenditure may have been caused by a decreased requirement in workload rather than by fatigue. This is shown in Chapter 3 where the heart rates during the second half were significantly lower than during the first half ($p<0.01$) when all games were considered.

4.3.1 Maximum estimated energy expenditure

The mean estimated energy cost for the most demanding game for each subject was 3860 kJ, with a range of 1563 kJ, which demonstrates the wide range of energy cost demonstrated by players of a similar standard in games of a comparable competitive nature. The mean estimated energy expenditure per minute for all subjects ranged from 42.07 $kJ.min^{-1}$ to 64.40 $kJ.min^{-1}$ (3.05-3.99 $kJ.kg^{-2/3}.min^{-1}$).

There was no significant difference between the estimated energy expenditure for the first and second halves ($p>0.01$) when the most demanding game was used for each subject.

There was no significant difference in the total estimated energy expenditure between playing positions ($p>0.01$). Indeed the two extremes of total estimated energy expenditure were by midfielders, however when the estimated energy expenditure was expressed in relation to body weight, the two extremes were by strikers.

Although, the range of RER values was 0.70-1.00, for all but one subject the mean RER was greater than 0.98, for this subject the mean RER was 0.92. The standard deviations for these mean RER's were all less than 0.03.

Table 4.1 Total estimated energy expenditure (kJ) and the rate of estimated energy expenditure ($kJ.kg^{-2/3}.min^{-1}$) for the most demanding match for each subject

Subject	1st Half (35 min) (kJ)	2nd Half (35 min) (kJ)	Whole match (70 min) (kJ)	Rate of energy expenditure ($kJ.kg^{-2/3}.min^{-1}$)	Position
B	2171	2170	4341	3.95	D
D	1727	1603	3330	3.09	D
G	1927	1797	3724	3.61	D
I	1833	1857	3690	3.24	D
A	2320	2188	4508	3.86	M
E	2064	1934	3998	3.62	M
H	2167	2209	4376	3.84	M
K	1485	1460	2945	3.05	M
C	1940	2061	4001	3.99	S
F	2161	1986	4147	3.66	S
J	1791	1715	3506	3.09	S
L	1912	1848	3760	3.54	S
Mean	1958 ± 233	1903 ± 237	3860 ± 461	3.55 ±0.35	
Range	1485-2320	1460-2209	2945-4508	3.05-3.99	

4.3.2 Differences in individual estimated energy expenditure between matches.

The data sets collected from the 4 or 5 matches for each player were analysed to give the range of estimated energy expenditure over several matches of a similar standard, in order to determine whether the most demanding game was representative of the "normal" energy cost for each player.

In respect to energy demand, Table 4.2 shows that some players will expend a similar amount of energy regardless of the score. Subjects A, G, I, K had a less than 5% difference in estimated energy expenditure over 4-5 matches despite playing matches which had varying results. With the exception of player H in midfield the greatest range of estimated energy expenditure between matches is by three of the strikers (C, F & J) .

Table 4.2 Range of estimated energy expenditure with the result of games for all subjects in 4-5 matches.

Subject	Highest energy cost of match (kJ)	Score	Lowest energy cost of match (kJ)	Score	Difference (kJ)	% Difference	Position
I	3690	L 2-1	3607	W 2-0	83	2.2	D
A	4508	W 3-1	4408	W 2-1	100	2.2	M
G	3724	L 2-1	3588	W 7-0	136	3.7	D
K	2945	L 5-1	2806	W 3-0	139	4.7	M
E	3998	W 1-0	3751	L 1-0	247	6.2	M
D	3330	D 0-0	3056	W 5-0	274	8.2	D
L	3760	W 3-1	3451	W 3-0	309	8.2	S
B	4341	L 5-0	3916	W 6-0	425	9.8	D
F	4147	W 1-0	3573	W 3-0	574	13.8	S
H	4376	L 2-1	3593	L 2-0	783	17.9	M
J	3506	L 2-0	2823	W 2-0	683	19.5	S
C	4001	W 2-1	2916	W 1-0	1085	26.4	S

4.4 Discussion

The mean rate of energy expenditure was 55.14 kJ .min^{-1}. which is much higher than values given in other studies. For example, Skubic and Hodgkins (1967) (n=2) estimated an energy expenditure of 36.12 kJ.min^{-1}. using a similar method as this research, both studies showed a similar mean heart rate but the subjects of Skubic & Hodgkins (1967) had a lower mean oxygen uptake, 1.79 l.min^{-1} compared to 2.8 l.min^{-1} in this study. The changes in the rules, style of play, playing surface and fitness of players suggest that the energy requirements of modern women's hockey will be greater than the values from earlier studies. It is often assumed that playing in midfield in team games is more physically demanding than other positions because of the dual role of attack and defence. It would seem from the data presented here (Table 4.1) that in top level hockey the importance of the team playing as a close unit erases these differences and that the energy cost of the most demanding games are determined individually rather than by position played; this is in disagreement with studies done in football, (Reilly & Thomas, 1976 (estimated distance covered), Ali & Farrally, 1990 (estimated energy expenditure)). This idea of a "playing unit" demands that defenders overlap in attack and strikers work back in defence; there is also a great deal of positional interchange with players being encouraged to assume the role relevant to the part of the pitch they find themselves in and for other players to cover this player. Hence positions are not as clearly defined as they perhaps once were. Similar trends have been identified in soccer (Reilly et al., 1990).

The ranges of estimated energy expenditure (Table 4.2) show a trend whereby games which have the lowest energy cost tend to be those which are won easily. If this is the case then there are significant implications for the more successful teams in that there will be few games in a season when they are working at the energy expenditure required for the most competitive games. Although some players may compete weekly at close to their maximum energy expenditure, for other players this may only occur 2-3 times in a season. This is especially true for those players who show a wide range of energy expenditure between games. Consequently, there may be a requirement to train above the "normal" rate of energy expenditure to prepare for highly competitive matches.

The range of energy cost displayed by subject H (783 kJ) is surprising in that the two extreme games were both highly competitive and important. However, in the game with least energy expenditure she was tightly marked which reduced her involvement in the game, showing that in a highly competitive match an individuals opponent may influence a players energy expenditure rather than the result of the game.

The mean estimated RER value for the heart rates recorded during match play (greater than 0.99 for 11 of the subjects) showed that carbohydrate was the main fuel source, so an important consideration for women hockey players is to make sure that they have replenished their glycogen stores prior to competition and to be aware that their glycogen stores may be severely reduced during a match. Consequently, players should replenish their glycogen stores by consuming carbohydrate immediately after the match, as it has been found that the muscle resynthesises glycogen at the highest rates within 1-5 hours of exercise (Williams, 1991)

Throughout this study a number of assumptions have been made. Firstly, that heart rate is a valid estimation of energy cost during "multiple-sprint" activity, and that the heart rate - oxygen uptake relationship established in the laboratory at steady state holds under field conditions. During the game a player's heart rate very rarely reaches steady state and so this methodology assumes that the rate of change of oxygen uptake is the same as that of heart rate (i.e. where a player records a certain heart rate at the end of a five second period, it is assumed that the equivalent oxygen cost is maintained for the same five second period). Also, dehydration during the game may result in a lower stroke volume and consequently a higher heart rate to maintain cardiac output (Astrand & Rodahl, 1986); in this case heart rate would overestimate oxygen uptake. This may be the reason why there was no significant difference in the energy expenditures for the first and second halves. It may be that as a player fatigues her movements become less efficient and so the energy cost of a specific activity increases. Consequently, a player's energy expenditure may be similar during the first and second half but her work rate may not. A movement analysis of the actual work done would give an additional insight into the problems of fatigue and may reveal if the heart rate - oxygen uptake relationship is affected by fatigue or dehydration towards the end of the match.

Secondly, it has been assumed that the heart rates measured during the game are a true reflection of the physical workload and are not affected by psychological factors. At high workloads it is likely that the psychological influence is to some extent reduced (Rhode & Esperson, 1988) since the physiological response is so great.

Nevertheless this may result in some overestimation of the energy cost of match play as the elevation in heart rate due to psychological factors cannot be determined.

The correlation of 0.57 between a player's estimated total energy expenditure and her body weight, shows that a factor in determining a player's total energy expenditure will be her body weight. Nevill et al. (1992) suggested that when comparing physiological values of individuals in isolation of body weight these variables should be divided by body mass in units of $kg^{2/3}$ (see Table 4.1). In relation to position played there were no significant differences in the rates of energy expenditure when expressed in relation to body weight ($kg^{2/3}$).

In conclusion, it has been shown that despite using players of a similar standard and when comparing their most demanding games there was a large range of energy expenditure, and this occurred between players in the same position. This would suggest that to a large extent energy expenditure is individually determined. Allowing for the fact that this methodology may tend to overestimate energy expenditure, top level women's hockey places a high physical stress on players over 70 minutes with an energy expenditure in the region of 55 $kJ.min^{-1}$ or 3.55 $kJ.kg^{-2/3}.min^{-1}$.

Chapter 5

A time-motion analysis of women's hockey.

5.1 Introduction

The studies in chapters three and four have identified the metabolic demands in terms of heart rate response and the estimated energy expenditure during women's hockey. It was suggested that heart rate during the second half may be higher at a given work intensity than during the first half as a result of either heart rate drift and/or less efficient movement caused by fatigue. By establishing the nature and intensity of activity during the first and second halves, the effects of fatigue can be determined by establishing whether players perform less work during the second half.

The monitoring of heart rate and estimation of total energy expenditure cannot be used to determine the contribution of the different energy systems in providing this energy or as a basis for the identification of the appropriate type of training. In order to obtain further information on the physiological requirements of the game, it is necessary to establish the nature and intensity of the activity.

Time-motion analysis records the time spent in different activities (Mayhew & Wenger, 1985; McKenna et al., 1988; Otago, 1983). This type of analysis can be used to measure the amount of time which is spent in discrete movements, determine work : rest ratios, and investigate the contribution that different energy systems make to the game.

As no time-motion studies are available in women's hockey it is worthwhile examining studies in other "multiple-sprint" sports. In soccer, Mayhew & Wenger (1985) and Yamanaka et al. (1988) split the movements into low intensity activities (standing, walking and jogging), and high intensity activities (running and sprinting). In both these studies any game-related activities e.g. tackles/jumps were considered as high intensity activity, whereas Ali & Farrally (1991) included all ball contacts in the category that preceded the event. These studies did not consider changes in direction as separate movement categories e.g. jogging backwards was classified as jogging. It was found that in soccer between 86.8% (Mayhew & Wenger, 1985) and 93% (Ali & Farrally, 1991) of the time was spent in low intensity activity whereas in Australian Rules this is 94.2% (McKenna et al., 1988).

In soccer, Mayhew & Wenger (1985) found that the mean time of each period of high intensity activity was 4.4 seconds, with a work : rest ratio of 1:7, and that the activity changed approximately every 6 seconds, whereas in Australian Rules the activity changed every 7.3 seconds (McKenna et al., 1988) and 80% of the high intensity activity lasted less than 6 seconds. The maximum period of high intensity activity reported by McKenna et al. (1988) for both soccer and Australian Rules was 24.3 seconds and 21.7 seconds respectively.

The short duration of high intensity activities linked with a low work : rest ratio in the above studies would suggest that the predominant anaerobic energy system in football is the alactic creatine phosphate system with the occasional longer periods of high intensity stressing anaerobic glycolysis (Mayhew & Wenger, 1985; McKenna et al., 1988). The relative contribution of these two energy systems in these types of "multiple-sprint" sports is not known and may vary between sports depending on the game characteristics.

The aim of this study is to assess whether hockey has similar characteristics to other "multiple-sprint" sports by examining the intensity and duration of hockey movements. A second aim is to establish whether there is a difference in the workload between the first and second halves.

5.2 Methodology

Ten of the subjects in this study (A-J) were the same subjects as described in Chapter 3 (section 3.2.1). The other two subjects met the original criteria and played in the same positions as the subjects they replaced. All games analysed were either first or second division National League matches.

Each player was videoed continually for a whole match using a portable video camera (Panasonic NV-A2) and recorder (Panasonic NV-180). The video camera had a stopwatch which was started in conjunction with the game. The video recording was replayed and stopped after each discrete movement, the stopwatch display allowed for accurate timing of each activity period. Each activity was measured to the nearest second. The time spent in each movement category was entered into a computer statistical package for analysis.

Nine discrete movement categories were identified :-

Low intensity activities : standing, walking, walking backwards/sideways (bk/sd), jogging.

High intensity activities : jogging bk/sd, cruising, cruising bk/sd, sprinting, hockey-related activity where the player was directly involved with the ball, e.g. dribbling, passing, stopping, tackling. Jogging bk/sd was defined as a high intensity activity as it has been calculated to have a similar energy expenditure to cruising (Reilly & Bowen, 1984)

The work : rest ratio for each player was calculated by dividing each period of low intensity activity by the preceding period of high intensity activity.

5.3 Results

Figure 5.1 shows the percentage time spent in each activity. It can be seen that walking is the activity in which most time is spent. For one player this accounted for almost half the match, another player spent 25% of the time standing. A mean percentage time of 11.6% was spent moving in a direction other than forwards. Only 3.57% of the time was spent involved in hockey-related activities. Each activity lasted a mean length of 1.85 ±0.43 seconds and occurred between 54-90 times during a match showing that some players may be involved almost twice as much as others in hockey-related activities. The maximum time any player was involved with the ball on a single occasion was 10 seconds.

The time spent in high intensity activity during the game ranged from 17.5% (12 min 13 s) to 29.2% (17 min 31 s). There was a significant difference between the time spent in high intensity activity for the 1st and 2nd halves ($p<0.01$), as shown in Table 5.1. There was a correlation of 0.72 between $\dot{V}O_2$ max and the time spent in high intensity activity.

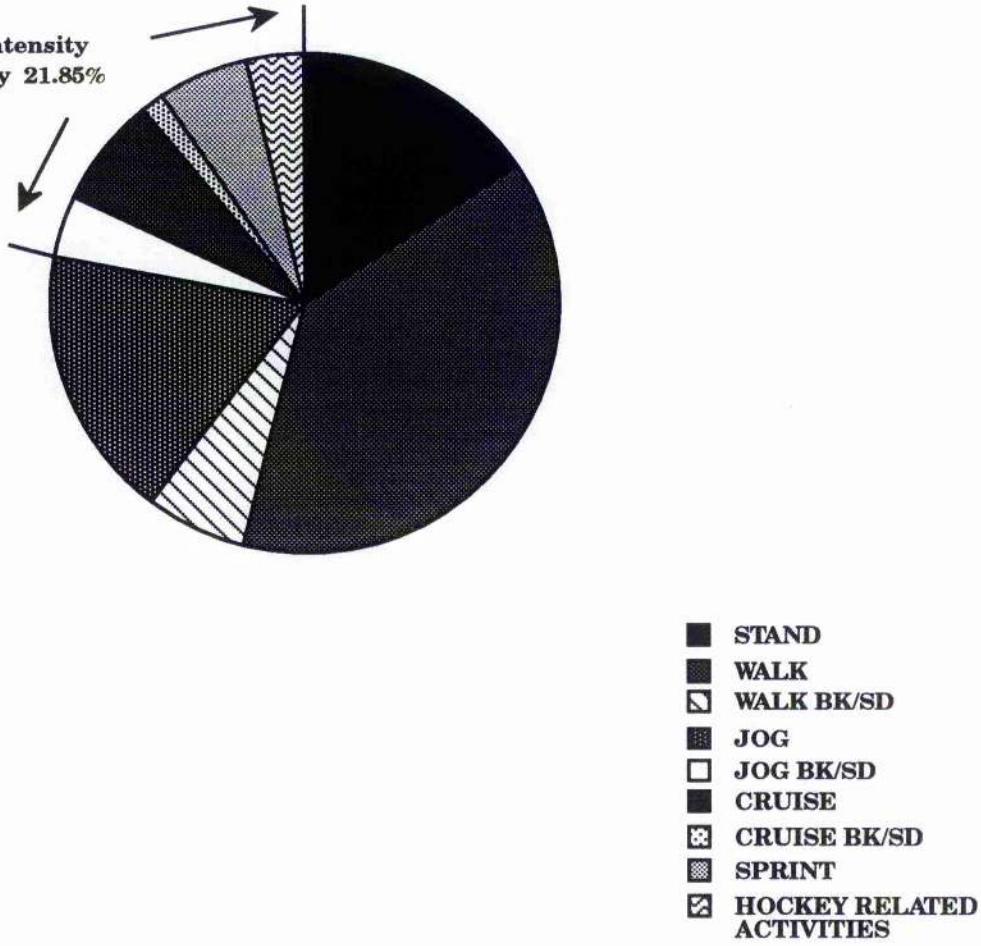


Figure 5.1 - Pie chart of total time spent in each activity

The mean length of time of each period of high intensity activity was 5.22 ±0.61 s. (Range of subject means 4.73-6.82 s) and the mean length of time of each period of low intensity activity was 18.22 ±3.8 s, (range of subject means 14.14 - 24.30 s). The maximum time that each player was involved in a single period of high intensity activity ranged from 17 seconds to 62 seconds, and the maximum periods of low intensity activity ranged from 66 seconds to 196 seconds.

Table 5.1 **Time spent (minutes, seconds) in high intensity activity for 1st and 2nd halves along with position, result and $\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$).**

Subject	$\dot{V}O_2$ max	Position	High Intensity 1st half	High Intensity 2nd half	Score
A	53.4	M	9 min 47 s	7 min 45 s	L 5-1
B	53.1	D	9 min 23 s	8 min 17 s	L 5-1
C	61.0	S	10 min 58 s	8 min 47 s	L 5-1
D	44.8	D	6 min 40 s	6 min 31 s	W 1-0
E	47.3	M	7 min 29 s	6 min 26 s	W 1-0
F	48.2	S	10 min 12 s	7 min 50 s	W 1-0
G	49.6	D	7 min 22 s	6 min 05 s	W 7-0
H	52.4	M	9 min 58 s	9 min 24 s	L 3-1
I	47.6	D	6 min 54 s	5 min 53 s	L 3-1
J	44.6	S	6 min 07 s	5 min 44 s	W 7-0
K	48.4	M	7 min 28 s	5 min 22 s	W 2-1
L	47.0	S	6 min 42 s	6 min 27 s	W 2-1
Mean	50.06		8 min 14 s	7 min 03 s	
± *SD*	±4.34		±1 min 29 s	±1 min 19 s	

The mean : work rest ratio was 1:5.7, with a range from 1:3.8 to 1:7.9, showing that some players have, on average, half the recovery of others. For all but 3 players the most frequently occurring work : rest ratio was less than 1:1 and for the other 3 players the most commonly occurring work : rest ratio fell between 1:1 and 1:2 showing that players are frequently required to work at much lower work :rest ratios than the mean value would suggest.

From observation of Table 5.1 no trends emerge with respect to either the score or position when related to time spent in high intensity activity. For example, comparing defenders D and I, it can seen that they spent a similar time in high intensity activity (13 min 11 s and 12 min 47 s respectively) despite player D being involved in match in which her team won 1-0 and player I in a match which was lost 3-1.

Table 5.2 shows the mean duration in seconds that a player spent in each activity before changing to another activity. Although walking was the activity that had the longest mean duration (6.64 ±0.89 s), this is still a relatively short period of time before changing to another activity. The mean time for cruising and sprinting is 3.63 and 3.13 seconds respectively, again showing the short duration of specific activities. This is further emphasised by the fact that there was a range of between 813 -1081 changes of activity during a match (Table 5.3).

