EFFECTS OF FATIGUE ON SELECTED INJURY RISK FACTORS IN ASSOCIATION FOOTBALL

by

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Abstract

As the game of soccer progresses players become fatigued and this can affect both performance and injury. In particular, the risk of injury may increase as the game progresses. The aims of this thesis were to establish i) the exposure of players to injury risk during English Premier League soccer (association football) matches in relation to selected factors which may influence that risk, ii) a comprehensive reference database for isokinetic strength in elite and sub-elite soccer players, iii) the effects of fatiguing exercise simulating the work-rate of competitive soccer on performance of lower-limb muscles and finally, iv) the effects of fatiguing exercise on the electrical activity of major lower-limb muscles.

Injury risk was assessed by rating the injury potential of playing actions during competition. Close to 18, 000 actions were notated. On average 1788 (± 73) events (one every 3 s), 767 (± 99) events with injury potential (one every 6 s), and 2 (± 1) injuries (one every 45 min) per game were recorded. An overall injury frequency of 53 per 1000 playing hours was calculated. Playing actions with high injury risk were linked to contesting possession, while other actions had relatively low injury risk. Injury risk was highest in both the first and last 15-min periods of the game, reflecting the intense engagements in the opening period and the possible effect of fatigue in the closing period. Injury risk was concentrated in the areas of the pitch where possession of the ball is most vigorously contested which were specific attacking and defending zones close to the goal.

Dynamic strength of knee flexors and extensors of 28 elite and sub-elite English soccer players was measured using an isokinetic dynamometer. A difference between the two groups of players with regard to quadriceps strength at all angular velocities (1.05, 2.09, 5.23 rad.s^{-1} $_{(con)}$ and 2.09 rad.s^{-1} $_{(ecc)}$) for both legs ($P < 0.001$) was observed. For relative quadriceps strength, differences were found between the groups at 2.09 $_{(ecc)}$ rad.s^{-1} ($P < 0.001$) and 5.23 rad.s^{-1} ($P < 0.05$) for both legs. A difference was found in hamstrings strength (peak torque) between groups for the dominant leg at 1.05 ($P < 0.03$), 2.09 $_{(ecc)}$ rad.s^{-1} ($P < 0.002$) and for the non-dominant leg at all angular velocities ($P < 0.002$). For relative hamstrings strength, differences were found at 2.09 $_{(ecc)}$ rad.s^{-1} ($P < 0.05$) for both legs. The elite players were stronger in all these measures, had better balance between hamstrings/quadriceps ratio, left/right ratio, higher fast-speed/slow-speed ratio and were more flexible than sub-elite players. Limitations of sample availability weakens the inferences to be drawn from the data. Nevertheless, it seems that several years of soccer training and match-play at a high level improve the strength of knee extensors and knee flexors and also flexibility in elite players.

Thirteen sub-elite soccer players' lower limb-muscle strength was measured on an isokinetic dynamometer before, during and after a 90-min soccer-specific intermittent exercise protocol. Significant reductions ($P < 0.001$) in peak torque for both quadriceps and hamstrings muscles at all angular velocities (1.05, 2.09, 5.23 rad.s^{-1} $_{(con)}$ and 2.09 $_{(ecc)}$ rad.s^{-1}) were observed. The levels of peak torque and relative peak torque of knee extensors and knee flexors were greater pre-exercise than at half-way and greater at half-way than post-exercise. For the hamstrings/quadriceps ratio, significant changes were found ($P < 0.05$) for both legs, the ratio being greater pre-exercise than post-exercise. It was concluded that there is a continuous reduction in muscle strength which applies across a range of functional characteristics during exercise which mimics the reducing work-rate in soccer.

Electromyography activities of selected muscle (rectus femoris, biceps femoris, tibialis anterior, gastrocnemius) of ten soccer players were recorded and stored using a Biopac system, before, during and after a soccer specific intermittent protocol. For rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius a significant main effect ($P < 0.01$) was found for condition (pre-game, half-way and post-game), speed (6, 12, 15 and 21 km.h^{-1}) ($P < 0.01$) and interaction between condition and speed ($P < 0.01$). The root mean square (RMS) value was greater pre-game than post-game and the RMS increased with increasing speed continually from 6 km.h^{-1} to 21 km.h^{-1}. The median frequency values for biceps femoris and gastrocnemius were greater pre-game than post-game and also for rectus femoris and gastrocnemius the values increased significantly with increasing speed continually from 6 km.h^{-1} to 21 km.h^{-1}. The results indicated that the EMG activity in major lower-limb muscles was greater before than after a simulated game. This showed that fatigue has an effect on muscle activity and is likely to be the cause of reduced activity during exercise which mimicked the reducing work-rate in soccer.