Table 5.2 The mean and standard deviation of the duration of each activity in seconds

Activity	Time (s)	±*S D*
Stand	4.66	±0.82
Walk	6.64	±0.89
Walk bk/sd	2.78	±0.36
Jog	4.23	±0.39
Jog bk/sd	2.52	±0.32
Cruise	3.63	±0.43
Cruise bk/sd	2.01	±0.07
Sprint	3.13	±0.31
Hockey	1.85	±0.43

Table 5.3 **The mean, standard deviation and range (all subjects) of occurrences of each activity per match.**

Activity	Mean	±*S D*	Range
Stand	143.75	±24.3	119-202
Walk	238.80	±27.9	180-290
Walk bk/sd	93.80	±18.5	68-123
Jog	172.70	±42.6	94-223
Jog bk/sd	58.30	± 7.5	18-104
Cruise	84.25	±33.7	42 - 61
Cruise bk/sd	27.50	±10.7	13- 44
Sprint	75.00	±19.9	51-107
Hockey	74.20	±12.2	54- 90
All activities	969.10	±73.6	813-1081

There were no trends apparent in any aspects of the movement analysis when related to position played. Although midfielders appeared to be involved in more changes of activity these differences were not significant ($p>0.01$). The mean number of changes of activity for midfielders was 1038 ±33, for strikers 944 ±53 and for defenders 925 ±78.

5.4 Discussion

From Figure 5.1, it can be seen that in the region of 60% of the time is spent either standing or walking. If jogging is considered as a low intensity activity then 78% of the time is in low intensity activity although this ranges from 71.8% -83.6% between players.

Some players spend much greater time in high intensity activity than others, (range from 12 min 13 s - 20 min 44 s). There was a correlation of 0.72 between the time spent in high intensity activity and a player's $\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$). This would suggest that there is a relationship between a player's aerobic power and the amount of high intensity work done, but this only explains about 50% of the variance, suggesting that other factors such as anaerobic capacity, team tactics and the level of the opposition will also have an influence on the time players spend in high intensity activity. In soccer Reilly et al. (1990) reported strong correlations between a player's $\dot{V}O_2$ max and both the total distance covered and the number of sprints players engage in, supporting the suggestion that a player's potential for high intensity activity is related to her aerobic power.

There was a large range (51-107) in the number of sprints performed by each player. This not only shows the variability in physiological demands of match play but also suggests that the ability to maintain and reproduce sprinting speed is of greater importance to some players but is not positionally related.

In relationship to soccer, women hockey players spent slightly longer in each period of high intensity activity, 5.2 seconds compared to 4.4 seconds (Mayhew & Wenger, 1984), and had slightly less recovery with a work : rest ratio of 1:5.7 compared to 1:7 (Mayhew & Wenger, 1985). The time spent sprinting was greater than that found in soccer by Yamanaka et al. (1988) and Ali & Farrally (1991). In comparison with football, hockey would appear to be played at a greater intensity with more frequent changes in activity. In international competition this intensity may be even greater as ball boys/girls replace the ball as soon as it leaves the pitch reducing the recovery time. Recent changes in the obstruction rule (Hockey Rules Board, 1992) are intended to lead to less stoppages, further increasing the demands of the game.

As the mean time for periods of high intensity activity was between 4.73-6.82 seconds, it might be assumed that the energy system predominately used is the alactic creatine phosphate system with little accumulation of lactate (Astrand & Rodahl, 1986). However, studies by Holmyard et al. (1988) and Tumilty et al. (1988) which involved repeated short maximal sprints at work : rest ratios similar to women's hockey found an increase in blood lactate. This would suggest that anaerobic glycolysis is used during very short bursts of high intensity activity with limited recovery. Consequently, there will be an accumulation of lactate in women's hockey, some of which is presumably removed during any longer periods of low intensity activity. The studies reviewed by Astrand & Rodahl (1986) involved high but not maximal intensity work, whereas the studies by Holmyard et al. (1988) and Tumilty et al. (1988) involved maximal sprints. This difference in intensity may account for the variation in lactate response.

There was a significant difference ($p<0.01$) between the time spent in high intensity activities for the first and second halves. A factor which may affect the work rate in the second half is the score. From Table 5.2, it can be seen that all players had a lower work rate in the second half regardless of the score, indicating that this explanation is unlikely. A more likely explanation is that fatigue reduces work rate in the second half. The changes in substitution rules since this study allowing for rolling substitutes may reduce the fatigue effects. Studying one player over several matches may give a better insight to the relationship between work rate and result.

There was no significant difference in any aspects of the movement analysis when related to player position with the exception of the number of changes of activity in a match. This would suggest either that top level hockey demands that players work as a unit and as such there are no positional differences in terms of physiological demands. Alternatively the small numbers in each group (4) did not allow positional differences to emerge and that individual differences were a greater factor. From observation of the matches it was apparent that at this level players frequently adopted other positions or roles within the team throughout the game other than their initial position, suggesting that unlike football (Reilly et al., 1990) positional differences are not significant. This implies that all outfield players could follow a similar conditioning programme as the increased number of changes of activity in midfielders did not affect any of the other variables e.g. work : rest ratios, length and number of sprints or time spent in hockey related activities.

Although the alactic and lactate anaerobic systems provide the immediate energy, a demand will be made on the aerobic system in order that the creatine phosphate stores are replenished and any lactate accumulation is resynthesised during the periods of low intensity activity. The more efficient a player is at this recovery the more potential she will have for high intensity activity. Thus, aerobic training will significantly improve performance and this may explain the correlation between $\dot{V}O_2$ max and the time spent in high intensity activity.

Since the mean time for a sprint is 3.13 ±0.31 seconds, very rarely will players reach maximum speed as this is achieved after 5-6 seconds (Dick, 1989). Consequently, in terms of sprint training for hockey the most important factors will be the reaction to a stimulus i.e. game perception, the ability to accelerate from either a rolling or standing start, and the ability to change from a sprint to a hockey-related activity. In terms of the optimal training for developing speed there has been little research done in this area especially with respect to games players.

Some speed training should be at a work : rest interval similar or slightly less than that found in the game for overload to occur. For 9 players the most frequently occurring work :rest ratio was less than 1:1 suggesting that some sprint training should take place at this intensity.

As the mean length of each occasion where a player is directly involved in the game is less than 2 seconds, and as this involvement is usually at a high intensity workload, there is a need to practice hockey techniques at match intensities i.e. practices where players are allowed several seconds to collect, make a decision and pass a ball are not preparing them for match play. Practice restrictions such as two-touch should be encouraged to speed up the decision-making techniques.

In conclusion, hockey is a multiple-sprint activity requiring the development of aerobic power to aid the replenishment of the creatine phosphate stores and maximise lactate removal. The fact that players are engaged in significantly less high intensity activity during the second half may be as a result of fatigue. Similar physiological demands are made on players in different positions, suggesting that a generalised conditioning programme may be appropriate to all outfield players.

Chapter 6

A comparison between the use of heart rate analysis and time-motion analysis to estimate energy expenditure in women's hockey.

6.1 Introduction

The results of the heart rate analysis study showed that players are required to maintain a mean heart rate at around 86% of their maximum heart rate, with an energy expenditure in the region of 55 $kJ.min^{-1}$ suggesting that women's hockey is physiologically very demanding. In contrast the time-motion study has shown that players spend less than a quarter of the game in activities which have a greater intensity than jogging, the mean length of high intensity activity is 5.22 ±0.6, giving a mean work: rest ratio of 1:5.7, thus suggesting that the physiological demands are less than the heart rate analysis implies.

The time-motion study (Chapter 5) has identified that players are engaged in less high intensity activity during the second half whereas the results of the energy expenditure study (Chapter 4) suggested that players expend similar amounts of energy during the first and second halves. By applying both techniques to the same match, the differences between the two methods can be established and some of the problems may be highlighted. In order to compare the two studies directly, it is necessary to assign an energy cost to the activities identified in the time-motion analysis.

Although movement analysis has been used to estimate the energy expenditure of daily activity (Durnin & Passmore, 1967; Reilly & Thomas, 1979) and simulated match play (Ballor et al., 1989), there would appear to be no literature on the estimation of the energy cost of match play by this method.

A study by Ballor et al. (1989) compared the estimation of energy expenditure by heart rate and by video analysis to energy expenditure during simulated basketball activity. Ballor et al. (1989) found that video analysis underestimated by 27.7% and heart rate overestimated by 16% the value measured from oxygen uptake, a 43.7% difference between the two methods. The use of a cycle ergometer to establish the heart rate - oxygen uptake relationship in this study is likely to be a source of error as the mode of exercise used to establish the relationship should relate directly to the type of exercise in the field situation (MacDougal et al., 1982). Also the assumption that the energy cost of 1 litre of oxygen is 5 kcal will lead to an overestimation of the actual energy cost as the heart rates monitored during the simulation (mean 118 ±27 beats.min^{-1}) suggest that carbohydrate was not the only source of fuel.

The aim of this study was to examine the differences between the use of heart rate analysis and video analysis to estimate the energy expenditure of women's hockey.

6.2 Methodology

The subjects and games analysed are those described in Chapter 5 and the method for estimating of energy expenditure from heart rate is that described in Chapter 4.

6.2.1 Estimation of energy expenditure from time-motion analysis.

Nine movement categories were identified (standing, walking, walking backwards/sideways (Bk/Sd), jogging, jogging Bk/Sd, cruising, cruising Bk/Sd, sprinting, hockey related activity). Each movement category was assigned an energy cost in kJ.min^{-1}. The energy cost for standing is well documented and was assumed to be 6.7 kJ.min^{-1} (McArdle et al., 1986). The energy cost of walking was calculated from the expired air collected during the 4 km.h^{-1} and 6 km.h^{-1} workloads on the treadmill when establishing the regression equation for each subject (section 4.2.2). Similarly for jogging the energy cost was calculated from the 8 and 10 km.h^{-1} workloads, and for cruising from the 12 and 14 km.h^{-1} workloads.

The energy cost of sprinting is not well documented and was calculated using an equation put forward by Heyward (1991).

$$\dot{V}O_2 \text{ ml.kg}^{-1}\text{.min}^{-1} = \text{m.min}^{-1} \times \frac{0.2 \text{ ml.kg}^{-1}\text{.min}^{-1}}{\text{m.min}^{-1}} + 3.5 \text{ ml.kg}^{-1}\text{.min}^{-1}$$

A speed of 461 m.min^{-1} was used (13 s /100m) because this was the upper limit of the range of sprinting speeds observed and it allowed for the extra energy required for acceleration and the stooped position which occurs in hockey. This speed was observed between the 25 yard and half-way lines when a player (subject B) was sprinting forward to support a breakaway attack. Dufour (1993) stated that the sprinting speed of soccer players is in the region of 450 $m.min^{-1}$ and Bangsbo et al. (1991) suggested speeds of up to 500 $m.min^{-1}$.

The energy cost of moving in a direction other than forwards has been investigated by Reilly & Bowen (1984). Using 9 male soccer players on a treadmill at three speeds (5, 7 & 9 $km.h^{-1}$) and three directional modes (forwards, backwards and sideways), they found that the additional energy cost of running backwards / sideways could be predicted from

$$\text{Additional energy (kcal)} = (-0.799 \times \text{speed in km.h}^{-1}) + 0.731$$

It was assumed that this equation was still accurate at speeds higher than in their study.

The energy cost of dribbling a hockey ball has been investigated on the treadmill by Reilly & Seaton (1990). In seven male hockey players dribbling increased the energy expenditure between 15-16 kJ above the energy cost of the running speed. (8 & 10 $km.h^{-1}$). It was assumed that all hockey skills in this study were performed at maximal intensity (i.e. sprinting) and that all hockey related activities had a similar increase in energy expenditure as dribbling in the Reilly & Seaton (1990) study.

6.3 Results

The mean energy cost for each activity for all subjects is shown in Table 6.1. The range shows the need to determine energy costs individually.

The mean energy expenditure for all subjects estimated from the time-motion analysis was 2846 ±284 kJ with a range of 2198 to 3299 kJ. The mean energy expenditure from heart rate was 3873 kJ ±436 kJ and this ranged from 3197 to 4660 kJ (see Table 6.2). There was a significant difference between the two estimates ($p<0.01$).

There was not a significant difference ($p>0.01$) between the energy cost of the first and second halves for each player (Table 6.2) when estimated from heart rate. There was however a significant difference ($p<0.01$) when estimated from time-motion analysis.

Table 6.1 The mean, standard deviation and range of the estimated energy cost for each movement category ($kJ.min^{-1}$)

Activity	Mean	±*SD*	Range
Standing	6.7		
Walking	21.0	±1.6	18.9 - 23.9
Walking Bk/Sd	32.0	±3.5	22.0 - 35.9
Jogging	46.6	±4.9	35.2 - 52.6
Jogging Bk/Sd	69.7	±6.8	54.8 - 76.7
Cruising	63.2	±4.4	55.2 - 68.4
Cruising Bk/Sd	106.5	±6.1	93.9 - 113.4
Sprinting	127.8	±8.2	109.1 - 137.4
Hockey	142.1	±8.1	124.6 - 152.9

Table 6.2 The mean estimated energy expenditure (kJ), standard deviation and range for the first and second halves from heart rate and time-motion analysis.

	Estimated energy expenditure from time-motion analysis			Estimated energy expenditure from heart rate analysis			
	1st Half (kJ)	2nd Half (kJ)	Whole match (kJ)	1st Half (kJ)	2nd Half (kJ)	Whole match (kJ)	% difference
Mean	1468	1377	2846	1970	1903	3873	26.3
SD	152	146	284	225	225	436	4.7
min	1134	1065	2199	1620	1577	3197	16.1
max.	1695	1604	3299	2365	2294	4660	33.0

6.4 Discussion

A mean difference of 26.3% was observed in match energy expenditure between estimates from the heart rate and time-motion analysis. However which of the two estimates is closer to the actual value is unclear. It would seem reasonable to assume that the true value lies somewhere between the two estimations, as was the case in the simulated study of basketball by Ballor et al. (1989). It is likely that time-motion analysis underestimates energy expenditure due to the additional energy requirements of changing activity (Reilly & Seaton, 1990). Heart rate may overestimate energy expenditure due a change in the linear relationship between heart rate and oxygen uptake during non-steady state activity (Ogushi et al. 1993)

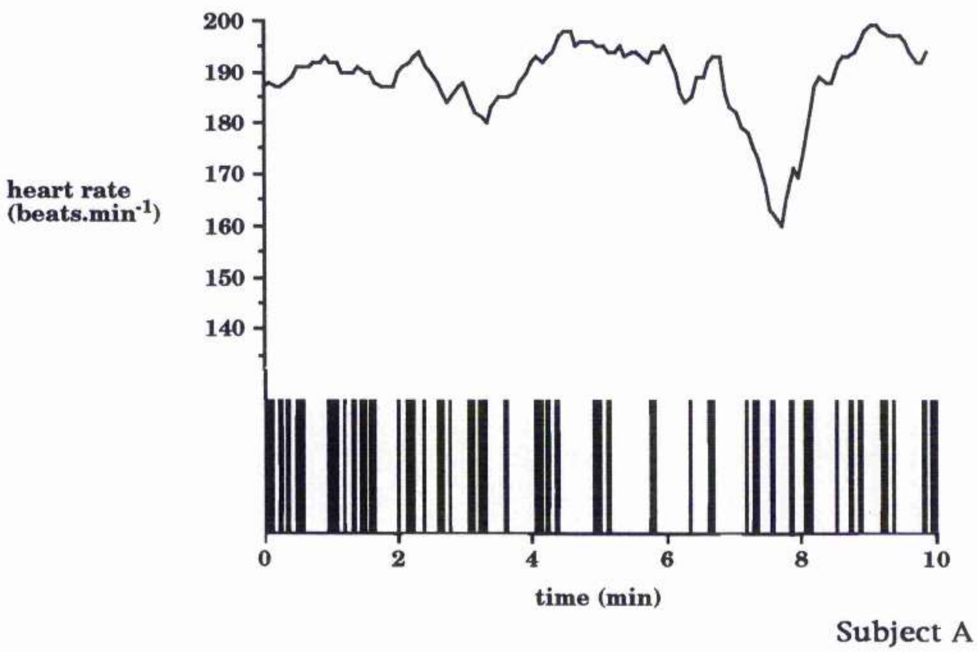
Time-motion analysis showed that as a player fatigued, her work rate decreased yet the heart rate remained at similar levels to the first half. It has been observed that in endurance events there is an upward drift in heart rate to compensate for reducing stroke volume, and this has been associated with dehydration (Astrand & Rodahl, 1986). This would partly explain the high second half heart rates and lead to an overestimation of energy expenditure in the later stages of the game.

The 26.3% difference found in this study is less than that found by Ballor et al. (1989). They observed a 43.7% difference for simulated basketball activity, despite a much lower mean heart rate, 118 ±27 beats.min^{-1} compared to the mean value of 171 ±7 beats.min^{-1} in this study. The differences between the two methods in the study of Ballor et al. (1989) may be partly due to the errors in the heart rate methodology previously discussed and, secondly, the method of assigning energy values from the literature may have underestimated the true costs as the value of 18.9 kJ.min^{-1} seems low for basketball activity. The problem with simulated match play is that the stress and intensity of competition cannot be replicated.

The coefficient of variation (17.9%) for the percentage difference between the two methods would suggest that not only do the two methods give different estimations, the differences between methods for each subject varies considerably. These differences were found to be significant between players ($p<0.01$, F-test) suggesting that the errors in both methods may differ for individual players. When both estimations for each subject were correlated, the correlation coefficient of 0.84 shows that a player who had a low estimation of energy expenditure from heart rate analysis would also have a low estimation from time-motion analysis when compared to the other subjects.

Problems were revealed with the use of heart rate to estimate energy expenditure. In the most extreme situation, subject A had a mean heart rate of 188 beats.min^{-1} which represents a work rate of 93% of her maximum heart rate. It is unlikely that this level of physiological functioning could be maintained for 70 minutes, suggesting that factors other than work rate are affecting heart rate. A mean heart rate for all subjects of 171 ±7 beats.min^{-1} relates to a work intensity similar to cruising when these subjects were observed on the treadmill. From the movement analysis 78% of the time is spent at a workload of lower intensity than this which further supports the view that factors other than workload influenced heart rate. The effect of psychological factors on resting heart rate prior to competition has been documented (McArdle et al., 1986) but the extent to which this is overridden by high intensity exercise is not clear.

Figure 6.1 shows the heart rate and movement intensity for the first 10 minutes of two matches. This illustrates that there is not a strong immediate relationship between movement intensity and heart rate although the underlying pattern is reflected. It is unlikely that the monitoring of heart rate every five seconds was not sensitive enough to detect changes in movement intensity. The periods of rest between high intensity activity would not appear to be great enough to allow heart rate to recover to the level that low intensity movements would suggest. Heart rate seems to respond at a slower rate than the activity changes. Hence heart rate cannot be used to indicate the movement intensity for small segments of the game but may be used to give an overall picture.



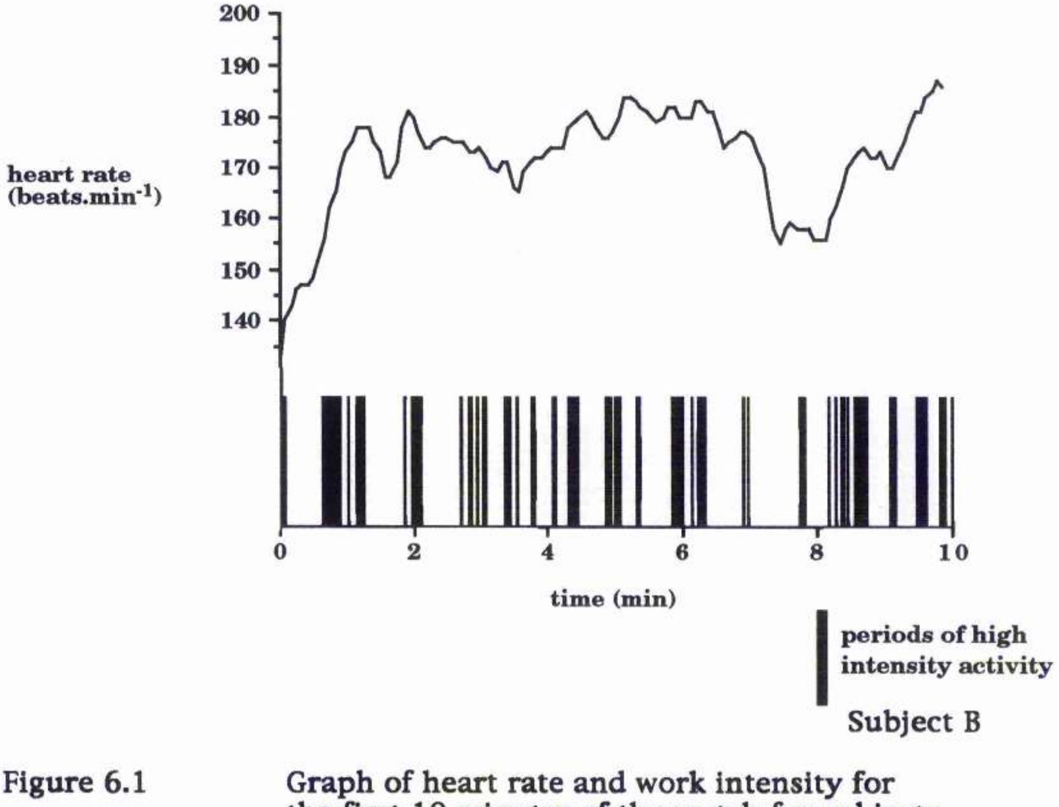


Figure 6.1 Graph of heart rate and work intensity for the first 10 minutes of the match for subjects A & B

This is supported in a study by Holmyard et al. (1988) in which 10 rugby players performed 2 tests of 10 maximal 6 second sprints. In one test there was a recovery of 30 seconds, in the second a recovery of 60 seconds. The peak heart rates for each protocol were both recorded during sprint 5 and were 188 ±18 beats.min^{-1} and 180 ±14 beats.min^{-1}. The heart rates dropped in the region of 10 beats per minute in each sprint during recovery. There was no significant difference ($p>0.05$) in the recovery heart rates between the two protocols which suggests that a work : rest ratio of 1:10 will not lead to a great drop in heart rate during the recovery period. This supports the view that the high heart rates observed during match play could be mainly a physiological rather than a psychological response.

The method of time-motion analysis whereby a steady state energy cost was assigned to discrete movements within a non-steady state activity does not make allowance for the frequent changes of activity during match play (Ballor, et al., 1989). With approximately 1000 changes of activity, if even a small additional energy cost was required to change activity, this might significantly influence the total energy expenditure. This problem could be addressed by applying a mathematical model to each change of activity to estimate the additional energy requirements. For example the additional energy cost of changing from walking to jogging could be calculated and added to the estimated energy cost for jogging. This would have to be done for all combinations of activities.

The number of changes of activity was similar to that found in competitive football (Reilly & Thomas, 1976) but it should be remembered that a football match is played over 90 minutes whereas a hockey match is over 70 minutes. Consequently there is a change of activity every 4.2 seconds in hockey as opposed to every 5.4 seconds in football.

In hockey the game often requires a stooped position even when not directly involved in play and this will require an additional energy cost. Similarly carrying a hockey stick (approximately 600- 750 grams) reduces running efficiency and increases energy cost. As a player fatigues, her movements may become more inefficient so an energy cost which was assigned to an activity at the start of the match may underestimate the true energy cost towards the end of the match.

The equation used for sprinting assumed linearity at a high intensity i.e. the energy cost of steady state aerobic activity can be applied to anaerobic activity. Whether this leads to an under-estimation or over-estimation is unclear. The speed (461 $m.min^{-1}$) assumed for the calculation is likely to overestimate the true speed found in match play as it was very rarely that players sprinted for long enough to attain this assumed speed. With the inefficiency of the sprinting style found in hockey, this value may well be closer to the true value than allocating an energy cost at a slower speed.

It has been assumed that each hockey activity was performed at a sprinting speed. This was because it was often difficult to classify the speed of movement as the majority of hockey-related activity took place within one second. Ali & Farrally (1991) classified football actions into the movement activity which preceded the event. It was felt that in hockey this would lead to an underestimation of the intensity of the action because most hockey related activities take place as high intensity actions in the stooped position.

In conclusion, time-motion analysis gives a lower estimation than heart rate analysis. It is suggested that time motion analysis underestimates energy expenditure due to the additional energy required to change activity. Further research is required to determine whether heart rate analysis overestimates energy expenditure due to a change in the heart rate - oxygen uptake linear relationship. It would seem reasonable to assume that the energy cost of women's hockey lies somewhere between 40.7 and 55.3 $kJ.\ min^{-1}$, reflecting that 22% of the game was spent in high intensity activity with around 1000 changes of activity.

Chapter 7

The errors in the use of heart rate analysis and time-motion analysis to estimate energy expenditure during intermittent activity

7.1 Introduction

In the comparison between heart rate analysis and time-motion analysis to estimate energy expenditure in women's hockey (Chapter 6), a mean difference of 26.3 ±4.7% was found. In order to determine the magnitude of the errors involved in the use of both heart rate and time motion analysis to estimate energy expenditure in "multiple-sprint" sports, it is necessary to compare both methods with the direct measurement of energy expenditure at physiological intensities similar to match play.

This may be done directly through the use of a whole body calorimeter, where heat production is measured in an insulated chamber. Indirect calorimetry involves the measurement of oxygen uptake, with the equivalent calorific cost being applied to each litre of oxygen used dependant on the fuel source. This method gives comparable results to whole-body calorimetry (McArdle et al., 1986).

Direct calorimetry, although highly accurate, is impractical for the majority of sporting activities (McArdle et al., 1986). Indirect calorimetry requires the use of either a mouthpiece and two way breathing valve or a face mask to allow for the collection of expired air, plus varying amounts of collection and/or analysing equipment, which inhibits their use in the field situation. This is especially true in team sports where the restrictions placed on individuals by the equipment does not allow full participation in the sport. At best these techniques can be used in simulated match play where restrictions are imposed, for example no physical contact with the subject.

The Cosmed K2 portable oxygen analyser is a system which has recently been developed to measure oxygen uptake continuously (up to seven hours with measures taken every 15 seconds) in the field situation. The advantage of this system is that it allows changes in oxygen uptake to be observed which can be related to corresponding changes in heart rate and activity. Although still placing some restrictions on the subject due to the face mask, the rest of this system (battery back, transmitter / analysing unit) is compact and fairly lightweight allowing subjects to participate in simulated match play.

Several studies have attempted to establish the errors in the use of the linear relationship between heart rate and oxygen uptake, determined in the laboratory at steady state workloads, to heart rates monitored in the non-steady state field situation as a method of estimating energy expenditure.

Malhotra et al. (1963) collected expired air at different steady state workloads on the cycle ergometer to establish the heart rate / energy expenditure regression equation. An error of between 0.6-7.0% was found between the true value measured from expired air and that estimated from heart rate analysis for a variety of tasks including marching, running, hopping and hammering (heart rates ranged between 95-150 beats.min^{-1}).

Astrand & Rodahl (1986) suggested that the difference in the use of heart rate to estimate energy expenditure ranges by ±15% when compared to the actual value measured from expired air.

Ogushi et al. (1993) collected expired air in Douglas Bags during a friendly soccer match for two subjects for between 141-168 seconds in both the first and second halves. It was found that the estimation of oxygen uptake by heart rate from the linear regression equation overestimated oxygen uptake by 12 ml.kg^{-1}.min^{-1} when compared to the actual oxygen uptake measured in the Douglas Bags a difference of 26.7%. Ogushi et al. (1993) suggested that these differences are caused by the differing heart rate - oxygen uptake response during intermittent exercise.

In a study of simulated basketball match play Ballor et al. (1989) found a mean difference of 16% (n=10) between the use of heart rate and the direct measurement of oxygen uptake to estimate energy expenditure. The regression equation for heart rate and oxygen uptake was established on a cycle ergometer and applied to the heart rate recorded every minute. Expired air was analysed continually during the simulation using an on-line system with values being reported every minute. The simulated game lasted 30 minutes with each period of activity lasting between 15 seconds to 5 minutes; the mean heart rate was 118 ±27 beats.min^{-1}.

Almost no validation has been done on the use of time-motion to estimate energy expenditure, Ballor et al. (1989) found that time-motion analysis underestimated by 27.7% the energy expenditure measured by the analysis of expired air during simulated match play. This study also found a 43.7% difference between the heart rate and time-motion methodologies for estimating energy expenditure.

It is the aim of this study to determine the errors involved in using both heart rate analysis and time motion analysis, by comparing the estimated energy expenditures with the measured value through the collection of expired air at exercise intensities similar to those found in women's hockey.

7.2 Cosmed K2 oxygen analyser

At the outset of this research it was envisaged that the K2 Cosmed oxygen analyser would be used to determine the errors in the use of heart rate and time motion analysis as methods of estimating energy expenditure in women's hockey. It was felt that this equipment would allow for the direct collection of expired air during simulated match play.

A validation and reliability study was carried out on the Cosmed K2 oxygen analyser (Appendix 5). This system in its present format was found to underestimate oxygen uptake at the workloads required for this study and was found to be a less reliable measure of oxygen uptake than the Quinton on-line system.

7.3 Methodology

7.3.1 Subjects

All 16 subjects, mean age 20.9 ±3.0 years, were female games players who competed at University level or above, and trained/competed 3 or more times per week. The heart rate - oxygen uptake regression equation was established as described in Chapter 4.

7.3.2 Intermittent treadmill activity

In order to allow for the continual collection of all expired air it was decided to use the treadmill in the laboratory to simulate movement intensities than a simulated match play in the field situation where the subject would have to wear cumbersome equipment and stop every 2 minutes to allow the Douglas Bags to be changed.

Each subject was given a 5 minute warm-up in which the treadmill speed was progressively increased up to the workload before her final workload when determining the heart rate - oxygen uptake regression equation (section 4.2.2). The subject then was allowed to stand for 2 minutes, during this period the subject put on a nose clip and inserted the mouthpiece. The tubing from the mouthpiece and breathing valve was connected to a two-way tap which allowed for the continual collection of expired air into Douglas Bags, the collection time for each bag was recorded. The treadmill, heart rate monitor, stop watch were started and the first Douglas Bag opened simultaneously.

A protocol was designed to replicate the heart rates and work : rest ratios found in women's hockey. A pilot study found that increasing the treadmill speed alone did not give a high enough intensity to elicit the type of heart rate response found in match play. As a result both the speed and gradient were increased for the periods of high intensity activity.

After each burst of high intensity activity, there followed a slightly longer period of low intensity activity which was either standing, walking or jogging. Expired air was collected continually for about 15 minutes.

The Douglas Bags of expired air were analysed as before. Heart rate was recorded every 5 seconds using a short range telemetry system (Sports Tester PE 3000) and all changes in treadmill speed and incline were noted.

The respiratory exchange ratio (RER) was calculated separately for each bag from $\dot{V}CO_2/\dot{V}O_2$. The kJ equivalent for each litre of oxygen at this RER was then multiplied by the total number of litres of oxygen in each bag, to give the energy cost for each bag. These were then summed to give the true total energy expenditure for the non-steady state protocol.

7.3.3 Energy expenditure from time-motion analysis.

Each discrete movement during the non-steady state protocol was ascribed an energy cost. The energy cost of standing was assumed to be 6.7 $kJ.min^{-1}$ (McArdle et al., 1986). For every subject each speed on the treadmill was assigned an energy cost which was calculated from the results of the heart rate regression equation protocol. The energy cost of running on a gradient at a given speed was calculated using an equation put forward by Heyward (1991).

The mean work : rest ratio for each subject was calculated by dividing a period of low intensity activity (standing, walking, jogging) by the preceding period of high intensity activity (running on the flat/gradient).

7.3.4 Treatment of data

The data in this study were assumed to be parametric in nature. Therefore, a paired sample t-test was used to test for differences between the estimations of energy expenditure and the measured value. The level of significance used was $p<0.01$.

7.4 Results

The raw data and analysis for subject A are presented in Appendix 6. The subjects' mean and standard deviation for $\dot{V}O_2$ max. was 45.3 ±6.3 $ml.kg^{-1}.min^{-1}$ with a range from 36.3 - 62.2 $ml.kg^{-1}.min^{-1}$, which demonstrates the wide range of aerobic fitness levels found in this group of female games players.

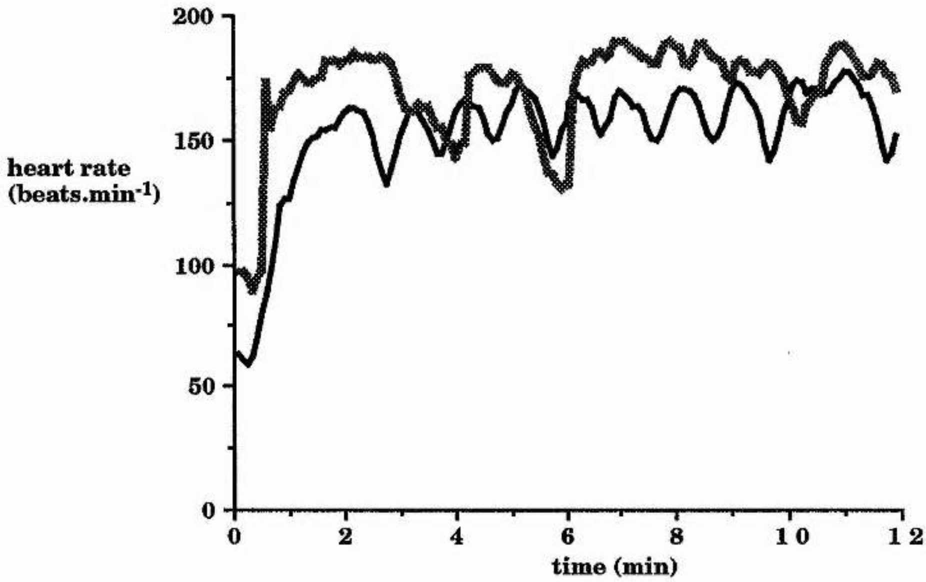
The mean heart rate response for all subjects was 169 ±8 $beats.min^{-1}$ suggesting that the treadmill protocol elicited similar heart rates to those found during match play. In Figure 7.1, the heart rate response for subject M during the intermittent treadmill protocol has been plotted against the heart rate recorded for the same subject during the first part of two hockey matches. This shows that the heart rate response on the treadmill demonstrates a similar pattern and falls within the range of heart rates found during match play.

The range of mean heart rates was 152-180 beats.min^{-1}, showing that although the protocol set individual work levels that aimed to produce a similar heart rate response for all subjects, this was not achieved. Differences in the mean heart rates can be explained partly by the fact that for some players their heart rate dropped much more rapidly during the recovery period than for others and for some subjects the heart response during the highest intensity activity was not as high as expected despite the player looking tired.

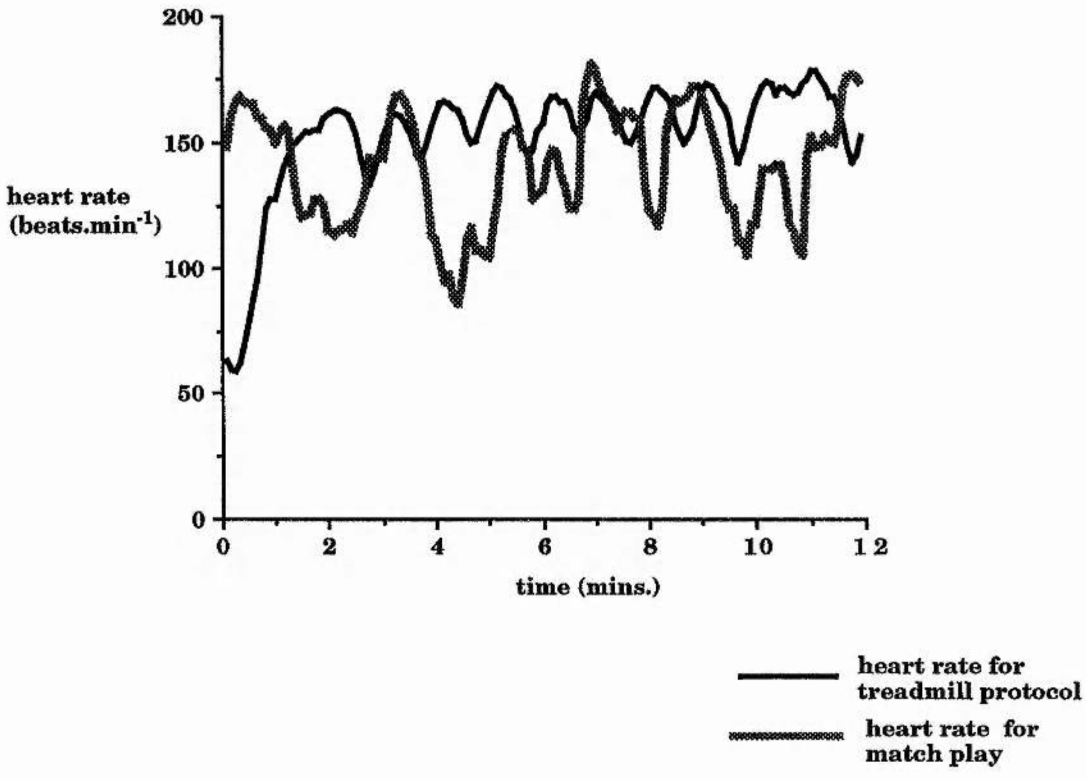
Table 7.1 shows the average energy expenditure (kJ.min^{-1}) for each subject from expired air, heart rate analysis and time-motion analysis. There was a significant difference between the estimate of energy expenditure from heart rate analysis when compared to the true value measured by expired air ($p<0.01$), a significant difference between time-motion analysis and the true value ($p<0.01$) and a significant difference between the heart rate analysis and time motion analysis estimations ($p<0.01$).

Table 7.1 shows that for all subjects the estimation of energy expenditure from movement analysis underestimates in comparison with the measurement from expired air, the mean underestimation was 16.6 ±4.8 % (7.6 ±2.7 kJ.min^{-1}). Subject E shows that in some cases there may be little difference between both methods 3.1% (1.2 kJ.min^{-1}). The greatest difference between the two methods is shown by subject P, this was 22.6% (11.4 kJ.min^{-1}).

Over the 15 minute period the calculation of energy expenditure from heart rate over-estimated by a mean of 3.7 ±5.1% (1.6 ±2.2 kJ.min^{-1}), in comparison with the true value measured from expired air. From Table 7.1 it can be seen that in 4 cases the heart rate method showed a slight underestimation, the maximum underestimation being 3.3%. With the exception of subject L (15.4% difference), all other estimations showed less than an 8.6% difference with six of the subjects showing a difference of less than 2%.