From the studies described, the main conclusion is that fatigue as reflected in muscle performance is likely to have an effect on injury risk in soccer. In particular fatigue reduces muscle strength and balance as the game progresses. Failure to provide enough muscle force and maintain suitable muscle balance due to fatigue may lead to an increasing likelihood of injury. Specifically, the observed increases in injury risk towards the end of the game can be linked to the effect of fatigue because of the reduction in muscle activity, strength and muscle balance evident at the end of the game.

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LIST OF PUBLICATIONS

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2. Rahnama, N., Reilly, T. and Lees, A. (2002). Injury risk associated with playing actions during competitive soccer. *British Journal of Sports Medicine*, 36, 354-359.
3. Rahnama, N., Reilly, T. and Lees, A. (2002). A novel computerised notation and analysis system for assessment of injury and injury risk in football. *Physical Therapy in Sport Journal*, 3, 183-190.
4. Rahnama, N., Reilly, T., Lees, A. and Graham-Smith, P. (2002). A critical incident analysis of injury risk in competitive soccer play. *Physical Therapy in Sport Journal*, 3, 44-45.
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6. Rahnama, N., Reilly, T. and Lees, A. (2003). Comparison of muscle strength in elite and sub-elite English soccer players. *Journal of Sports Sciences*, 21, 249-250.
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8. Rahnama, N., Reilly, T. and Lees, A. (2002). Assessment of muscle strength in elite and sub-elite soccer player. Communication to the International Football and Sports Medicine Conference, Beverly Hills, Los Angeles, California, USA, (22-24 March).

9. Rahnama, N., Reilly, T. and Lees, A. (2002). A critical incident analysis of injury risk in competitive soccer. In: Proceedings of the 3rd International Congress on Physical Education and Sports Science, Tehran, Iran, 26-28 February, p, 89.

10. Rahnama, N., Reilly, T. and Lees, A. (2002). Isokinetic knee strength changes during football simulated game on a treadmill. Communication to the 9th Iranian Students Seminar in Europe, Birmingham, UK, (24-25 August).

11. Rahnama. N., Reilly, T. and Lees, A. (2003). Muscle fatigue. Communication to the 2nd National Physical Education Conference, Ahvaz, Iran, (22-26 February).

12. Rahnama. N., Reilly, T. and Lees, A. (2003). Hand notation system for assessment of injury in football. Communication to the 2nd National Physical Education Conference, Ahvaz, Iran, (22-26 February).

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LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

1. INTRODUCTION

1.1. INTRODUCTION TO THESIS

Soccer entails physical contact in the course of tackling or contesting possession of the ball with opponents, which inevitably leads to injury of varying severity. The majority of injuries are unintentional, resulting from an error on the part of the player concerned or by another player. The error may lead to an accident and some of these accidents result in an injury (Reilly and Howe, 1996). The injury risk of soccer can be evaluated using epidemiological methods. However, an individual player may be at more or less risk due to a number of extrinsic and intrinsic risk factors. Further, this risk and these risk factors may be affected by the fatigue which develops as the game progresses. Identification of exposure and predisposition to injury is a first step towards prevention.

Injury risk in soccer is conventionally assessed by the injury incidence rate, defined in terms of the number of injuries and the exposure to injury, usually in terms of time. Injury data are published widely in the literature. Injury incidence is an expression of risk to players for the game as a whole, but it does not detail the risk associated with extrinsic risk factors such as specific actions, position on the pitch, and duration of play which may lead to injury. Consequently, to understand fully the risk of injury that a player is exposed to during soccer play, and the effects of fatigue on this risk, it is necessary to analyse the actions made in a game and to relate these actions to the risk each may possess and the subsequent injuries, which may result from them. Such an analysis will provide a more detailed understanding of injury risk in soccer which will have importance for designing appropriate injury prevention and rehabilitation programmes.

Intrinsic risk factors are numerous and embrace, for example, the mental state of the player, the level of fitness and the existence of predisposing factors such as muscle weakness or a previous musculoskeletal injury (Reilly and Howe, 1996). One of the most important of these risk factors is in relation to muscle activity. Muscle activity manifests itself as muscle weakness, muscle imbalance and poor co-ordination in muscle activation. Players who carry muscle weaknesses into competition are likely to experience situations where the muscle fails and injury occurs. Such weaknesses can be identified if players undergo a regular profiling of their muscle strength capabilities by isokinetic muscle function testing. The assessment of muscle strength has become increasingly important as it is realised that a large variation in this human attribute exists and is affected by personal and environmental factors. Individuals with well-developed strength capabilities are less prone to musculoskeletal strain, sprain injuries and back fatigue than their weaker counterparts when placed on physically demanding activities (Chaffin et al., 1978). These isokinetic muscle function testing facilities are becoming available for teams with a systematised sports science support programme and so there is need for a reference database for elite and sub-elite soccer players.