(i) more demanding match



(ii) least demanding match

Figure 7.1 Graph of heart rate for subject M during intermittent protocol, compared to the heart rate during two hockey matches of differing intensities

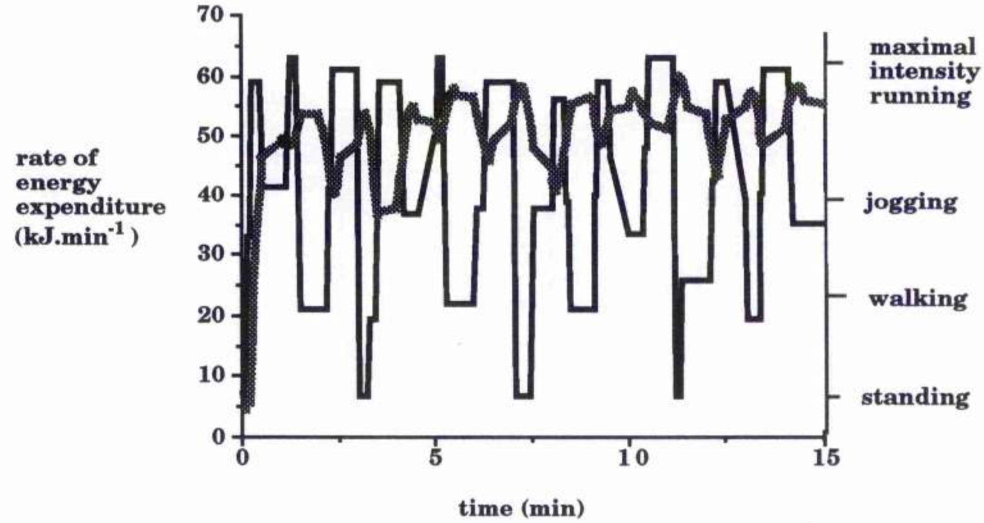
Table 7.1 **The average rate of energy expenditure ($kJ.min^{-1}$) estimated from heart rate and time-motion analysis and measured by the collection of expired air.**

Subject	Time-motion analysis ($kJ.min^{-1}$)	Heart-rate analysis ($kJ.min^{-1}$)	Measured value from expired air ($kJ.min^{-1}$)
A	38.66	49.73	47.60
B	38.23	45.58	46.42
C	40.94	48.08	49.14
D	40.39	53.88	49.62
E	35.86	35.79	37.02
F	35.59	43.03	43.39
G	35.53	45.34	44.76
H	32.51	37.17	36.75
I	33.58	42.40	40.31
J	37.67	44.53	44.34
K	33.08	42.76	39.57
L	33.05	42.78	37.08
M	41.00	54.67	51.36
N	35.50	49.25	45.89
O	40.40	52.77	48.75
P	39.83	51.29	51.23

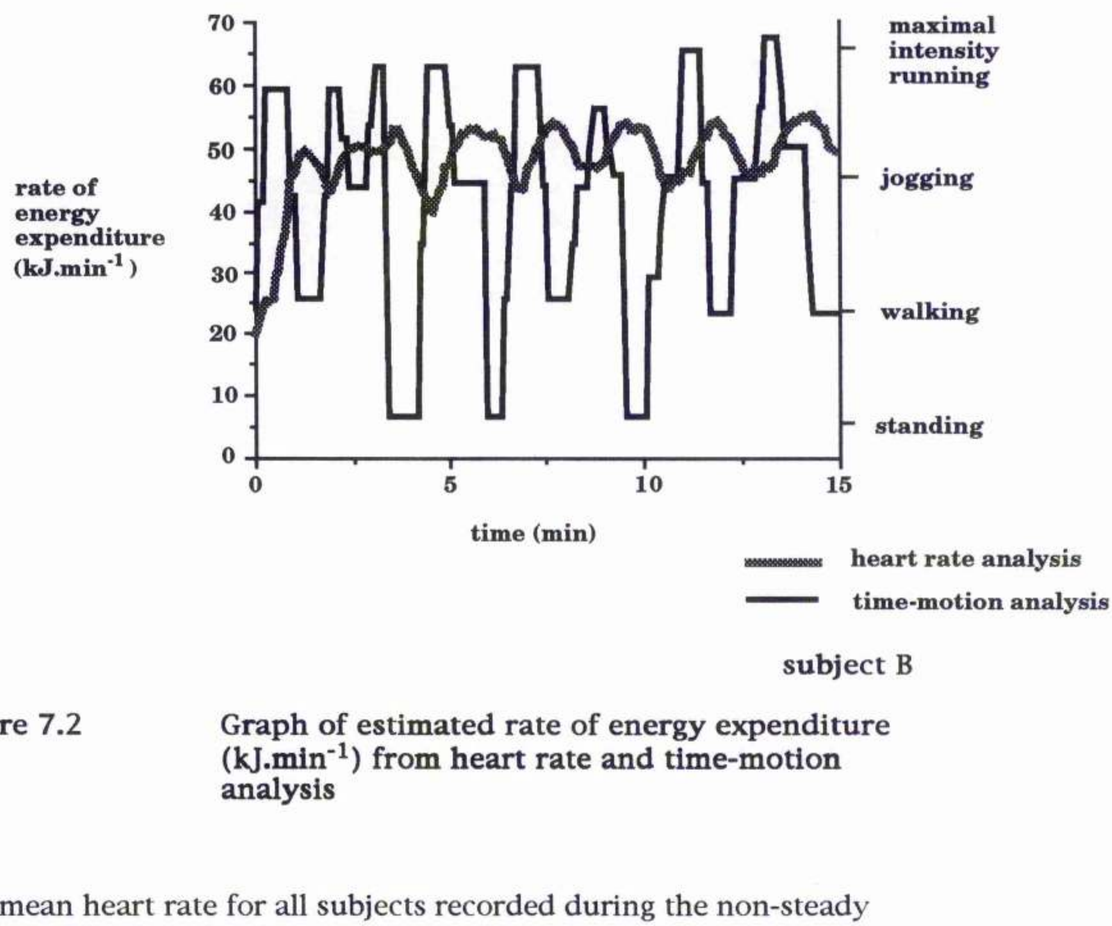
Figure 7.2 shows the rate of energy expenditure ($kJ.min^{-1}$) as estimated by both the heart rate and time motion analysis plotted against time for two subjects. It can be seen that the heart rate response lags behind the activity changes, e.g. heart rate is still increasing but treadmill speed has been reduced.

7.4 Discussion

The use of a motorised treadmill did not allow for the movement intensity to be altered quickly enough to replicate exactly the periods of high intensity activity found in women's hockey, e.g. it took between 5-10 seconds for the treadmill speed to reach the highest intensity workload from a walking speed. The subjects were unable to run fast enough on the treadmill to elicit game equivalent heart rates so increases in treadmill gradient were necessary.



subject A



subject B

Figure 7.2 **Graph of estimated rate of energy expenditure (kJ.min^{-1}) from heart rate and time-motion analysis**

The mean heart rate for all subjects recorded during the non-steady state protocol was 169 ±9 beats.min^{-1} which is similar to the mean value of 171 ±7 beats.min^{-1} recorded during women's hockey match-play (Chapter 3). It can be seen from Figure 7.1 that when the heart rate trace for subject M is compared to two heart rate traces obtained from her during hockey matches the treadmill protocol did produce a heart rate response similar to that found during match play. The main difference was that during the treadmill protocol the heart rate response was more regularised than that found in match play. The differences in the two heart rate traces for match play, shown in Figure 7.1, illustrate the wide variation in heart rate response for one player during two matches of the same competitive standard.

The mean work : rest ratio for all subjects was 1:1.7 which falls within the range of the most frequently occurring work : rest ratios found in women's hockey (Chapter 5). The mean length of each period of high intensity activity was 30.1 seconds which is much longer than the equivalent periods of high intensity activity found in women's hockey (mean value of 5.2 secs). Consequently, the periods of low intensity activity were also longer. This was unavoidable due to the mechanical restraints of the treadmill. However, there are periods of the game where these lengths of high and low intensity periods do occur although not as frequently as in this study.

The use of heart rate to estimate energy expenditure gave a mean difference of 3.7 ±5.1% when compared to the direct measurement from expired air. This is in agreement with Malhotra et al. (1963) who found a mean difference of 3.5%, but is lower than the differences suggested by Astrand and Rodahl (1986) of ±15% and Ballor et al. (1989) of +16%. Only subject L showed differences of these magnitudes. In these previous studies the heart rates were below 150 beats.min^{-1} which may have affected the heart rate oxygen - uptake relationship especially at heart rates less than 110- 120 beats.min^{-1} where maximum stroke volume may not have been attained (McArdle et al., 1986). In the study of Ballor et al. (1989), a source of error may have been the use of an on-line system to measure oxygen uptake, as the values were reported every minute and may not have been a true reflection of the actual energy cost.

Ogushi et al. (1993) study a difference of 26.7% between the estimation of oxygen uptake from the heart rate - oxygen uptake regression equation and the direct measurement of expired air in soccer. Whether a period of 2-3 minutes midway through each half can be used to measure the differences during a longer period of intermittent activity is unclear.

The 15 minute period of this study is not likely to be long enough for there to be any change in the heart rate - oxygen uptake relationship due to a reduction in the stroke volume and corresponding increase in heart rate which has been observed during prolonged exercise and is often attributed to dehydration (Astrand & Rodahl, 1986). This change in the heart rate - oxygen uptake relationship has been observed in women's hockey (Chapter 6) where there was a reduction in movement intensity but not in heart rate response during the second half. Whether this can be attributed to heart rate drift caused by dehydration or whether it is a result of an increase in oxygen uptake at specific workloads due to inefficient movement caused by fatigue is unclear. Consequently, the estimation of energy expenditure during the second half from heart rate analysis may be subject to a greater error when compared to the first half due to the change in the heart rate - oxygen uptake relationship.

The mean difference of 16.6 ± 4.84% between the estimation of energy expenditure from time-motion analysis and the true value measured from the collection of expired air is smaller than the difference of 43.7% observed by Ballor et al. (1989) between the two methods during simulated basketball match play. This type of study is very dependent on accurate estimates of the energy cost of each discrete movement. Since Ballor et al. (1989) ascribed energy costs to each movement from the literature, no allowance was made, for example, for differences in running economy, whereas in this study the energy cost of most movements was determined for each subject.

A second explanation is that the calculation of total energy expenditure during intermittent activity cannot be calculated from summing the individual components, and there is a significant additional energy cost associated with changing activity. This under-estimation caused by match analysis will be greater during match play as the activity changes more frequently than in this study, e.g. in team sports a player is involved in the region of 1000 changes of activity during a match (Bangsbo et al., 1991; Reilly & Thomas, 1976; Chapter 5). A slight additional energy cost involved in changing activity will make a significant contribution to the total energy cost. This is supported by Reilly & Borrie (1992) who stated that any energy expenditure in hockey based on the speed of locomotion will underestimate the actual energy cost.

From Figure 7.2 it can be seen that heart rate cannot be used to predict energy expenditure at a specific point in time as the heart rate response is slower and less extreme than the changes in activity. The energy cost of standing is between 5.4 - 6.7 kJ min^{-1} for the weights of females used in this study (McArdle et al., 1986), but if measured from the heart rate response when standing during the intermittent protocol the energy cost would be between 40-60 kJ.min^{-1} as a result of the oxygen debt caused by the preceding period of high intensity activity (Figure 7.2). Consequently, heart rate can be used to calculate the total energy expenditure but cannot be used to determine the individual rates of energy expenditure for specific tasks, especially low intensity tasks which form part of an overall high intensity activity.

In conclusion, heart rate analysis gives a better estimation of total energy expenditure during intermittent activity than movement analysis. However, time-motion analysis gives a better indication of the intensity of activity at a given point in the game. The mean error of 3.7% between the estimation from heart rate analysis and the true value of energy expenditure suggest that heart rate analysis is a valid method of estimating energy expenditure during match play.

Chapter 8

Discussion

8.1 Introduction

The preceding studies have outlined the physiological demands of women's hockey and estimated the errors in the methodologies used to determine these demands. The aim of this chapter is firstly to discuss these methodologies and their validity as tools for use in the real game situation. Secondly the findings of these studies in relation to the metabolic demands of women's hockey and the original research hypothesis will be discussed.

8.2 Measurement of heart rate during match play

The accurate measurement of heart rate during "multiple-sprint" sports assumes that the equipment used is reliable and valid. Throughout this study the Sport Tester PE3000 heart rate monitor was used as it has been found to give values within 2 beats.min^{-1} of a simultaneous ECG telemetry system (Ali & Farrally, 1991) during a soccer match. In Chapter 4 the Sport Tester PE3000 was found to be reliable means of measuring heart rate during match play, with a loss of data in approximately one in five matches monitored. The remaining data sets were assumed to be an accurate measure as they did not contain obviously corrupt data. Other assumptions made in the measuring of heart rate are that the heart rate measured every five seconds is a good measure of the actual heart rate, that the heart rates observed during match play are caused by purely physiological responses to the work intensity and that the steady state heart rate - oxygen uptake regression equation can be applied to "multiple-sprint" activity. These assumptions will now be discussed in greater detail.

8.2.1 Measurement of heart rate every five seconds

Throughout this study, it was assumed that the heart rate recorded every five seconds was a good measure of the actual heart rate during match play. The plot of heart rate against movement intensity (Figure 7.2) shows that the heart rate response is much slower in relation to the corresponding changes in movement intensity. In tennis singles Elliot et al. (1985, in Reilly, 1990) found a higher mean heart rate of 153 beats.min^{-1} between points than during the rallies (150 beats.min^{-1}) showing the delayed response of heart rate. During supramaximal cycle ergometry, Yamaji & Shephard (1987), found that heart rate continued increasing for several seconds after the cessation of exercise, these increases were found to be greater as the load increased. Heart rate increased by between 4.9 and 6.6% during the recovery period from the peak value at the end of exercise. From Figure 7.3, it can be seen that there is a heart rate overshoot for both subjects A and B, the heart rate of subject B reached a plateau before dropping at the cessation of exercise whereas for subject A the heart rate peaked and then dropped. Bunc et al. (1988) found that $\dot{V}O_2$ max. was negatively correlated to t1/2 (the half time of heart rate response to the onset of constant exercise and the cessation of exercise) showing the aerobically fitter player has a faster heart rate response to an increase in exercise intensity. Bunc et al. (1988) also suggested that this heart rate response is slower if the increase in exercise intensity takes place at already elevated heart rates. The maximum oxygen uptake for subject A was 46 $ml.kg^{-1}.min^{-1}$ compared to 36 $ml.kg^{-1}.min^{-1}$ for subject B, which might explain the differences in the heart rate response for the two subjects. This highlights the problems of comparing heart rate response for several players without relating to oxygen uptake as it is not necessarily the player doing least work who will have the either the largest fluctuations in heart rate or the lowest mean heart rate. For example for two subjects of differing aerobic fitness performing the same "multiple-sprint" activity, the subject with the greater aerobic fitness will show greater fluctuations in heart rate and the lower mean heart rate.

8.2.2 Heart rate as a measure of physical load in competition.

One of the major assumptions in this project has been that the heart rates measured in the match situation are a physiological response and not, as it has been suggested, that psychological factors are the cause of the high heart rates found in match play (McArdle et al., 1971). A study by Holmyard et al. (1988) where 10 rugby players repeated ten 6 second sprints with either a 30 or 60 second recovery obtained heart rate responses in the range of 160-188 $beats.min^{-1}$ during the sprints and recovery, which are very similar to the heart rates recorded in this study during women's hockey match play. In a study using "multiple-sprint" activity at intensities similar to soccer Nevill et al.

(1993) observed a range of mean heart rates from 178 ±9-183 ±11 beats.min^{-1}. This would suggest that the heart rates obtained during hockey match play could be obtained from physiological work intensity alone, with the psychological factors being overridden by the physiological response. These studies would support the view that the high mean heart rate observed during "multiple-sprint" sports are a true reflection of the physiological workload due to the fact that the recovery periods between periods of high intensity activity are not long enough to allow the heart rate to drop significantly.

Tumilty et al. (1993) observed mean heart rates of 173 beats.min^{-1} (87% of the subject's maximum heart rate) during four 5-minute periods of simulated soccer match play. The heart rates observed during the simulation were similar to those observed during actual match play, supporting the suggestion that the high heart rates found during multiple-sprint sports are caused by the physiological demands.

8.3 Time-motion analysis as a measure of physical load in competition.

It has been previously stated that in soccer a player's pre-game glycogen levels are related to the amount of time spent in high intensity activity (Saltin, 1973). During the time-motion study there was no control over players' dietary intake before matches. Therefore some of the differences between the time spent in high intensity activity or total energy expenditure may be a result of varying levels of glycogen stores rather than as a result of their aerobic fitness or the demands of the game.

This time-motion study has given a good indication of the nature of women's hockey and the range of physical demands placed on players at National League level. The range of match results show that despite selecting matches of a similar competitive level, these were not always evenly contested. Consequently, the results of the time-motion analysis were to a large extent influenced by the outcome of the match and as a result the findings in relation to positional differences should be treated with caution. It may be that there are positional differences when identified in terms of right and left sided players. The number of players used in this study did not allow for this to be examined.

8.4 Measuring the metabolic demands of women's hockey

The studies in Chapter 5, 6 and 7 which observed the relationship between a time-motion analysis and a heart rate analysis, identified a number of factors which would suggest that in order to obtain a comprehensive picture of the metabolic demands of women's hockey both techniques should be applied simultaneously.

8.4.1 The uses of heart rate and time-motion analysis

The observation of heart rate allows for comparisons to be made of player stress over several matches (Figure 3.1). This may be used to compare the differences in, for example zone, compared to man-to-man marking or playing in a different formation. A graph showing a large fluctuation (Figure 3.1 (iv)) around the mean would suggest that the player has time to recover between periods of high intensity activity whereas a small fluctuation around a high mean heart rate would suggest that the player is under constant stress (Figure 3.1 (i), the first half). Heart rate, however, cannot be used as an indication of fatigue as this research has shown that despite heart rates remaining similar during the first and second halves, the amount of time spent in high intensity activity declined. Also, as has been previously stated heart rate can also be used to give a good estimation of total energy expenditure.

Movement analysis monitors exactly the workload on a player at any given point in a match whereas heart rate analysis gives a more general outline of the most stressful periods of the game, the delayed response of heart rate in relation to changes in movement intensity (Figure 7.3) identify the problems of using heart rate to indicate movement intensity or energy expenditure at specific points during the match.

8.4.2 The errors in the use of heart rate and time-motion analysis as an estimation of energy expenditure

The null-hypothesis that "For each player, during match play there is no significant difference between the estimation of energy expenditure from heart rate and time-motion analysis" was rejected, this raised the question of which of the two techniques was the more valid measure of energy expenditure in "multiple-sprint" activity. The study in Chapter 7 was used to test the null-hypothesis, which stated that "During intermittent activity on the treadmill, there is no significant difference between the use of heart rate to estimate energy expenditure and the measurement of energy expenditure from the collection of expired air". Although this hypothesis was rejected ($p<0.01$), the errors in the use of heart rate were in the region of $3.7 \pm 5.1\%$, which shows that this methodology can be used to give a good measure of energy expenditure during multiple-sprint activity. These differences are much smaller than the errors suggested by previous studies in "multiple-sprint" activity (Ballor et al., 1989; Ogushi et al., 1993), the larger errors found in these studies may have been caused by the methodologies adopted (see 2.2.3) rather than actual differences. Heart rate analysis has been found to be a non-obtrusive method of measuring the energy expenditure of players during "multiple-sprint" activity.

The use of heart rate will result in a slight over-estimation of total energy expenditure for the majority of subjects, but it can now be assumed that the rate of energy expenditure estimated for women's hockey in Chapter 4 from heart rate analysis is a good indication of the actual energy expenditure in women's hockey. As the individual errors for each subject will be slightly different, the comparison of the rate of energy expenditure between subjects should be used with caution.

In order to determine whether time-motion analysis could be used to estimate energy expenditure the following null-hypothesis was tested "During intermittent activity on the treadmill, there is no significant difference between the use of time-motion analysis to estimate energy expenditure and the measurement of energy expenditure from the collection of expired air". This hypothesis was rejected. There were large errors associated with this method 16.6 ± 4.84 % in the treadmill study in Chapter 7. It is probable that these are even greater in the field situation where it is more difficult to determine the true energy cost of specific activities. This study has shown that due to the additional energy requirements of changing activity, acceleration and deceleration, it cannot be used to accurately estimate energy expenditure. This is in agreement with Reilly & Borrie (1992) who suggested that the use of time-motion analysis to estimate energy expenditure during hockey match-play will underestimate the true value.

Using heart rate and time-motion analysis simultaneously will provide a greater understanding of the physiological stress placed on players during "multiple-sprint" sports. Heart rate analysis to measure a players energy expenditure and the physiological stress she is under, movement analysis to measure the work rate in terms of contribution to the game and the work: rest ratios. It must be remembered, though, that the measurement of both energy expenditure and work rate only tell us a player's physical contribution to the game. Neither of these analysis determines the player's effectiveness.

8.4.3 The relationship between energy expenditure and movement intensity

There was a good correlation between the energy expenditure estimated from both heart rate analysis and time motion analysis when expressed in relation to body weight and high intensity activity (r=0.80 and r=0.71 respectively). However this correlation was reduced when energy expenditure was expressed as $kJ.match^{-1}$ (r=0.55 and r=0.44 respectively). This demonstrates the effect of a player's weight on total energy expenditure, consequently the use of energy expenditure adjusted for body weight should be used to compare players and the rate of energy expenditure between sports. A second factor affecting total energy expenditure will be efficiency, for example in the study in Chapter 6 subject A had an energy cost of running at 12 $km.h^{-1}$ of 0.97 $kJ.kg^{-1}.min^{-1}$, whereas subject F had an energy cost of 0.90 $kJ.kg^{-1}.min^{-1}$ for the same workload. This would suggest that total time spent in high intensity activity is a better indication of a players contribution to the game rather than work rate expressed in $kJ.kg^{-1}.min^{-1}$ as although there is a good correlation between the two indices, a less efficient player may appear to have a higher work rate than a more efficient player.

8.4.4 Fatigue during the second half

The results of the study in Chapter 4 accepted the null-hypothesis that "There is no significant difference between the energy expenditure (estimated from heart rate analysis) for the first and second halves." However, the null-hypothesis which stated that "There is no significant difference between the energy expenditure (estimated from time-motion analysis) for the first and second halves" was rejected. From the time-motion analysis (Chapter 5) it can be seen that players spend less time in high intensity activity during the second half. In contrast, the heart rate analysis would suggest that players have a similar work rate in the first and second halves. The similar heart rates during the second half may have been caused by a change in the relationship between heart rate and oxygen uptake at given workloads. If this is the case then heart rate would not be a good estimation of energy expenditure during the second half. This changing relationship has been observed in endurance activity (Astrand & Rodahl, 1986) and is referred to as heart rate drift. An alternative explanation might be that as the player becomes fatigued during the second half and her movements become less efficient, then the oxygen cost of specific activities will increase. In this case the estimation of energy expenditure during the second half can be obtained from heart rate as the heart rate would reflect the increased oxygen cost of each activity. Hence a drop in the quantity of high intensity work may not necessarily equate to a drop in energy expenditure if the energy cost of each activity increases.

8.5 The metabolic demands of women's hockey

The metabolic demands of women's hockey have been estimated in this study to range from 40.1 $kJ.min^{-1}$ to 64.4 $kJ..min^{-1}$ or a total energy expenditure of 2806-4508 $kJ.match^{-1}$. These values firstly identify the high rates of energy expenditure during top level women's hockey and secondly the range of demands on players. These studies were conducted during National League matches so it is likely that at international level the energy requirements and the intensity of the game will be even greater. The presence of ball boys/girls means that the ball is replaced immediately it leaves the pitch, so reducing stoppage time. The greater aerobic fitness found in studies on National Squads (Canadian national squad 59.3 $ml.kg^{-1}.min^{-1}$ Ready & van der Merwe (1986/87); Welsh national squad, 54.5 $ml.kg^{-1}.min^{-1}$, Reilly & Bretherton, (1986)) would suggest that players at National level are capable of sustaining play at a high intensity for longer than that observed in this study.

8.5.1 Positional requirements

The null-hypothesis that "In women's hockey, there is no significant difference in the energy expenditure (estimated from heart rate) in relation to position played" was accepted. No positional differences have been found in either the time-motion analysis or the estimation of energy expenditure from heart rate. This is in contrast to the findings in soccer where midfielders have been found to have higher energy expenditures (Ali & Farrally, 1990) and to cover greater distances (Reilly & Thomas, 1976) than both strikers and defenders. This would suggest that differences in both energy expenditure and work rate during women's hockey match play are determined to a large extent by individual factors for, example, body weight, efficiency and aerobic capacity rather than by positional requirements. This questions the recommendations of Cooke (1985) and Aitken & Thompson (1988) who both suggested that hockey players should follow individualised training programmes, both stating that midfielders should concentrate on the development of the aerobic system. Aitken & Thompson (1988) suggested that this should also be the emphasis for defenders, whereas Cooke (1985) suggested that defenders should emphasise the training of the anaerobic systems. The results in Chapter 5 of the time motion analysis suggest that all players need to develop the ability to reproduce sprinting speed which has been related to aerobic capacity (Tumilty et al., 1993) .

8.5.2 Range of metabolic demands for individual matches

The null-hypothesis that "In women's hockey, there is no significant difference in the total energy expenditure (estimated from heart rate) for one player over several matches" was rejected. This shows that despite competing in matches of a similar competitive level players may be subjected to differing workloads. This has implications for the players from the stronger teams as there may be several weeks where they play at a reduced work rate and are then required to play at a greater intensity against a team of similar standard.

The range of energy expenditures found for the least and most demanding matches for each subject in Chapter 4 (difference 2.2-26.4%), identifies the problems of using an analysis of a single match to observe the physiological demands of "multiple-sprint" sports. Players monitored in a single match may show significant differences in total energy expenditure and time spent in high intensity activity and this may not be a good measure of the metabolic demands placed on the player throughout the season.

The time-motion analysis in Chapter 5 monitored a single match for each subject, consequently the results of this study must be treated with caution as the results might represent the most, least or mean workload for the season for each subject.

8.5.3 Aerobic fitness

The null-hypothesis that "There is no correlation between a player's aerobic power and the time spent in high intensity activity" was rejected. The correlation of 0.72 found in Chapter 5 between the time spent in high intensity activity and a player's $\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$) suggests that to a certain extent the player's work load during the game is related to her aerobic fitness. The importance of aerobic fitness for performance in "multiple-sprint" sports was emphasised by Tumilty et al. (1993) who found a significant negative correlation between the decrement in sprint performance (for multiple sprints during simulated match play) and a player's $\dot{V}O_2$ max. Tumilty et al. (1993) study found no correlation between a players single sprint time or anaerobic capacity and "multiple sprint" performance, implying that the ability to reproduce speed is of more importance than maximum speed for performance in "multiple-sprint" sports.

8.6 Comparison with other "multiple-sprint" sports

The application of training programmes from one sport to another is only valid if the physiological demands of both sports are similar. Reilly & Borrie (1992) suggested that fitness training programmes developed by soccer players may be applied to the conditioning of hockey players. The results of this study will now be compared both with studies in hockey and studies in other "multiple-sprint" sports. This will determine whether National League women's hockey has similar physiological demands to other levels of hockey and to other "multiple-sprint" sports.

8.6.1 Energy expenditure

In order to compare the rate of energy expenditure directly with values esimated from different sports by other researchers, the rate of energy expenditure has been presented in the form of $kJ.kg^{-2/3}.min^{-1}$ to allow for differences in body weight (Nevil et al. 1992). From this study the mean energy expenditure of women's hockey is in the region of 3.18-3.55 $kJ.kg^{-2/3}.min^{-1}$ (means of least and most demanding matches for all subjects), the range being 2.49-4.00 $kJ.kg^{-2/3}.min^{-1}$. These values are all greater than the values reported for hockey in the literature, the exception being the value estimated by Skubic & Hodgkins, (1967) of 2.57 $kJ.kg^{-2/3}.min^{-1}$ for women's hockey and 2.87 $kJ.kg^{-2/3}.min^{-1}$ (Malhotra et al., 1983) for men's hockey on Astroturf, both of which fall into the bottom of the range found by this study and below the mean of the least intense games for all subjects. This suggests that hockey is now played at a greater intensity than previously documented.

In comparison with other "multiple sprint" sports , McArdle et al. (1971) found a mean energy expenditure of 2.44 $kJ.kg^{-2/3}.min^{-1}$ for women's collegiate basketball, with a maximum mean energy expenditure of 3.16 $kJ.kg^{-2/3}.min^{-1}$, Skubic & Hodgkins (1967) found a slightly lower energy expenditure of 2.13 $kJ.kg^{-2/3}.min^{-1}$, both these values were estimated from heart rate. This would suggest that despite women's basketball having fewer players which might suggest greater involvement in the game, the work rate was actually lower than that found for women's hockey.

In soccer, Ali & Farrally (1990) found a mean energy expenditure of 2.64 $kJ.kg^{-2/3}.min^{-1}$ for semi-professional soccer players estimated from heart rate, which is lower than that reported Reilly & Thomas (1979) of 4.17 $kJ.kg^{-2/3}.min^{-1}$ for professional soccer players. The mean rates of estimated energy expenditure observed in this study for women's hockey (3.18-3.55 $kJ.kg^{-2/3}.min^{-1)}$. suggest that the range of energy expenditure for women's hockey falls within the values estimated for soccer.

The differences between the values obtained by Ali & Farrally (1990) and Reilly & Thomas (1979) show the range of energy expenditure that might be expected within competition at different levels within the same sport. Although the differences observed by Ali & Farrally (1990) between semi-professional and recreational players of 2.64 and 2.39 $kJ.kg^{-2/3}.min^{-1}$ respectively are not as great as those between the studies of Reilly & Thomas (1979) and Ali & Farrally (1990) for professional and semi- professional players. This suggests that the energy costs of professional soccer is much greater than other levels of competition.

The method used by Ali & Farrally (1990) involved the use of the Leger 20 m shuttle test (Leger & Lambert, 1982) to establish the heart rate oxygen uptake regression equation. It is doubtful whether this is as valid as measuring actual oxygen uptake at steady state workloads on the treadmill, as the time delay in the heart rate response to increasing workloads may have led to errors in the slope of the regression equation. Also, a player's running efficiency will govern his oxygen uptake at a specific running speed. Hence the values obtained by Reilly & Thomas (1979) are likely to be the better estimation of energy expenditure during soccer match play. Consequently, it can be concluded that, the majority of women's hockey is played at a lower rate of energy expenditure than professional soccer.

8.6.2 Movement analysis

The percentage of total time (21.9%) spent in high intensity activity during women's hockey match play is considerably greater than that observed during soccer matches of 0.4% (Brodowicz et al., 1990), 8.1% (Bangsbo et al., 1991) and 10.4% (Ohashi et al., 1993). This would suggest that women's hockey has a higher work rate than that found in semi-professional and professional soccer. However the comparison of studies which used different methods and different criteria for categorising high intensity activity must be treated with caution. Both sports need to be analysed using the same methodology before the true differences in the intensities can be identified.

The mean duration of each sprint in women's hockey was found to be 3.13 ± 0.31 seconds, which is within the range of mean lengths sprints reported by Brodowicz et al. (1990) in soccer of 0.67 ± 0.99 seconds for defenders and 3.38 ± 2.28 seconds for strikers and slightly greater than the values reported by Bangsbo et al. (1991) of 2.1 seconds. These values would suggest that the majority of sprints in women's hockey are similar to those found in soccer. The frequency of sprints in soccer is much less than those observed in women's hockey (75 ± 19.9) if the findings of Bangsbo et al. (1991) of a mean of 19 sprints per match are used. However, the distance-motion study of Reilly & Thomas (1976) on professional soccer players found a mean of 62 ± 15 sprints per match showing that in some cases soccer players will have to make as many sprints as hockey players. Whereas hockey players will have to sprint on average once every 60 seconds, soccer players sprint in the region of once every 90 seconds (Reilly & Thomas, 1976), suggesting that hockey players should train to improve speed endurance at greater intensities than soccer players..

Chapter 9

Implications for further research and the training of women hockey players

9.1 Analysis techniques

The methodology used in this study for time motion analysis is very labour intensive making it impractical for collecting an extensive range of data, for example the range of physical demands on a player throughout a season or the difference in intensity of matches at differing levels. It also cannot be used for immediate feedback where a coach wants to identify players' contributions during a specific match. Developments in computer systems now allow for this information to be inputted during real match time (Ali & Farrally, 1991; Hughes, 1993), either directly or from a video recording, but for each player analysed the time taken to input the data is still equivalent to the length of the time of the match.

In this study it was found necessary to film players individually as there were no pitches which had suitable vantage points to situate one or several cameras to film the whole pitch. This again increases the amount of labour required for this type of analysis, and the number of players which can be analysed during a single match is restricted by the number of cameras and operators available. Even more complex methods of time-motion analysis such as that developed by Ohashi et al. (1988) using two video cameras with potentiometers which were linked to a computer system are still labour and equipment intensive. Consequently, until a method is developed which is less labour intensive it is unlikely that time-motion analysis will be used extensively in multiple-sprint sports by coaches.

The analysis of heart rate was found to be a non-invasive technique for estimating energy expenditure during team sports. However, it is unlikely that this type of analysis will be adopted by hockey players / coaches in the near future. Reasons for this are firstly, the cost of both laboratory facilities to establish the heart rate - oxygen uptake regression equation and the cost of heart rate monitors. As women's hockey in Britain is still very much an amateur sport struggling to attract major sponsorship, there is little extra money available for this type of work. Another reason is that the total energy expenditure for each match is not a necessary factor in determining training loads or assessing match performance (this is supported by the low correlation between a player's time spent in high intensity activity and total energy expenditure), it may be that heart rate data may be more useful in assessing the demands placed on individual players over several matches.

A major time consideration in the heart rate monitoring methodology was the transference of data from the Sport Tester package on the BBC computer into IBM format for statistical analysis. Recent developments in the Sport Tester PE 3000 and similar short range telemetry systems now allow for the data to be downloaded directly into an IBM compatible computer and then exported in ASCII format to the appropriate statistical package. This allows the heart rate data to be analysed almost immediately, giving feedback on the intensity of the game.

Recent developments also allow for the recording of beat to beat heart rate for up to 4 hours (Heart rate Recorder BHL-6000). This means that the rate of change of heart rate during non-steady state activity could be more closely analysed.

9.2 Future research in "multiple-sprint" sports

The methodologies employed in this research could be applied to the other "multiple-sprint" sports. This would allow for a direct comparison to be made between the metabolic demands. A greater insight into, for example, the relationship between aerobic power and work rate, the work : rest ratios and differences in work rate at different levels of competition could also be gained. In order to further determine the physiological nature of "multiple-sprint" sports, the relationship between oxygen uptake and heart rate in the non-steady state needs greater understanding. The factors affecting the onset of fatigue during the second half also need investigating.

9.2.1 Energy expenditure during match play

The use of Douglas Bags to collect expired air in Chapter 7 meant that the total energy expenditure estimated from the heart rate oxygen uptake regression equation could be compared with the energy expenditure measured from the collection and analysis of expired air.

However, this method does not allow for a comparison between the rate of change of oxygen uptake and heart rate during "multiple-sprint" activity, the use of the treadmill restricting the type of activities which could be used. The Cosmed K2 portable analyser would allow for the heart rate measured every 15 seconds to be compared with the oxygen uptake at this time, and would allow more information to be gained about the use of heart rate to measure energy expenditure in the non-steady situation. The relative freedom that the Cosmed K2 allows means that it could be used in a simulated match situation allowing for oxygen uptake to be measured under similar intensities to match play. Further developments in the technology of the Cosmed K2 and refinements to the face mask suggest that it may become a more accurate measure of oxygen uptake than was found during this research (Appendix 4).

9.2.2 The energy expenditure of whole matches

The estimation of energy expenditure from time-motion analysis suggested that there was a significant difference in energy expenditure between the first and second halves, whereas the estimation of energy expenditure from heart rate analysis suggested that there was a similar energy expenditure for each half. Two explanations have been put forward for these differences, firstly as a player fatigues the energy cost of each activity increases through inefficient movements, hence the energy cost of a specific activity would be greater in the second half. An alternative explanation is that the heart rate - oxygen uptake relationship changes in a manner similar to that observed in prolonged endurance activity, possibly through dehydration (Astrand & Rodahl, 1986). This results in a higher heart rate for a given oxygen uptake which would mean that the use of the heart rate - oxygen uptake regression equation would over- estimate energy expenditure in the second half.

In order to determine which of or if a combination of these factors is responsible for the differences in the estimation of energy expenditure during the second half, it would be necessary to repeat the heart rate oxygen uptake regression equation protocol immediately after a match. This would establish whether the oxygen uptake heart rate regression equation was the same under both conditions.

9.3 Individual work rates in women's hockey

The results of the heart rate analysis and time-motion study have identified the metabolic demands of women's hockey in National League matches for players of National Squad standard. The metabolic cost of other standards of women's hockey are likely to differ from these values. As Ekblom (1986) reported in soccer, the higher level of competition was associated with more time spent in high intensity activity. Ekblom also suggested that players work at a similar percentage of their maximum oxygen uptake (80%) regardless of the level of competition, suggesting that players at a higher competitive level have an increased aerobic fitness. In order to determine whether this is in fact the case in women's hockey, it would be necessary to complete both heart rate and time-motion analyses on district league games and international matches. The results of these studies could also be used to validate the relationship between $\dot{V}O_2$ max and work intensity during the match as these studies are likely to produce a greater range of $\dot{V}O_2$ max values and times spent in high intensity activity.

Both the time-motion study and heart analysis identified no positional differences in terms of time-spent in activity, work : rest ratios, nature of heart rate response or rate of energy expenditure. Whether this is true at lower levels of competition where players tend to have more specific "positions" is unclear.

The lack of positional differences in all variables measured and the range of energy expenditures for individual subjects over a number of matches suggest that the standard of opposition is one of the major factors determining the metabolic demands of the match. This is, however, not the only factor influencing the work rate as the good correlation between the time spent in high intensity activity and maximal aerobic capacity showed that aerobic fitness is also a factor in determining the work rate which a player can maintain. This would suggest that aerobic conditioning should be emphasised in training.

9.4 The training of women hockey players

The results of the studies described here have practical implications for the training of women hockey players. The training of players in all "multiple-sprint" sports is complex, as there is an interaction between the different energy systems. Although players may need to develop all aspects of fitness, including endurance (cardiovascular and muscle) strength, speed, power and flexibility. This next section will focus only on the areas that have been identified by this research.