Muscular fatigue usually occurs in the course of a soccer game, especially towards the end of play. Players may be able to continue to exercise at low intensities but have a reduced ability to perform maximally (Drust, 1997). Muscle fatigue is reflected in a decline in work-rate and an increase in injury towards the end of a game. Reilly and Thomas (1976) noted that in 32 out of 44 English professional soccer matches, more distance was covered in the first half than in the second, the difference being significant. The injury incidences are greater in the second half predominantly during the last quarter of the match (Hawkins et al., 2001). A reduction in muscle strength is likely due to a decrease in the number of fibres that can be recruited to generate force and/or the decrease in neuromuscular stimulation. The consequences of this fatigue on muscle strength, muscle balance and muscle co-ordination as evaluated by isokinetic muscle function testing have not been investigated.

Although there is valuable information in the literature about the physical demands of soccer play, the dynamic changes of muscle strength characteristics during a game and the injury risk related to these as a result of fatigue are not known. It is hoped that through this study a greater insight will be gained into the injury risk associated with selected aspects of soccer matches, isokinetic strength profiles of both elite and sub-elite soccer players, and the effects of fatigue on muscle strength and activity of major lower limbs muscles.

1.2. AIMS AND OBJECTIVES OF THESIS

The series of studies in this thesis were designed with the aim of identifying the effects of fatigue, typical of a soccer game, on selected extrinsic and intrinsic risk factors related to soccer injuries. The extrinsic risk factors include playing actions, playing zone, duration of play and playing at either home or away. The intrinsic risk factors include muscle strength, muscle balance, and muscle activation and co-ordination.

This aim was achieved by means of the following objectives which were:-

1. To assess the exposure of players to injury risk during English Premier League soccer matches in relation to selected factors which may influence that risk.

2. To establish a comprehensive isokinetic strength reference database for elite and sub-elite soccer players.

3. To establish the effects of a soccer-related simulation task, used to induce fatigue, on the strength characteristics of lower-limb muscles in sub-elite soccer players.

4. To establish the effects of fatigue on the electrical activity of major lower limb muscles at different speeds (walking, jogging, running and sprinting) of locomotion on a treadmill, as used in the soccer-related simulation task.

These objectives were met by a programme of research, which encompassed four main studies:

1. An investigation into the injury risk associated with playing actions during competitive soccer.

2. An assessment of musculoskeletal function profile in elite and sub-elite English soccer players.

3. An investigation into the muscle fatigue during exercise simulating the work-rate of competitive soccer.

4. An investigation into the electromyographic analysis of selected muscle during a simulated soccer game.

CHAPTER TWO

A REVIEW OF THE LITERATURE

2.0. A REVIEW OF THE LITERATURE

With the global growth in the popularity of soccer as an activity for participants, the number of soccer-related injuries has increased. Nowadays, injury in soccer has become recognised as a recreational and an occupational hazard for amateurs and professional players. For a solution to this problem, a prevention programme can be recommended. To achieve injury prevention, it is necessary to have knowledge of the epidemiological and aetiological factors that influence injury occurrence. Over the past decade, there has been an increase in epidemiological surveys of sports injuries and, as a consequence of this, much scientific interest in factors related to soccer injuries.

To understand these issues fully, this chapter will provide a review of (i) the theoretical background for studying soccer injuries, focusing on the epidemiology and aetiology of injuries in soccer; (ii) themes in notational analysis techniques used in the collection of injury statistics; (iii) musculoskeletal strength and its relation to injury; (iv) muscular fatigue and (v) electromyography as a means of monitoring muscle activity.

2.1. INJURY IN SOCCER

2.1.1. Definitions of injury

Injury has been defined in many ways. Inklaar (1994a), and Jung and Dvorak (2000) reported that there is no general agreement with respect to the definition of injury in soccer. An early definition of soccer injury was provided by McMaster and Walter (1978), who defined injury in relation to missed playing time. By recording every injury, in effect they degraded the data by including even minor abrasions and blisters. Keller et al. (1987) supported the inclusion of an element of time lost from practice or play in the definition, which was used by Sullivan et al. (1980), Ekstrand and Gillquist (1983). Lewin (1989), McGregor and Rae (1995), and Inklaar et al. (1996) refined the definition by including injury from participation in soccer leading to missing training or a competitive game. Lewin (1989) used the expression: "loss of two games or training sessions" in the definition. Hawkins and Fuller (1999) used missed competition and training of at least one day, not including the injury day. The National Athletic Injury Registration System (NAIRS) of the United States defined an injury as reportable if it limits athletic participation for at least the day after the day of the injury (van Mechelen et al., 1992). This definition seems more useful, but it does not cover all aspects of injury. The Council of Europe defined injury as an injury occurring as the result of participation in official soccer activities with one or more of the following consequence: reduction in the amount of sport activity, need for advice regarding treatment, and adverse social or economic effects (Dvorak and Junge, 2000).