9.4.1 Aerobic training

The relationship between aerobic power and the time spent in high intensity activity demonstrated the importance of aerobic fitness to hockey players. The players in this study had a mean $\dot{V}O_2$ max of 49.9 ± 4.5 $ml.kg^{-1}.min^{-1}$ (Table 3.1) which is similar to the value found by Cheetham & Williams (1987) of 50.1 ±4.1 $ml.kg^{-1}.min^{-1}$ for English county players but is much lower than the value reported for the Canadian squad (59.3 $ml.kg^{-1}.min^{-1}$) prior to the 1984 Olympic games (Ready & Merwe., 1986/87). The differences between the players in this study and the Canadian players suggests that a greater emphasis should be placed on the development of the aerobic capacity of Scottish squad players. The lack of positional differences found in this study, in respect to the metabolic parameters measured, suggests that all players need to place the same emphasis on aerobic training.

9.4.2 Speed-endurance training

The mean number of sprints found in women's hockey match play was 75 ±19.9, with a mean work : rest ratio of 1:5.7 and the mean length of each sprint being 3.13 ±0.31 seconds. These values show that players are required to reproduce sprinting speed over a large number of repetitions. As stated in Chapter 5 there is limited research into the most effective means of training speed-endurance for players in "multiple-sprint" sports. In order to create an overload effect players should train at a greater intensity than that found in match play. As one of the aims of the training session should be to develop the ability to maintain sprinting speed towards the end of the match, the intensity of the work : rest ratio should not be so great that sprinting performance significantly declines by the end of the set. Recovery between sprints should vary to include standing/walking/jogging and backwards/sideways movements; sprints should be initiated from each of these activities. The emphasis should be on maintaing sprinting quality towards the end of the session.

9.4.3 Dietary requirements

The energy requirements of women's top level hockey may be much greater than previously reported. This intensity of exercise implies that muscle glycogen could affect performance, similar to the situation found in football (Ekblom, 1986; Kirkendall et al., 1988). The need for fully replenished glycogen stores before a match or training through a high carbohydrate diet must be emphasised with players.

Players should also be made aware of the decrement in performance through dehydration. Although Shephard & Leatt (1987) have stated that this should only be a problem during warm conditions as players can consume up to a litre of fluid in the course of a match. From the video recording from the time-motion analysis it can be seen that the only time players drink is at half-time. It is unlikely that during this period enough fluid is replaced to maintain performance during the second half. Players should be educated in the need to ingest a carbohydrate drink just prior to the start of the match, at half time and when there are any stoppages during the match.

9.5 Conclusions

This research has shown that the use of individual heart rate - oxygen uptake regression equations gives a good estimate of energy expenditure in "multiple-sprint" sports. Provided energy expenditure is expressed in relation to body weight ($kJ.kg^{-2/3}.min^{-1}$), this method of heart rate analysis can be used as a means of comparing the metabolic demands either between players in the same sport or different sports.

Time-motion analysis was found to underestimate the true energy cost of "multiple-sprint" sports and as a result this method cannot be used to estimate energy expenditure. This form of analysis is required to establish the nature of the activity and the work : rest ratios of the sport as these cannot be determined from heart rate analysis.

Women's hockey was found to be played at a higher metabolic rate than previously reported This can be attributed to a number of factors including changes in playing surface and an increase in the amount of training and level of competition since these earlier studies.

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Appendices

Appendix 1

Pilot work for heart rate methodology.

A1.1 Introduction

The aim of these studies was to determine whether it was practical to use a short range telemetry system (Sport Tester PE 3000 heart rate monitor) to record heart rate in women's hockey during National League matches and whether more than one player could be monitored at once as this is unclear from previous studies. Ali & Farrally (1991) found that due to interference between monitors only one player could be monitored per match, whereas the study by Rhode & Esperson (1988) suggested that it was possible to monitor more than 1 player per match. The maximum range of the short range telemetry system is 1.5 metres so players must come within this distance to cause interference.

The Sport Tester PE 3000 was used to record heart rate as it has been found to be one of the most valid and accurate heart rate monitors available (Leger & Thivierge, 1988). The use of this heart rate monitor has been validated during soccer match play (Ali & Farrally, 1991) against a standard ECG telemetry system. The memory space of the watch receiver allows for the recording of heart rate data every five seconds for up to eighty minutes. This memory space enables the continual monitoring of heart rate throughout a hockey match (seventy minutes match play plus five minutes half-time).

A1.2 Methodology

In pilot study A, two players were monitored continually during three friendly matches each, and in pilot study B, three players were monitored during the same friendly match. Pilot study C, involved one of the players from pilot study A, being monitored in a National League game. It was decided that the best way of carrying receiver watch was to remove the strap and place the watch in the pocket of the players skirt where it was least likely to be damaged. In order to use the five second recording mode on the receiver watch it was necessary to start the watches within 2-3 minutes of the start of the match as the maximum storage space in the watches memory for five second recordings is 80 minutes.

A1.3 Results

Five complete sets of data were recorded in study A, in the other game some of the data points were lost, possibly due to a loss of contact between the skin and the electrodes, corrupt data was identified as being either zero values or eight constant values.

In study B, there appeared to be no interference between the systems , with two complete sets of data being recorded and an incomplete data set from the third. Observation of this incomplete data set showed two periods with zero values, which were most likely to have been caused by a loss of contact between the electrodes and the skin.

In study C a complete set of data was recorded for the player during a competitive match

A1.4 Discussion

As the data loss in studies A and B appeared to have been caused by a loss of contact between the skin and the electrodes it was decided to use electrode gel to increase the conductivity between the two.

From study B, it was decided that the nature of women's hockey would allow several players to be monitored during one match. If the situation arose where two subjects were likely to be marking each other then only one of these player was monitored.

In study C, one of the subjects monitored in a friendly match was then monitored during a National league match, she found little inconvenience in being studied in the competitive situation.

From Figure 3.1 of heart rate traces during match play, it can be seen that it is difficult to define exactly the length of each half. This meant that the time of each half had to be measured in conjunction with the starting of the heart rate monitor.

It was decided that it was feasible to monitor women's hockey during competitive match play without affecting the subjects performances, but that the subjects needed to be familiarised with the heart rate monitors during training sessions. It was also assumed that the nature of the monitoring equipment was likely to lead to some loss of data.

Appendix 2

Computer program for transferring heart rate data.

A2.1 Computer program

The following method was used to transfer the heart rate data stored in the receiver watch of the Sport Tester PE3000 heart rate monitor, to a statistical package (Minitab) on an IBM compatible computer.

The Sport Tester PE3000 programme only allowed for data to be downloaded into a BBC computer through the Sport Tester PE3000's own software package. In order to save the data outwith this programme in a spooled format the following procedure was completed. The Basic system was entered on the BBC computer and the Sport Tester PE3000 software disc put into drive 0, the disc on which the heart rate data was to be saved, was put into drive 1. the following instructions were then typed in PAGE=&1900 (return) ?&73=0:?&80=0:?&81=6:86=0 (return) *FX6,000 (return) Load"capture" (return) *spool":1.name" (return) Run (return).

The instructions for the Sport Tester programme appeared on the screen and were followed as normal. The option to display data was selected and the data scrolled through on the screen. The finish option was selected and in basic *spool was then typed.

A BBC computer and IBM compatible computer with a facility for the transfer of data (KERMIT) were then linked and both computers switched on without inserting any discs. The following was then typed into the BBC computer SET BAUD 9600 (return) SET FILE TYPE BINARY (return) SET DELAY 0 (return) and the F2 option selected on the IBM compatible computer and the following typed in KERMIT (return) SET BAUD 9600 (return) SERVER (return).

The data disc was then inserted into the BBC computer and SEND "FILENAME" (return) was typed in where "filename" was the name of the heart rate files. A formatted disc was then inserted into the IBM compatible computer and the Kermit programme was exited. The transferred files were copied on to disc. They were then cleaned in Microsoft word as other information other than the heart rates was transferred with each file. The data was also put into row format at this point, ready for transferring to the Minitab statistical package.

Appendix 3

Heart rate response during heart rate - oxygen uptake regression protocol

A3.1 Heart rate response during heart rate - oxygen uptake regression protocol

Figure A3.1 shows the heart rate response for subject B during the regression equation protocol. It can be seen from the graph that during the collection period at each workload there was a very small fluctuation of heart rates around a mean value, however there was not an increasing heart rate during the collection period. This supports the use of a 3 minute protocol to establish the heart rate oxygen uptake regression equation. It is likely due the fact that these were well trained subjects and that the increments in workload were fairly small (usually leading to an increase in heart rate of around 15 beats.min^{-1}) that the subjects had reached steady before each collection period.

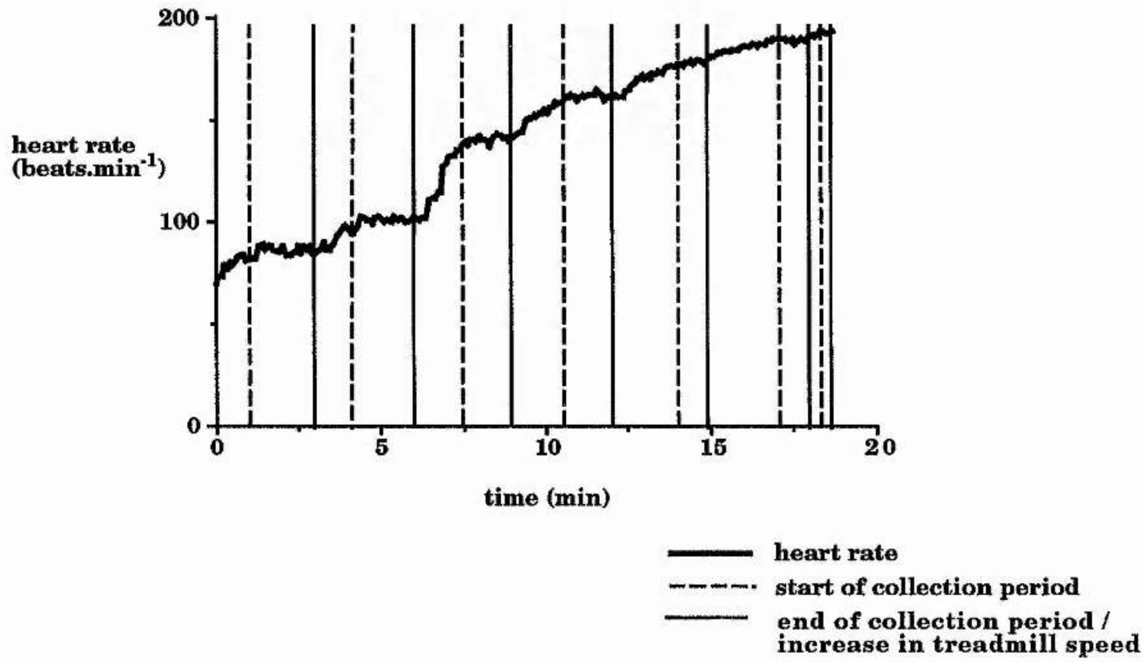

Figure A3.1 Graph of heart rate response during regression equation treadmill protocol

Appendix 4

Raw data for heart rate - oxygen uptake regression equation

A4.1 Data from treadmill protocol

The following data was collected for subject A during the protocol to establish the relationship between heart rate and oxygen uptake. The weight of subject A was 68 kg

Table A4.1 Raw data for heart rate - oxygen uptake regression equation for subject A

Treadmill speed ($km.h^{-1}$)	Heart rate ($beats.min^{1}$)	Collection Time (s)	Fe O_2	Fe CO_2 %%	$\dot{V}E$ ATPS	Gas Temp ^0C
4	93	120.18	17.3	3.5	54.5	20.6
6	115	110.85	17.2	3.7	68.4	20.6
8	154	80.84	17.05	3.9	80.9	20.6
10	174	75.45	17.05	4.0	95.1	20.6
12	183	57.73	17.05	4.1	83.0	20.6
14	191	50.03	17.1	4.1	80.1	20.6
16	198	41.49	17.7	3.9	86.2	20.6

Barometric Pressure 764 mm Hg

Table A4.2 Processed data for heart rate - oxygen uptake regression equation for subject A

Treadmill speed ($km.h^{-1}$)	Heart rate ($beats.min^{-1}$)	$\dot{V}E$ STPD ($l.min^{-1}$)	$\dot{V}O_2$ ($l.min^{-1}$)	$\dot{V}O_2$ ($ml.min^{-1}.kg^{-1}$)	RER
4	93	24.7	0.91	13.42	0.94
6	115	33.7	1.27	18.63	0.97
8	154	54.6	2.13	31.31	0.99
10	174	68.8	2.66	39.16	1.03
12	183	78.5	3.02	44.37	1.06
14	191	87.4	3.30	48.59	1.08
16	198	113.4	3.63	53.39	1.21

A4.2 Regression equations

Figure A4.1 shows the regression equation for heart rate - oxygen uptake, the differing slopes for walking and running can be clearly seen.

The linear regression equation for walking was :

$\dot{V}O_2$ ($l.min^{-1}$) = (0.016 ×heart rate) - 0.612

The linear equation for running was :

$\dot{V}O_2$ ($l.min^{-1}$) = (0.034 ×heart rate) -3.128 $r^2 = 0.99$

Figure A3.2 shows the linear equation for the respiratory exchange ratio and oxygen uptake. This equation was applied to oxygen uptake values which were less than 2.24, at oxygen uptake values equal or greater than this the RER value was assumed to be 1. This oxygen uptake value corresponds to a heart rate of 157.9 beats.min^{-1}.

RER = (0.041 ×$\dot{V}O_2$) + 0.908 $r^2 = 0.952$

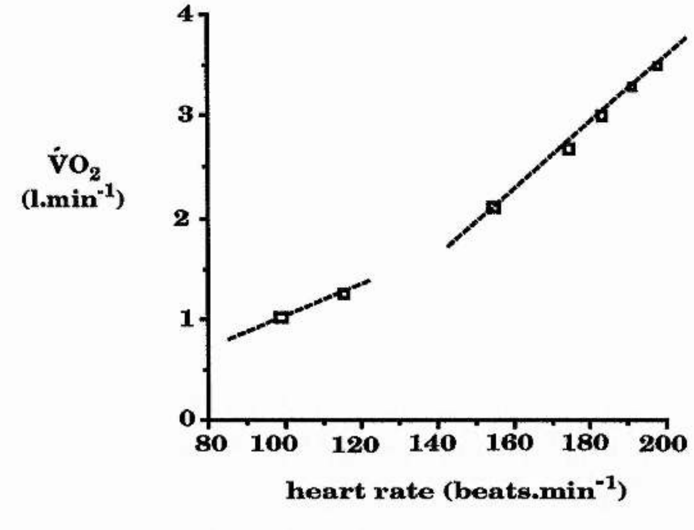

Figure A4.1 **Graph of heart rate - oxygen uptake regression equation for subject A**

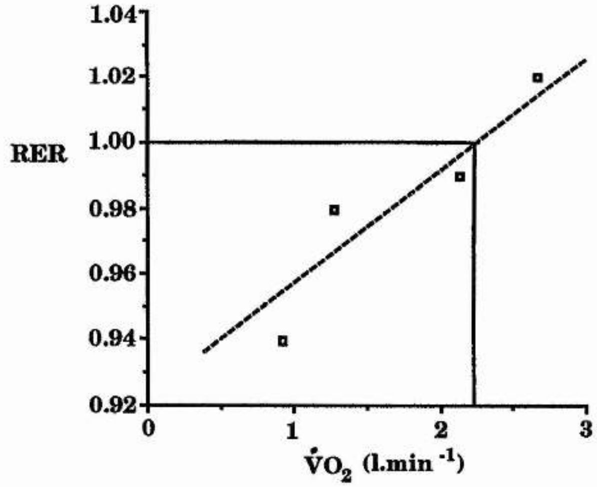

Figure A4.2 Graph of oxygen uptake - RER regression equation

Appendix 5

Validity and reliability of the Cosmed K2 to measure oxygen uptake

Catalogue data : Lothian, F., Farrally, M. R. and Mahoney, C. (1993).
Validity and reliability of the Cosmed K2 to measure oxygen uptake.
Canadian Journal of Applied Physiology. 18(2): 197-206

A5.1 Abstract

The validity and reliability of the Cosmed K2 was tested in comparison with a Quinton-on-line oxygen analysing system. A female subject was monitored on a treadmill using a progressive protocol and was measured on three occasions with each system. It was found at low workloads, the Cosmed K2 and the Quinton gave the same measure of oxygen uptake; at higher workloads the Cosmed K2 gave lower values and at peak oxygen uptake the Cosmed K2 measured 22.2% less than the Quinton . The difference in the measurement of $\dot{V}E$ at peak oxygen uptake was 13%. The Cosmed K2's measurement of $\dot{V}O_2$ showed a greater variability between trials (variation coefficient 3.0-11.4%) than the Quinton (variation coefficient 1.1-3.9%)

A5.2 Introduction

A number of methods can be used to either measure directly or to estimate oxygen uptake in the field situation. The direct measurement is either by the collection of expired air into Douglas Bags or by the use of a respirometer e.g., Max Planck respirometer (Durnin & Passmore, 1967). Both sets of equipment hamper the subjects' movements and restrict the activities they can engage in. There is also a problem with resistance in the respirometer at flow rates greater than 50 $l.min^{-1}$ (Durnin & Passmore, 1967; McArdle, et al., 1986). Indirect measurement of oxygen uptake is either by heart rate (Malhotra, et al., 1963; Seliger, 1968) or video analysis (Ballor, et al., 1989), both methods are time consuming and subject to error, the use of heart rate tending to overestimate and the use of video analysis tending to underestimate oxygen uptake (Ballor, et al., 1989).

A system which has been designed to allow the continuous measurement of oxygen uptake to be made in field conditions over an extended period of time (up to 7 hours with a measure taken every 15 seconds) is the Cosmed K2 which is a portable telemetric system that measures $\dot{V}E$ (volume of expired air in litres per minute) and $\dot{V}O_2$ (volume of oxygen consumed in litres per minute). The benefit of the Cosmed K2 in comparison with the respirometer is that it allows for changes in oxygen uptake to be observed, whereas, for the respirometer only a total oxygen uptake can be measured.

A study to test the accuracy of the Cosmed K2 in comparison with the Jaeger on-line O_2 analysing system was carried out at the Italian Institute of Sport (Dal Monte, et al., 1989). An amateur cyclist was tested on 20 occasions alternately using the Cosmed K2 and Jaeger systems at seven workloads (50 watts to maximum); at least one day's rest was given between each test. Dal Monte found that there was no significant difference in the $\dot{V}E$ (mean max. $\dot{V}E$, 202 $l.min^{-1}$) at all workloads. In the measurement of $\dot{V}O_2$ (mean max. $\dot{V}O_2$, 4.85 $l.min^{-1}$) there was no significant difference except at the 100 watt workload between the systems. Although not statistically significant the Cosmed K2 measured slightly higher $\dot{V}O_2$ values at near maximal workloads.

In the above study the accuracy of the oxygen analyser was measured by first calibrating it with atmospheric air and then four known gases with an oxygen content from 13.5 to 18.5% were passed through the analyser. A correlation of 0.999 was obtained. A correlation of 0.99 was also found between $\dot{V}E$ from an artificial lung which was pumped through the turbine and the measured $\dot{V}E$ from the Cosmed K2 (10-230 $l.min^{-1}$).