Injury can also be described in terms of its severity. Injury severity is usually classified as minor, moderate or major depending on the length of time needed for recovery. A later definition of injury is based on its severity. van Mechelen et al. (1992) recommended the following criteria to account for the degree of injury severity: type of injury, length of treatment, absence from training and game, work disability, structural changes and permanent damage to the body, and costs of injury.

Coding and recording of injuries should be through the consistent use of a set of established definitions of injury, which are extensive and sufficiently descriptive to avoid error due to subjectivity. An operational definition could be one that precludes participating in the next game, or in training for two consecutive occasions.

Incidence and prevalence are the two common frequency rates, which have been reported in the sport injury literature (Powell et al., 1986). Prevalence rates concern the total number of cases, new or old, that exists in a population at risk at a specific period of time. Incidence rates concern the number of new injuries that occur in a population at risk over a specific period of time. Therefore, prevalence is a static measure and incidence rate is dynamic (Hunter and Levi, 1988).

2.1.2. Injury incidence rates in soccer

The injury incidence rate refers to the number of new injuries in a certain period of time divided by the total number of players predisposed to injury (Kuhn et al., 1997). The injury incidence rate has been calculated in different ways. In some investigations it has been calculated per 1000 hours of soccer irrespective of being related to games or training times (Inklaar, 1994a). In other research reports, the injury incidence rate has been calculated for both 1000 hours of games and 1000 hours of training (Ekstrand et al., 1983; Ekstrand and Tropp, 1990; Inklaar et al., 1996; Hawkins and Fuller, 1999). Thus, the risk per 1000 hours of exposure is calculated as: the number of injuries × 1000/total hours of exposure.

Inklaar (1994a) reported an overall analysis of injury incidence rate from different studies, ranging from 0.5 to 45 injuries per 1000 hours of games and training. The incidence of reported injuries varies due to different methods of data collection, study design and sample characteristics, as well as different definitions for injury.

As the popularity of soccer has grown, soccer injuries have become the subject of increasing medical interest, and many injury studies have been reported (McMaster and Walter, 1978; Sullivan et al., 1980, Albert, 1983; Ekstrand and Gillquist, 1983; Ekstrand et al., 1983). These data are summarised in Table 2.1.1.

Hawkins and Fuller (1996) reported the injury incidence (the ratio of the injuries recorded to the number of players taking part in all the matches analysed, expressed as a percentage) of 27.7 % per player for all injuries in 44 games played, and an injury frequency rate (number of injuries per 1000 hours of competition and/or training) of 6880 injuries per 100 000 hours played. With respect to injuries, which resulted from player to player contact, Hawkins and Fuller (1996) reported that 64 % of observed injuries were as a result of contact injury, which is in agreement with Hoff and Martin (1986) and Sandelin et al. (1985) who reported 66 % and 52 %, respectively. For each team, the average injury incidence of moderate injury is estimated to be 113/1000 game hours (Hawkins and Fuller, 1996) and 300/1000 game hours (Ekstrand et al., 1983). Hawkins and Fuller

(1999) later reported 8.5 injuries/1000 hours over three seasons of competition. In terms of the number of players injured at each club during each season, Hawkins and Fuller (1999) reported an astonishing 86 to 100%, which compares favourably with previous reports for UK clubs (91 % by Lewin, 1989, and 71-79 % by McGregor and Rae, 1995). This figure reveals the high risks to which players are exposed. Schmidt et al. (1985) reported that during a soccer tournament with 6600 participants, 5.2 % of the players were injured. The incidence of injury for an individual player was 19.1/1000 playing hours. Ekstrand and Gillquist (1983) estimated that the incidence of injury for an individual player during a year was 7.6/1000 practice hours and 16.9/1000 game hours. They reported that 256 injuries occurred among the 180 players during the year, that 62 % were minor injuries (absence from practice of less than 1 week), 27 % moderate injuries (absence from practice of more than 1 week but less than 1 months), and 11 % major injuries (absence from practice of more than 1 month). Nielsen and Yde (1989) found the injury incidence of all players was 3.6/1000 practice hours and 14.3/1000 game hours. Engstrom et al. (1991) reported that out of 41 players, who participated in soccer competition for 1 year, 80 % sustained 78 injuries during the year and so the incidence of injury was 24/1000 hours during the games, and 7/1000 hours during training.

Approximately two-thirds of injuries occur during competition and one-third during training. This proportion has been demonstrated in several investigations (MacMaster and Walter, 1978; Sullivan et al., 1980; Ekstrand and Gillquist, 1982, 1983; Albert, 1983; Ekstrand et al., 1983; Nielsen and Yde, 1989; Engstrom et al., 1990). Due to the high intensity of activity in competition, it would be expected that more injuries occur during competition than in training.

Table 2.1.1. Injury incidence rate (per 1000 hours) in game and training soccer (Dvorak and Jung, 2000). Studies are listed in reverse chronological order.

Authors	No. of players	Population	Study period	Games	Training
Hawkins and Fuller, 1999	108	Professional players	3 seasons	25.9	3.4
	30	Youth players	3 seasons	37.2	4.1
Luthje, 1996	263	Elite players	Season	16.6	1.5
Inklaar et al., 1996	75	Adolescents	Season	12.8	
	78	Adolescents	Season	16.1	
	79	Adolescents	Season	28.3	
	245	Adolescents	Season	15.8	
Arnason et al., 1996	84	Elite players	Season	34.8	5.9
Poulsen et al. 1991	19	Division 1	1 year	19.8	4.1
	36	Series 3 & 5		20.7	5.7
Engstrom et al., 1990	64	Elite players	1 season	13	3
Ekstrand and Tropp, 1990	639	Senior players	1 year		
	135	Division 1		21.8	4.6
	180	Division 2		18.7	5.1
Ekstrand et al., 1983	180	Division 4	1980	16.9	7.6
	144	Division 6		14.6	7.5
Nielsen and Yde, 1989	34	Division level	Season	18.5	2.3
	59	Series level		11.9	5.6
	30	Youth		14.4	3.6
Hoff and Martin, 1986	455	Adolescents	Competition	7.4	
Maehlum et al., 1986	1016	Adolescents	Norway Cup	9.9	
Schmidt et al., 1985	5275	Adolescents	Tournament	16.1	
Nilsson and Roaas, 1978	25,000	Adolescents	Tournament	14	

With respect to injury incidence rate and level of competition, Roass and Nilsson (1979), Sandelin et al. (1985), Nielsen and Yde (1989), and Ekstrand and Troop (1990) found a direct relation between injury incidence rate and the level of competition with the higher incidence rate associated with the higher level of play. In contrast, Hawkins et al. (1998) reported that there is no relation between injury incidence rate and level of competition. The weight of evidence suggests that players who play at a high level can expect to sustain more injuries than players who take part in competitions at a lower level.

In relation to data collection methods, Hawkins and Fuller (1998) determined injuries using indirect methods, i.e. by watching videos of matches, newspaper reports and contact with medical staff. Roass and Nilsson (1979), and Schmidt et al. (1985) obtained their data from contact with medical staff and service staff who had access to records. Cattermole et al. (1996) used questionnaires. Nilsson and Roaas (1978) and McMaster and Walter (1978) used the trainer for gathering data while Sullivan et al. (1980) made contact with coaches and parents for collecting information. The above methods are common in the collection of data for analysis of injury. Also it should be mentioned that directly watching the video recording of matches and then compiling information by reference to hospital records, using the personal medical documents and seeking information from the trainer are preferable to using only questionnaire or contact with parents and so on for gathering data. When there is no access to hospital records and personal documents or the trainer, a questionnaire can be used.

2.1.3. Nature of injuries

Many investigators have reported that strains, sprains and contusions are the predominant injuries sustained during both competition and training. These represented 65-80 % of all injuries in soccer (McMaster and Walter, 1978; Ekstrand and Gillquist, 1982, 1983; Albert, 1983; Poulsen et al., 1991; Hawkins and Fuller, 1999) (Table 2.1.2).

Table 2.1.2. Nature of injuries (%) published in six major studies.

	Albert, 1983	Ekstrand and Gillquist, 1983	Ekstrand and Gillquist, 1982	Hawkins and Fuller, 1999	McMaster and Walter, 1978	Poulsen et al., 1991
Sprain	27.6	29	41	40	35	71.8
Strain	31	18	13	20	47	12.3
Contusion	17.6	20	10	20	8.3	
Dislocation	3.5	2			5	7
Fracture	3.5	4		4	1.7	3.5
Bursitis	4.2	23	15		3.3	
Wound					3.3	3.5
Concussion	2.1					5.3
Others	10.5	4		9		5.3

Hawkins and Fuller (1999) reported a higher percentage of strains during both competition and training sessions in English soccer teams compared to European teams, which were examined by Ekstrand and Gillquist, 1983; Engstrom et al., 1990 and Angliett et al., 1994. Hawkins and Fuller (1999) claimed this difference may be due to less attention paid to general body conditioning in terms of strength and flexibility training, warming up and cool down by English soccer players.

Arnason et al. (1996) and Nielsen and Yde (1989) reported that most soccer injuries are traumatic, and the proportion of injuries caused by overuse varies from 9 % to 34 %. Inklaar et al. (1996) found that the distribution of traumatic and overuse injuries are not related to age. The distributions of injuries of English soccer players over two competition seasons are shown in Table 2.1.3. As explained earlier and as this table shows, most injuries occurred during competitive matches and most of them were traumatic.

Table 2.1.3. Nature of injuries sustained during competition and training (%) (Hawkins et al., 2001).