The aim of this study was to test the reliability and validity of the Cosmed K2 for use in the study of team sports against a Quinton on-line O_2 analysing system. In contrast with the validation by Dal Monte (1989), this study used running rather than cycling as the mode of work. This was to allow validation of the Cosmed K2 in an activity where the head was not stationary, as observation of the Cosmed K2 suggested that the most likely source of error would occur through leakage from the face mask especially where there was head movement. This is a similar situation to that which occurs in team sports. The use of the treadmill allowed the running speed to be set for comparison between the two systems and allowed for a range of workloads up to a maximum.

A5.3 Method

The subject used was an endurance trained female games player, age 25, weight 54 kg and whose $\dot{V}O_2$ max was known to be greater than 60 ml $kg^{-1}.min^{-1}$. (Personal Best for 5 miles was 29 min, 33 s). A continuous protocol was used on the treadmill (1% gradient): the subject started walking at 4 $km.hr^{-1}$ and the speed was increased by 2 $km.hr^{-1}$ every 3 minutes until the subject could no longer continue. This protocol was completed three times with both the Cosmed K2 and the Quinton on-line system (see Table A5.1); two tests were completed each day over 3 days, with 5 hours rest between trials.

Table A5.1 Protocol for testing

	Day 1	Day 2	Day 3	Day 4
9.30 a.m.	Familiarisation with Cosmed K2	Cosmed K2	Quinton	Cosmed K2
2.30 pm.	Familiarisation with Quinton	Quinton	Cosmed K2	Quinton

The Cosmed K2 consists of a face mask connected to a turbine system which measures $\dot{V}E$ by an optoelectronic sensor counting the number of revolutions per minute. The manufacturers claim that the turbine system will measure accurately flow rates in excess of 300 $l.min^{-1}$. The face mask covers both mouth and nose and is held in place by an elastic strapping. There are four sizes of face mask and each subject is fitted with the mask that is most air tight. The size of the mask required can be checked before connecting the turbine to the mask by placing the mask over the subject's face and sealing the front of the mask with the palm of the hand. The subject is then asked to exhale; leakage from the mask can then be detected if the subject is able to continue exhaling.

The transmitter and oxygen analysing unit consists of a mixing micro-chamber of 2-ml capacity with a polarographic electrode for analysing the percentage of O_2 in the expired air. A micropump draws a sample of expired air from the face mask just in front of the turbine, that is, before the expired air passes through the turbine. The flow rate of the sample expired air is the same as the flow rate through the turbine. The transmitter and oxygen analysing unit (weighing 400 g) is attached to the front of the subject, and a battery pack with antennae (weighing 400 g) which sends the data signal from the transmitter over a maximum range of 1.5 km, is attached to the subject's back by a harness. Additionally a Sport Tester PE 3000 transmitter and belt is used to monitor heart rate. The signal from the PE 3000 transmitter is sent direct to the remote receiver.

As there is no measurement of the percentage of CO_2 in the expired air, $\dot{V}O_2$ is calculated from the oxygen percentage used and $\dot{V}E$. In this calculation VI (volume of inspired air in litres) is assumed to equal $\dot{V}E$, that is., a respiratory exchange ratio (RER) equal to 1. The expired air is assumed to be at body temperature and atmospheric pressure when it is measured and corrected to STPD.

Once assembled and switched on the Cosmed K2 was left for 15 minutes to warm-up before it was calibrated using room air and a 3 litre syringe. Before calibration the subject's name, height, weight and age, and the barometric pressure were entered into the receiver unit. The subject was fitted with the Cosmed K2 and the selected mask strapped on tightly. Then the subject sat for 5 minutes to become used to the face mask and to check that all data including heart rate were being transferred to the receiver.

The Quinton on-line system gave a printout every 15 seconds of $\dot{V}O_2$ ($l.min^{-1}$), VE ($l.min^{-1}$, BTPS) and heart rate; the actual percentage of O_2 extracted was not included in the printout. The $\dot{V}E$ ($l.min^{-1}$, BTPS) values were corrected to STPD for comparison with the $\dot{V}E$ (STPD) values of the Cosmed K2. Heart rate was monitored using a five-lead ECG. The system was calibrated prior to each test according to the manufacturer's instructions using two span gases and a 3 litre syringe. The mouthpiece was attached to a two-way valve and connected to the system by lightweight tubing.

A5.4 Results

The $\dot{V}O_2$ ($l.min^{-1}$) and $\dot{V}E$ ($l.min^{-1}$) values for both the Cosmed K2 and Quinton at each workload were obtained by averaging the four values obtained during the last minute of each workload; they are shown in Tables A5.2 and A5.3. The results are presented in terms of percentage differences rather than significant differences.

Table A5.2 Oxygen uptake in litres.minute^{-1}

speed	Cosmed K 2					Quinton				
$km.h^{-1}$ (1% grad)	Day 1	Day 2	Day 3	Mean	*SD*	Day 1	Day 2	Day 3	Mean	*SD*
4	0.68	0.74	0.77	0.73	0.05	0.74	0.80	0.77	0.77	0.03
6	1.08	1.13	1.03	1.08	0.05	1.13	1.18	1.16	1.16	0.03
8	1.57	1.57	1.42	1.52	0.09	1.78	1.82	1.82	1.81	0.02
10	1.81	1.90	1.67	1.79	0.12	2.24	2.17	2.21	2.21	0.04
12	1.98	2.49	2.35	2.27	0.26	2.64	2.65	2.65	2.65	0.01
14	2.28	2.48	2.63	2.46	0.18	3.03	3.13	3.09	3.09	0.05
16	2.78	2.66	2.63	2.69	0.18	3.43	3.42	3.46	3.46	0.07
18						3.49				

Figure A5.1 shows the reliability of the Quinton to measure a similar oxygen uptake at each workload. From the data of the Quinton test on day 1 it can be seen that a workload of 16 $km.hr^{-1}$ represented an almost maximal oxygen uptake for this subject, and any further increase in workload did not maintain the linear increase in oxygen uptake. In all other tests the subject only completed the 16 $km.hr^{-1}$ workload and this value was used as peak $\dot{V}O_2$.

Table A5.3 Volume expired in litres.minute^{-1} at STPD.

speed	Cosmed K 2					Quinton				
km.h^{-1} (1% grad)	Day 1	Day 2	Day 3	Mean	*SD*	Day 1	Day 2	Day 3	Mean	*SD*
4	19.89	18.97	18.62	19.16	0.66	19.55	21.68	18.37	19.86	1.68
6	28.17	24.73	27.17	26.69	1.77	26.65	27.57	25.65	26.27	1.11
8	36.76	36.17	38.45	37.12	1.18	42.65	40.84	40.48	41.32	1.16
10	49.96	47.53	47.68	48.39	1.36	52.06	52.49	53.18	52.57	0.57
12	54.55	64.71	65.72	61.66	6.18	64.51	66.84	66.17	65.84	1.20
14	57.65	70.56	79.06	69.08	10.78	77.32	80.10	78.18	78.53	1.42
16	76.45	78.86	84.96	80.09	4.41	91.53	91.66	94.14	92.44	1.47
18						104.60				

Figure A5.1 also shows a variability in the measurement of $\dot{V}O_2$ by the Cosmed K2 at increasing workloads. A similar peak $\dot{V}O_2$ was measured using the Cosmed K2 in all three tests (variation coefficient = 2.97%). The variation coefficient for each workload ranged from 2.97-11.4%. The greatest variation between trials for the Cosmed K2 was observed at the 12 km.hr-1 workload, with a difference of 0.51 l.min^{-1} between Day 1 and Day 2, which meant that the measure on Day 2 was 25.8% greater than Day 1.

The regression equations in F igure A5.1 show the differences between mean $\dot{V}O_2$ measured by the Quinton and the Cosmed K2. It can be seen that there was a greater difference at higher workloads, there being a 22.2% difference in the mean peak $\dot{V}O_2$ measured at the 16 km.hr^{-1} workload. The smallest difference (5.2%) occurred at the 4 km.hr^{-1} workload. From Figure A5.2 it can be seen that whereas the Quinton reported minute volumes consistently between trials, the Cosmed K2 measures consistently similar values up to an expiry rate of around 50 l.min^{-1}; above this flow rate there was greater variability in the measurements. Figure A5.2 also shows that for running the Cosmed K2 underestimates $\dot{V}E$ in comparison to the Quinton; at 16 km.hr^{-1} there is a 13% difference in the peak $\dot{V}E$ values.

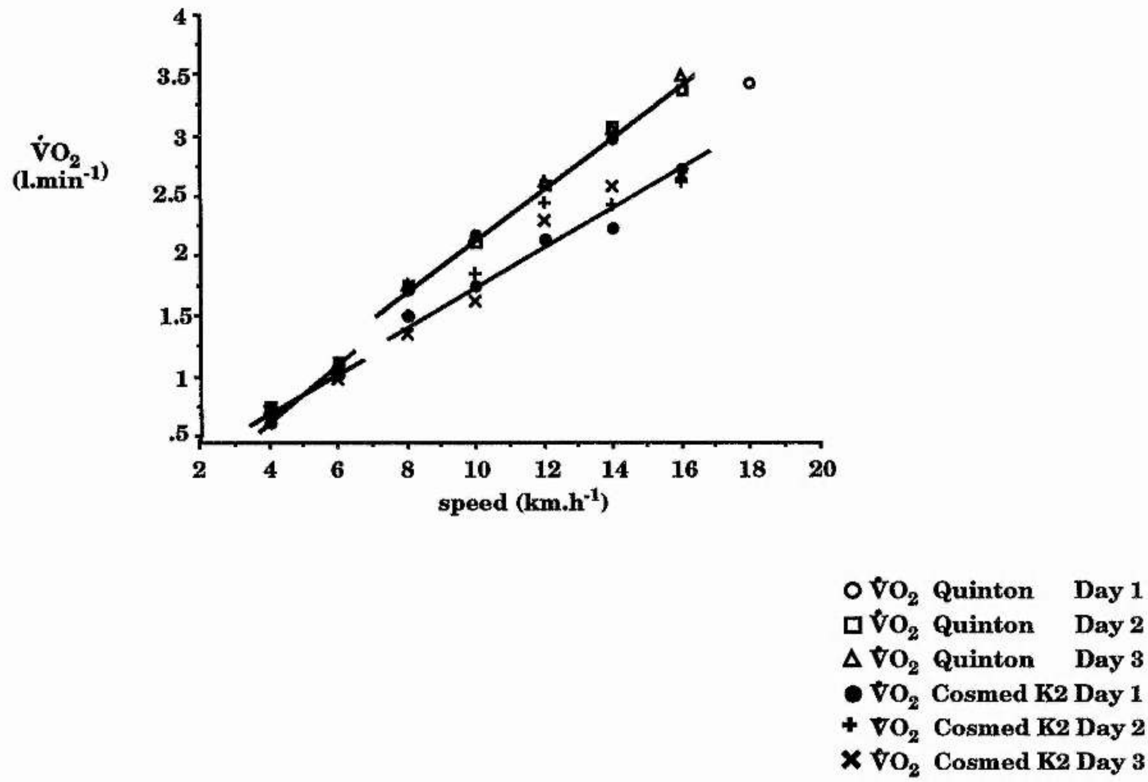

Figure A5.1 Graph of $\dot{V}O_2$ (l.min^{-1}) at STPD against speed (km.hr^{-1}) for both the Cosmed K2 and Quinton system

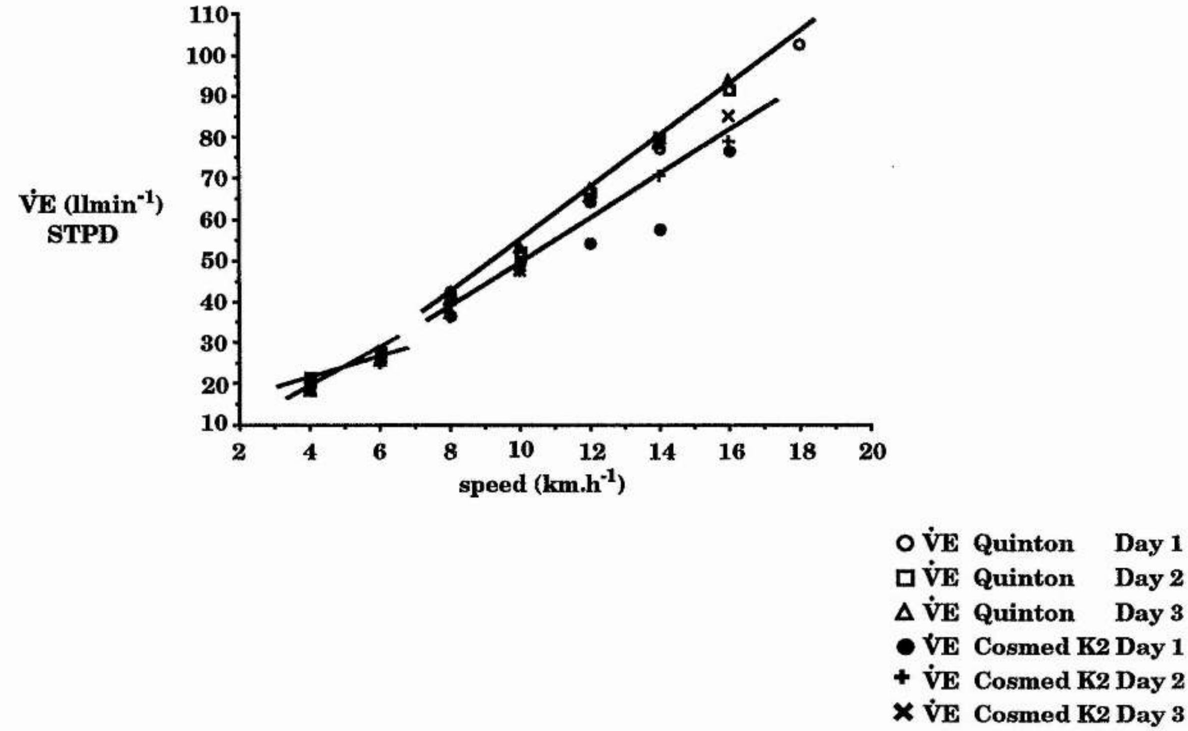

Figure A5.2 Graph of $\dot{V}E$ ($l.min^{-1}$) at STPD against speed ($km.hr^{-1}$) for both the Cosmed K2 and Quinton system

Figure A5.3 shows that there is a strong correlation ($r^2 = 0.98$)between the mean $\dot{V}O_2$ measured by the Cosmed K2 and the Quinton. There was also a strong correlation between individual trials (r^2 range 0.96-0.99).

$$\dot{V}O_2 \text{ Quinton} = (1.35 \times \dot{V}O_2 \text{ Cosmed K2}) - 0.19 \qquad r^2 = 0.98$$

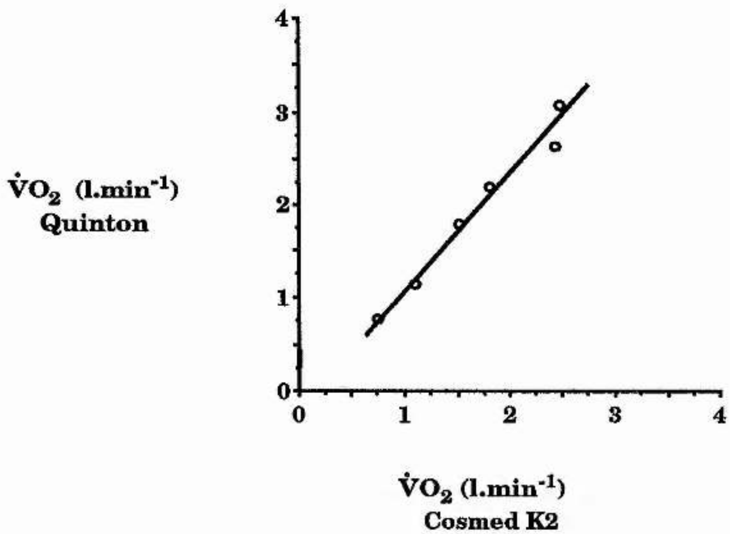

Figure A5.3 Graph of mean $\dot{V}O_2$($l.min^{-1}$) from the Quinton against mean $\dot{V}O_2$ ($l.min^{-1}$) from the Cosmed K2

A5.5 Discussion

The completion of six $\dot{V}O_2$ max. tests in 3 days by this subject was not felt to influence the results of this study, since all other training was suspended to save the glycogen stores and minimise fatigue. Also, she was accustomed to running on the treadmill with a mouthpiece, so there would be little training effect.

For the purposes of this study it has been assumed that the Quinton system gave a valid and accurate measurement of both $\dot{V}O_2$ and $\dot{V}E$. The measurement of $\dot{V}O_2$ max. as 3.46 $l.min^{-1}$ may be slightly overestimated as Heyward (1991) gives an oxygen cost of 3.21 $l.min^{-1}$ for running at 16 $km.hr^{-1}$ on a 1% gradient. However, this subject had previously recorded

$\dot{V}O_2$ maximums ranging between 3.3 and 3.55 using a different protocol and measured by both a Douglas Bag system and a Covox on-line system.

The results show that at workloads greater than 6 $km.hr^{-1}$ the Cosmed K2 underestimates the oxygen cost of each workload when compared to the Quinton, with a 22.2% difference at peak $\dot{V}O_2$. The small difference in $\dot{V}O_2$ at the 4 $km.hr^{-1}$ workload could be accounted for in the way in which the Cosmed K2 calculates $\dot{V}O_2$. The nature of the Cosmed K2 calculation of $\dot{V}O_2$ implies a slight underestimation of $\dot{V}O_2$, at low workloads (Dal Monte, et al., 1989). When the RER value is less than 1 the value of $\dot{V}I$ will be underestimated and this will consequently lead to an underestimation of $\dot{V}O_2$ but the greatest differences are at high workloads when the RER value is greater than 1. Here, $\dot{V}E$ will be greater than $\dot{V}I$, that is., a greater CO_2 production than O_2 consumption, and so will lead to an overestimation of $\dot{V}O_2$ at high workloads. From the results it can be seen that the $\dot{V}O_2$ measured by the Quinton is increasingly larger than that measured by the Cosmed K2, suggesting that at workloads where the RER exceeds 1 the actual difference between the two systems is greater than the results show. Dal Monte et al. (1989) suggests that these differences are not enough to be significant.

The maximum $\dot{V}E$ measured at 16 $km.hr^{-1}$ by the Cosmed K2 was 84.96 $l.min^{-1}$ compared to 94.14 $l.min^{-1}$ on the Quinton (both on the 3rd day), a 9.75% difference. This difference may be due to leakage from the face mask. This is supported by the break from linearity of the graphs of $\dot{V}E$ for the three Cosmed K2 tests, that is., there is not a constant measurement of $\dot{V}E$ in all three tests at the 14/16 $km.h^{-1}$ workloads which would occur if the problem were in the flow rate through the turbine; if this were the case there would be a constant error (see Figure A5.2). With only one subject, it cannot be determined whether leakage from the face mask is always a problem, but it should be noted that the manufacturers supply four different sizes of face mask.