Nature of injury	All injuries	Competition	Training
Muscular strain/rupture	37	35	42
Ligamentous sprain/rupture	19	20	18
Muscular contusion	7	9	4
Tissue bruising	6	7	3
Fracture	4	5	3
Other	4	3	5
Tendinitis	4	3	5
Inflammatory synovitis	3	3	4
Meniscal tear	2	2	3
Hernia	2	1	2
Overuse	2	1	2
Dislocation	1	1	1
Periostitis	1	1	1
Cut	1	2	1
Chondral lesion	1	1	1
Capsular tear	1	1	0
Paratendinitis	1	0	1
Bursitis	1	0	1
Blister	0	0	0
Skin abrasion	0	0	0
Not classified	3	3	2
Total	101	98	99

The vast majority of soccer injuries, over two-thirds of the total, can be regarded as minor. Around one-quarter is moderate in severity, necessitating absence from full activity for between 1-4 weeks. The remainder cause absence for longer than one month and are deemed to be serious. Studies of severity of injuries of English soccer players over two competitive seasons are shown in Table 2.1.4. The table shows 33 % of all English soccer players' injuries are slight and minor, 45 % moderate and the rest major.

Table 2.1.4. Severity of injuries sustained during competition and training (%) (Hawkins et al., 2001).

Nature of injury	All injuries	Competition injuries	Training injuries
Slight	10	9	11
Minor	23	24	21
Moderate	45	45	46
Major	23	22	22
Total	101	100	100

2.1.4. Location of injuries

With respect to location of injury, the prospective and retrospective studies reviewed in Table 2.1.5 indicate that a majority of injuries occur in the lower extremity (64-88 %). The most frequent sites of injury in the lower extremity are ankle, knee joint, and the upper leg (thigh). These injuries account for up to 35 % (Nielsen and Yde, 1989), 23% (Engstrom et al., 1991), and 23 % (Hawkins and Fuller, 1999) of all injuries, respectively.

Hawkins et al. (2001), in an intensive study on English soccer players, reported that greater number of injuries was sustained to the players' dominant side compared with the non-dominant side (50 % v 37 %). The lower extremity was the site of 87 % of injuries.

Table 2.1.5. Injury location as identified in various studies (%).

Location of injury	Albert et al., 1983	Ekstrand et al., 1983	Engstrom et al., 1991	Poulsen et al., 1991	Brynhildsen et al., 1990	Sandelin et al., 1985	Nielsen and Yde, 1989	Hawkins et al., 2001
Head/Spine	16.8	5	4		4.8	22		7
Upper extremity	7.8				5.6	14		3
Lower extremity	75.4	88	88	93	86.8	64		12
Hip/ Groin	11.3	13	6	13.6		9		12
Upper leg	17.7	14	15	6			35	23
Knee	17.6	20	23	23	20.1	22	22	17
Lower leg	4.2	12	9	2	14	6	19	
Ankle	24.6	17	26	19	9.6	20	8	17
Foot/Toe	12	9	7.9	3.6	7		35	6
Other	7	8	2.9	2.8				

2.1.5. Costs of injuries

From an economic point of view, the costs of injuries to soccer players are enormous. Most clubs spend huge amount of money each year for treatment and rehabilitation of injured players. For instance, during a 5-year period, 3616 injured soccer players were registered in Norway and these injuries led to 91500 days lost at work, in addition to £150,000 treatment cost (Roaas and Nilsson, 1979). Ekstrand (1982) reported a loss of US$420,000 in the whole of Swedish Division IV as a result of medical care costs for a season. "It is believed that there are in the region of 20 million sports injuries each year in Britain, about half of which are attributable to soccer alone"(Ball, 2000).

It has also been estimated that about £1 billion represents the cost of treatment and loss of production through time off work as a result of soccer injuries as a whole in Britain each year (Ball, 2000).

Pritchett (1981) investigated the injuries of high school soccer players and an average claim cost of $127 (U.S. dollars) for injuries reported in 1976 and 1977. Inklaar (1994a) stated that in general, a soccer player suffers one injury per year. One soccer injury costs $150 U.S. dollars. About U.S. $30 billion dollars per year has been estimated for the primary medical costs of players injuries registered by the international football association (FIFA).

"The overall level of injury to professional soccer players has been shown to be around 1000 times higher than that of industrial occupations which is generally regarded as high risk"(Hawkins and Fuller, 1999). Furthermore, about 2 percent of professional soccer players are retired each year due to injury (Hawkins and Fuller, 1999).

With respect to the above mentioned evidence, one can conclude that injuries are in fact a big problem in soccer and soccer players are known to be predisposed to high rates of injury compared with participants in other sports and other occupations (Ekstrand, 1982; Hawkins and Fuller, 1998 and 1999). Consequently, to minimise the rate of injuries, the early retirement of professional soccer players and the associated costs, and to provide a safe and healthy sports environment, preventive programmes are highly required.

In summary, it should be noted that treating sports injuries is often difficult, expensive and time consuming. Therefore, preventive strategies and activities are justified on medical as well as economic grounds.

2.1.6. Causes of injury

Injuries in soccer result from a number of complex factors. These are commonly categorised into extrinsic and intrinsic factors. Extrinsic or environment-related factors refer to all factors that impinge externally on the human body (Kannus, 2000) and it include the exercise load (competition and practice), inadequate equipment (shinguards, taping, shoes), playing field conditions, rules, position played, amount of training and foul play. Intrinsic or person-related factors refer to the makeup of an individual person include age, psychosocial characteristics, joint flexibility, muscle tightness, functional instability, previous injuries and inadequate rehabilitation (Inklaar, 1994b).

Current knowledge about the aetiology of soccer injuries is very limited. Some intrinsic and extrinsic factors have been identified. With respect to studies that have been done in this area, it can be concluded that intrinsic factors involve approximately 45 % and extrinsic factors involve 55 % of all soccer injuries (Ekstrand and Gillquist, 1983), Table 2.1.6.

Table 2.1.6. Mechanisms of injury (%) (Ekstrand and Gillquist, 1983).

Mechanisms	%	%
Player factors		42
Joint instability	2	
Muscle tightness	17	
Inadequate rehabilitation	12	
Untraining	11	
Equipment		17
Shoes	12.5	
Shinguards	4.5	
Playing surface		24
Rules		12
Other factors		5*
Total		100

* Corrected value. The original value quoted was 29 % which would lead to a total injury > 100 %.

Injury mechanisms associated with contact between players including tackling, being tackled and collisions accounted for 41% of all injuries (Hawkins and Fuller, 1998), a figure which is in agreement with Anglientti et al. (1994). Hawkins et al. (2001) in the later study reported that 38% of all the injuries were player-to-player contact injury as a result of tackling, being tackled and collisions (Table 2.1.7).

Ekstrand and Gillquist (1983) reported that running and turning were mechanisms for "no-contact" injuries. Of "non-contact" injuries, running, shooting, turning and overuse injury mechanisms were high and explained 45% of all injuries (Hawkins and Fuller, 1998). So, more attention should be paid to the main critical playing actions that are performed during the game.

Table 2.1.7. Mechanisms of injuries sustained during competition and training (%) (Hawkins et al., 2001).

Mechanisms	All injuries	Competition injuries	Training injuries
Running	19	16	26
Tackled	15	20	7
Other (non-contact)	9	8	11
Tackling	9	12	6
Twisting/turning	8	6	12
Collision	6	8	3
Stretching	6	6	6
Kicked	5	6	3
Shooting	4	3	8
Landing	4	4	3
Passing	4	3	4
Jumping	2	2	3
Other (contact)	1	1	2
Falling	1	1	1
Diving	1	0	2
Heading	1	1	0
Use of elbow	1	1	0
Hit by ball	0	0	1
Dribbling	0	0	0
Throwing	0	0	0
Not specified	4	3	2
Total	100	101	100

2.1.7. Injury and time of play

An additional view into the aetiology of an injury can be gained by considering the time of injury. With respect to time of injury occurrence, Hawkins and Fuller (1999) reported that more injuries were observed during the final 15 minutes of the first half and the final 30 minutes of the second half for both professional and young players. The results of Hawkins et al. (2001) in relation to times of injuries are shown in Figure 2.1.1. As a result of fatigue and consequently decreased work-rate and increasing mistakes, it would be expected that more injuries happen in the last 30 minutes of the game.