Differences between oxygen uptake measured on the Quinton and Cosmed K2 may be attributable to either differences in the measurement of $\dot{V}E$ or percentage O_2, or a combination of both. Since percentage O_2 is not given in the Quinton printout, variability in the measurement of percentage O_2

between the two systems can only be examined by substituting the measured $\dot{V}E$ on the Quinton into the Cosmed K2 calculations. Then the same $\dot{V}O_2$ values should be obtained (Figure A5.4) for the Quinton and the Cosmed K2. In the K2 test on Day 1 this gives similar values; however, in the tests on Days 2 and 3 at 14 and 16 $km.hr^{-1}$ it can be seen that the differences in $\dot{V}O_2$ measures are not caused solely by the differences in $\dot{V}E$ values. This would suggest a difference in the measurement of percentage O_2 extracted by each system. Without the actual measured percentage O_2 from the Quinton the extent of the percentage O_2 difference can only be estimated.

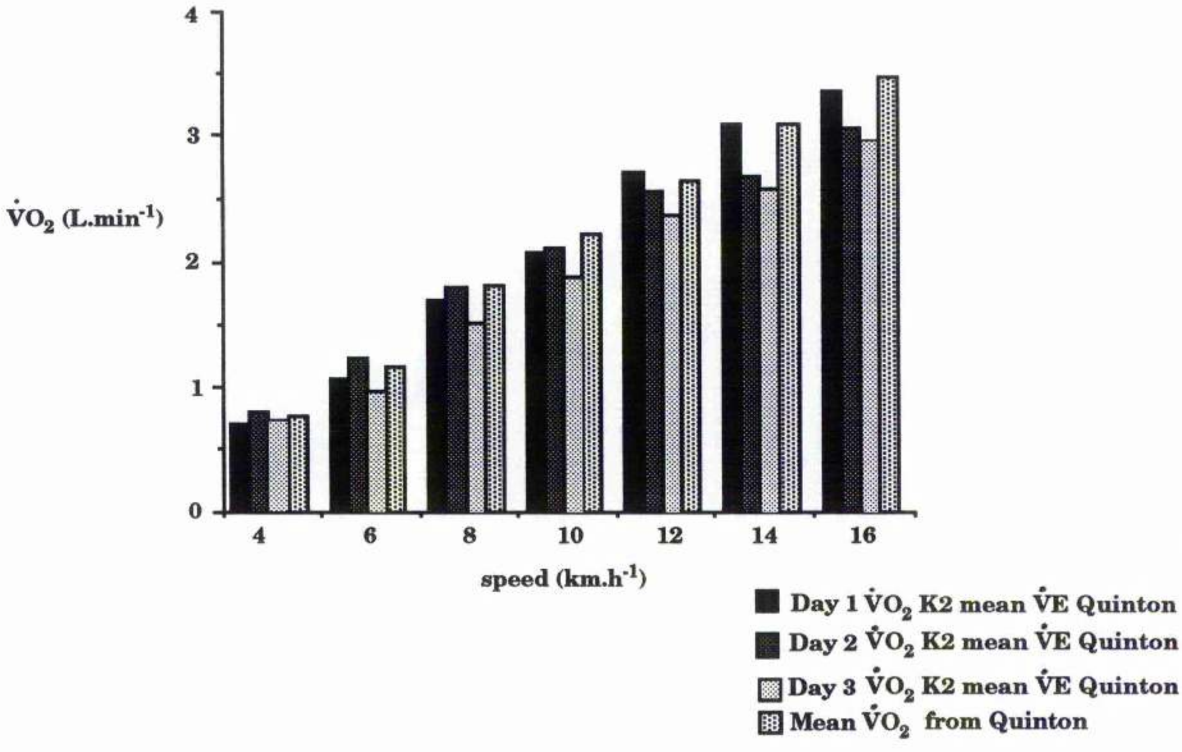

Figure A5.4 **Histogram of $\dot{V}O_2$ calculated by substituting the mean $\dot{V}E$ measured by the Quinton into the Cosmed K2 data for days 1-3 and the mean $\dot{V}O_2$ for the Quinton**

A validation of the Cosmed K2's oxygen analyser needs to be done in comparison with a system from which the actual measurements of percentage O_2 extracted can be obtained, so that there can be no doubt that any differences are caused by the analysers and not by the methods of calculation. The study by Dal Monte et al. (1989) validated the oxygen analyser using gases with an O_2 content of between 14-19%, however, this was done with the Cosmed K2 stationary. It is likely that the greatest error in any part of the Cosmed K2 system will occur at high workloads, that is, when it is being "bounced up and down". Validation of the O_2 analyser at rest does not necessarily hold for running at 16 $km.hr^{-1}$.

The low variability shown between the three trials on the Quinton suggest that the number of trials performed by the subject were not the cause of the larger variability measured by the Cosmed K2. The day-to-day variability (variation coefficient range 2.97-11.4%) of the Cosmed K2 show that the Cosmed K2 is not as a reliable measure of VO_2 as the Quinton.

Figure 3 shows that although there is a difference in the $\dot{V}O_2$ measured at each workload between the two systems, the values are highly correlated and thus a correction factor could be applied to values obtained when using the Cosmed K2. This correlation was obtained by using the mean $\dot{V}O_2$ from each system. The correlation between individual trials (r^2 0.96-0.99) shows that using mean values has not affected the relationship. This relationship would have to be individually determined for each subject by measuring $\dot{V}O_2$ at progressive workloads with the Cosmed K2 and with a reliable on-line or Douglas Bag system, as any error caused in $\dot{V}E$ by leakage from the face mask will be specific to the individual. It may be that for some subjects there will not be as strong a correlation. This would assume that the leakage from the face mask was constant from the treadmill to the field situation at any given $\dot{V}E$; this may not always hold true, for example, immediately after a period of high intensity activity the subject may well be stationary. There will still be large volumes of $\dot{V}E$ but less may escape as the mask is no longer being "bounced".

The study by Dal Monte et al. (1989) did not find any differences between the Cosmed K2 and the Jaeger on-line system for different work rates of a cyclist. In cycling there is very little movement of the head, which may have restricted the leakage from the face mask. During running there is vertical movement in the head, which causes the mask to "bounce", probably allowing expired air to escape. This may well be a problem at low workloads involving changes of direction which involve sharp head movements, thus limiting the accuracy of the Cosmed K2 in many sporting situations. A solution to this problem would be to attach the turbine system to a mouthpiece system similar to that used by the on-line system. This would eliminate the problems associated with a face mask, but it would be necessary to use a helmet to support the turbine.

In conclusion and assuming that the Quinton system is a valid criterion, at low workloads with an oxygen consumption of less than 1.10 $l.min^{-1}$, the Cosmed K2 gives an accurate measurement of $\dot{V}O_2$. At workloads greater than this the Cosmed K2 underestimates $\dot{V}O_2$. The leakage of air from the face mask is not entirely responsible for the difference in $\dot{V}O_2$ between the Cosmed K2 and the Quinton system. The oxygen analyser in the Cosmed K2 needs to be calibrated with a span gas as well as air. The greater variability of the Cosmed K2 shows that it is a less reliable measure of oxygen uptake than the Quinton system.

Appendix 6

Estimations of error in the use of heart rate and time-motion analysis, data for subject A

The following data was collected for Subject A during the study in Chapter 7 to establish the errors in the estimation of energy expenditure from both heart rate and time-motion analysis in comparison to the measured value. The weight of subject A was 64 kg.

A6.1 Heart rate - oxygen uptake regression equation

Pressure	761 mm Hg
Temperature	23 °C
Correction Factor	0.8945

Table A6.1 Raw data for heart rate - oxygen uptake regression equation for subject A

Speed	Heart rate	Collection time (s)	% CO_2	% O_2	Total volume expired ($l.min^{-1}$) ATPS
4	108	120.41	3.65	17.05	54.6
6	118	117.94	4.25	15.85	53.2
8	144	100.42	4.20	16.20	70.6
10	157	90.44	4.30	16.20	70.1
12	169	75.36	4.40	16.40	75.8
14	182	60.44	4.20	16.90	74.0
16	193	45.21	4.20	17.10	66.9
16 +2%	198	40.40	4.10	17.40	67.4

Table A6.2 Processed data Raw data for heart rate - oxygen uptake regression equation for subject A

Speed	Volume expired ($l.min^{-1}$) STPD	$\dot{V}O_2$ ($l.min^{-1}$)	$\dot{V}O_2$ ($ml.kg^{-1}.min^{-1}$)	RER	$KJ.min^{-1}$
4	24.34	0.96	15.08	0.88	19.34
6	24.21	1.29	20.14	0.79	25.84
8	37.73	1.85	28.85	0.85	37.59
10	41.60	2.02	31.64	0.88	41.53
12	53.98	2.48	38.70	0.95	51.69
14	65.71	2.63	41.16	1.04	55.65
16	79.42	2.98	46.60	1.11	63.02
16 +2%	89.54	3.05	47.60	1.20	64.38

A 6.2 Regression equations

Energy cost of walking = speed ($km.h^{-1}$) $\times$ 3.25 + 6.35

Energy cost of running = speed ($km.h^{-1}$) $\times$ 3.26 + 10.71

Energy cost of running on a gradient =

$$\left(m.min^{-1} \times \frac{0.2ml.kg.min^{-1}}{m.min^{-1}} \right) +$$

$$\left(grade(fraction) \times m.min^{-1} \times \frac{1.8ml.kg.min^{-1}}{m.min^{-1}} \times 0.5 \right) + 3.5ml.kg.min^{-1}$$

Oxygen uptake ($l.min^{-1}$) = 0.033 $\times$ heart rate - 2.604
(heart rates < 120 beats.min^{-1})

Oxygen uptake ($l.min^{-1}$) = 0.023 $\times$ heart rate - 1.486
(heart rates > 120 beats.min^{-1})

RER = 0.17 $\times$ oxygen uptake ($l.min^{-1}$) + 0.55

For oxygen uptakes greater than 2.64 $l.min^{-1}$ the RER value was assumed to be 1

A6.3 Data for oxygen uptake during intermittent treadmill activity

Pressure 763 mm Hg
Temperature 21°C
Correction Factor 0.906

Table A6.3 Raw data from intermittent treadmill activity

Bag	Collection time (s)	$\%CO_2$	$\%O_2$	Total volume (l) ATPS
1	135	4.40	17.00	123.1
2	120	4.45	17.05	122.5
3	120	4.39	16.95	142.4
4	125	4.15	17.20	136.7
5	115	3.98	17.10	132.8
6	115	4.20	17.02	130.1
7	110	4.03	17.10	118.3
8	60	4.10	17.00	73.7

Table A6.4 Processed data from intermittent treadmill activity

Bag	Volume expired $l.min^{-1}$ STPD	$\dot{V}O2$ $L.min^{-1}$	$\dot{V}O2$ $ml.kg^{-1}.min^{-1}$	RER	Total oxygen uptake from bag	Energy cost per bag kJ
1	49.57	1.90	29.66	1.14	4.27	90.24
2	55.49	2.08	32.54	1.18	4.16	88.00
3	64.51	2.51	39.26	1.12	5.02	106.18
4	59.45	2.17	33.83	1.13	4.51	95.32
5	62.77	2.39	37.41	1.04	4.59	96.96
6	61.50	2.37	37.06	1.08	4.55	96.06
7	58.46	2.22	34.72	1.05	4.07	86.07
8	66.77	2.61	40.78	1.04	2.61	55.15
Total					33.79	713.98

A.6.3 Time motion and heart rate analysis

Table A6.5 shows the treadmill speed, heart rate and the estimated energy expenditure every 5 seconds during the non-steady state treadmill protocol.

Table A6.5 Time-motion analysis data

Time	Heart rate	Speed ($km.h^{-1}$)	Gradient %	Estimated energy expenditure from treadmill activity ($kJ.min^{-1}$)	Estimated energy expenditure from heart rate analysis ($kJ.min^{-1}$)
0.05	90			6.70	7.00
0.10	86			6.70	4.45
0.15	90			32.85	7.00
0.20	88			32.85	5.72
0.25	99	14	4	59.01	12.86
0.30	117			59.01	25.05
0.35	132			59.01	31.15
0.40	142			59.01	36.14
0.45	149			59.01	39.69
0.50	156			50.18	43.29
0.55	162	9.4	0	41.36	46.40
1.00	167			41.36	49.03
1.05	168			41.36	49.56
1.10	167			41.36	49.03
1.15	166			41.36	48.50
1.20	166			52.12	48.50
1.25	166	15	4	62.89	48.50
1.30	166			62.89	48.50
1.35	167			62.89	49.03
1.40	169			62.89	50.08
1.45	172			41.93	51.67
1.50	174	4.5	0	20.96	52.74
1.55	176			20.96	53.81
2.00	176			20.96	53.81
2.05	173			20.96	52.21
2.10	171			20.96	51.14
2.15	168			20.96	49.56
2.20	165			20.96	47.98
2.25	160			40.96	45.36
2.30	154			40.96	42.26
2.35	151	14.5	4	60.95	40.71
2.40	150			60.95	40.20
2.45	153			60.95	41.74
2.50	158			60.95	44.32
2.55	162			60.95	46.40
3.00	166			60.95	48.50
3.05	169	0		6.70	50.08
3.10	173			6.70	52.21
3.15	176			6.70	53.81
3.20	176			6.70	53.81
3.25	174			6.70	52.74
3.30	171	4		19.34	51.14
3.35	166			19.34	48.50

Time	Heart rate	Speed ($km.h^{-1}$)	Gradient %	Estimated energy expenditure from treadmill activity ($kJ.min^{-1}$)	Estimated energy expenditure from heart rate analysis ($kJ.min^{-1}$)
3.40	156			19.34	43.29
3.45	149			19.34	39.69
3.50	143			39.17	36.65
3.55	144	14	4	59.01	37.15
4.00	145			59.01	37.66
4.05	149			59.01	39.69
4.10	155			59.01	42.77
4.15	160			47.90	45.36
4.20	164	8		36.79	47.45
4.25	169			36.79	50.08
4.30	173			36.79	52.21
4.35	177			36.79	54.34
4.40	178			36.79	54.88
4.45	178			36.79	54.88
4.50	176			36.79	53.81
4.55	174			36.79	52.74
5.00	173			49.84	52.21
5.05	171			49.84	51.14
5.10	170	15	5	62.89	50.61
5.15	168			62.89	49.56
5.20	170			62.89	50.61
5.25	173			42.41	52.21
5.30	176	4.8		21.94	53.81
5.35	179			21.94	55.41
5.40	182			21.94	56.87
5.45	183			21.94	57.35
5.50	184			21.94	57.84
5.55	182			21.94	56.87
6.00	181			21.94	56.38
6.05	179			29.85	55.41
6.10	176	8.3	0	37.77	53.81
6.15	173			37.77	52.21
6.20	170			37.77	50.61
6.25	168			37.77	49.56
6.30	165			48.39	47.98
6.35	161	14	4	59.01	45.88
6.40	161			59.01	45.88
6.45	164			59.01	47.45
6.50	166			59.01	48.50
6.55	168			59.01	49.56
7.00	173			59.01	52.21
7.05	177			59.01	54.34
7.10	180	0		6.70	55.90
7.15	182			6.70	56.87
7.20	185			6.70	58.32
7.25	185			6.70	58.32
7.30	184			6.70	57.84
7.35	182			6.70	56.87
7.40	179			6.70	55.41
7.45	175			6.70	53.27
7.50	171			22.23	51.14
7.55	165	8		37.77	47.98
8.00	158			37.77	44.32

Time	Heart rate	Speed ($km.h^{-1}$)	Gradient %	Estimated energy expenditure from treadmill activity ($kJ.min^{-1}$)	Estimated energy expenditure from heart rate analysis ($kJ.min^{-1}$)
8.05	154			37.77	42.26
8.10	151	14	0	56.36	40.71
8.15	151			56.36	40.71
8.20	154			56.36	42.26
8.25	156			56.36	43.29
8.30	160			56.36	45.36
8.35	164			56.36	47.45
8.40	167			38.66	49.03
8.45	173			38.66	52.21
8.50	176	4.5		20.96	53.81
8.55	179			20.96	55.41
9.00	181			20.96	56.38
9.05	180			20.96	55.90
9.10	179			20.96	55.41
9.15	176			39.99	53.81
9.20	172			39.99	51.67
9.25	169	14	4	59.01	50.08
9.30	166			59.01	48.50
9.35	167			59.01	49.03
9.40	169			59.01	50.08
9.45	171			59.01	51.14
9.50	174			59.01	52.74
9.55	177			46.27	54.34
10.00	178	7	0	33.53	54.88
10.05	181			33.53	56.38
10.10	183			33.53	57.35
10.15	182			33.53	56.87
10.20	182			33.53	56.87
10.25	181			33.53	56.38
10.30	180			33.53	55.90
10.35	179			33.53	55.41
10.40	177			33.53	54.34
10.45	176			48.21	53.81
10.50	175			48.21	53.27
10.55	173	15	4	62.89	52.21
11.00	171			62.89	51.14
11.05	173			62.89	52.21
11.10	176			62.89	53.81
11.15	179			62.89	55.41
11.20	182	0		6.70	56.87
11.25	185			6.70	58.32
11.30	187			6.70	59.29
11.35	188			6.70	59.78
11.40	187	6		25.84	59.29
11.45	186			25.84	58.81
11.50	183			25.84	57.35
11.55	178			25.84	54.88
12.00	176			25.84	53.81
12.05	171			25.84	51.14
12.10	168			25.84	49.56
12.15	164			42.42	47.45
12.20	160			42.42	45.36
12.25	157	14	4	59.01	43.80

Time	Heart rate	Speed ($km.h^{-1}$)	Gradient %	Estimated energy expenditure from treadmill activity ($kJ.min^{-1}$)	Estimated energy expenditure from heart rate analysis ($kJ.min^{-1}$)
12.30	156			59.01	43.29
12.35	159			59.01	44.84
12.40	163			59.01	46.93
12.45	167			59.01	49.03
12.50	170			59.01	50.61
12.55	174			59.01	52.74
13.00	178			39.17	54.88
13.05	180	4		19.34	55.90
13.10	182			19.34	56.87
13.15	183			19.34	57.35
13.20	182			19.34	56.87
13.25	181			19.34	56.38
13.30	178			19.34	54.88
13.35	174			19.34	52.74
13.40	170			40.14	50.61
13.45	167			40.14	49.03
13.50	166	14.5	4	60.95	48.50
13.55	167			60.95	49.03
14.00	171			60.95	51.14
14.05	174			60.95	52.74
14.10	178			60.95	54.88
14.15	180			48.05	55.90
14.20	182	7.5		35.16	56.87
14.25	185			35.16	58.32
14.30	185			35.16	58.32
14.35	185			35.16	58.32
14.40	184			35.16	57.84
14.45	182			35.16	56.87
14.50	182			35.16	56.87
14.55	180			35.16	55.90
15.00	179			35.16	55.41
Mean	168.4			38.66	49.73
SD	1.3			1.35	0.69

Appendix 7

Publications

Publications arising from this research

Lothian, F., Farrally, M. R. & Mahoney, C. (1993) Validity & reliability of the Cosmed K2 to measure oxygen uptake. *Canadian Journal of Applied Physiology.* **18**(2): 197-206.

Lothian, F. & Farrally, M. R. (1993) A validation of heart rate and video analysis as a means of estimating energy expenditure in team sports. In proceedings of *Sport Sciences in Europe 1993,* Cologne, Germany.

Lothian, F. & Farrally, M. R. (Accepted for publication June, 1993) Estimating the energy cost of women's hockey using heart rate and video analysis. *Journal of Human Movement Studies.*

Lothian, F. & Farrally, M. R. (Accepted for publication, August, 1993) A time-motion analysis of women's hockey. *Journal of Human Movement Studies.*