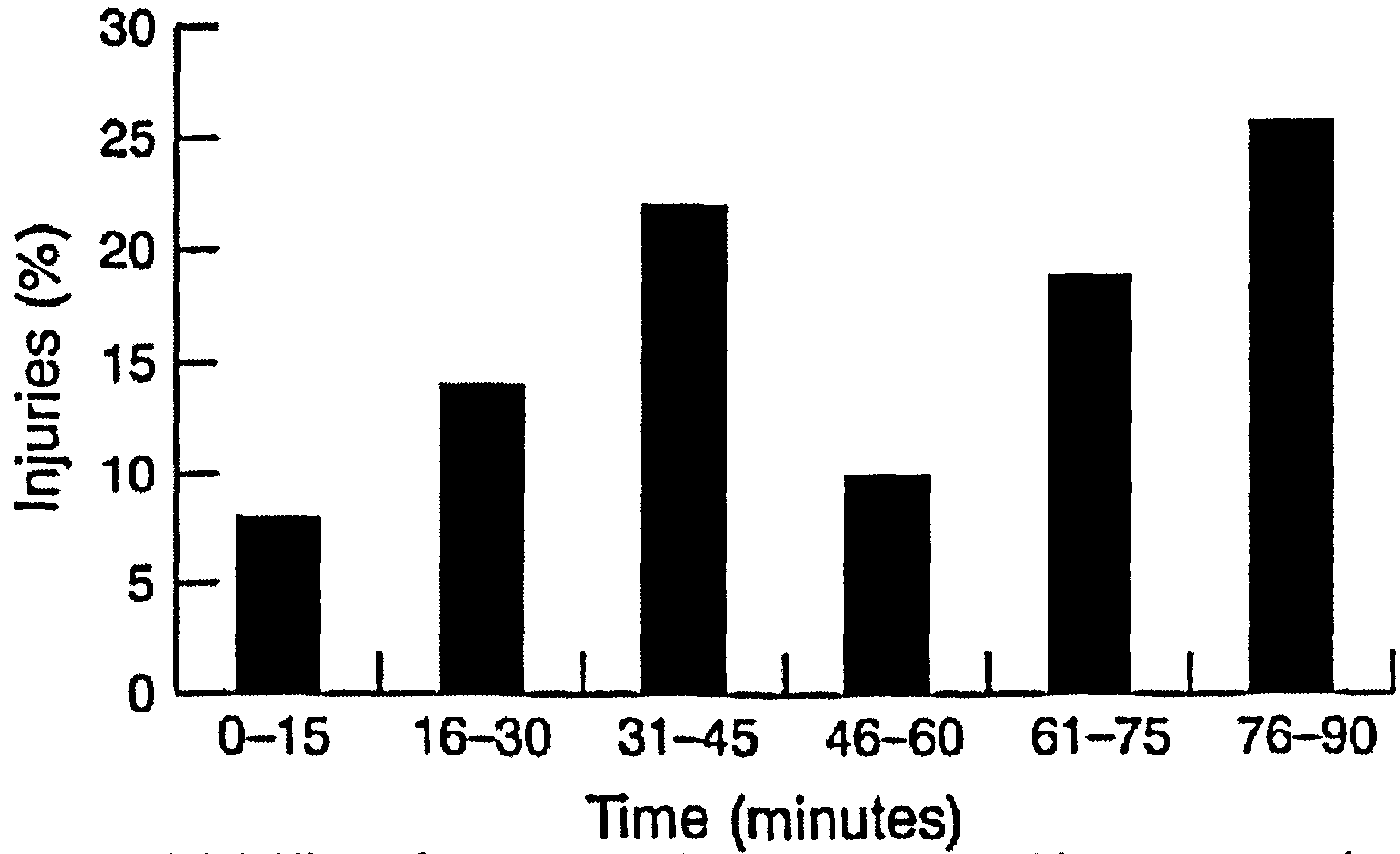


Figure 2.1.1. Time of occurrence of injuries in competitive soccer matches (Hawkins et al., 2001).

In summary, the previous mentioned aspects of soccer injuries, namely the definition, incidence, nature, location, costs, causes, and time are all related to actual injuries in soccer, there is clearly a lack of documents related to risk of injury associated with playing actions during a game. However, to understand fully the risk of injury that a player is exposed to during soccer play, it is necessary to analyse the actions made in a game and to relate these actions to the risk they may possess and the subsequent injuries which may result from them. It therefore provides a more detailed understanding of injury risk, which will have importance for designing appropriate injury prevention and rehabilitation programmes.

2.2. NOTATION ANALYSIS

Soccer play includes a numbers of main actions such as walking, jogging, running, sprinting, cruising and also many skills such as dribbling the ball, heading the ball, passing the ball and so on. The beauty and attraction of soccer are related to these movements as well as to the scoring of goals. There are high risks of injury in these actions. For prevention of injury, risk factors should be identified. In order to facilitate the identification of these factors, a notation analysis system is required. Regarding the importance of notation analysis, Reilly (1993) stated that notation analysis can be helpful in identifying precursors of injury.

The improvement and development of athletes' performance are the primary concerns of coaches. Brackenridge and Alderson (1985) claimed that coaching is a conscious act of interference, with respect to enhancement of performance. Major problems are the accurate evaluation of performance and then representing the results correctly. It has been reported that coaches' observations are often not clear or complete. For instance, Knapp (1963) completed a study in relation to memory and indicated that there are severe limitations in accurately remembering information about play. Franks and Miller (1986) reported that the maximum number of discrete items that most people can visually see, in a quick look, is between five to nine. It is very clear that coaches need to perfect a system for recording performance. Notation analysis provides an accurate and objective system of performance evaluation and therefore any planned intervention is less subjective.

In response to these problems, notation analysis systems have been developed. With reference to history it can be noted that dance notation was the initial system of movement notation. The first system of dance notation is known as "Labanotation" which was created by Rudolph Laban in 1948. The method that Rudolph Laban designed was useful for years. Rudolph Benesh and Jean Benesh (1956) after eight years developed the "Labanotation" and their system was known as "Choreology". Movement notation continued to develop. The analysis of soccer team performance existed in simple forms such as pen-and-paper systems, for many years. These systems were limited in terms of data collection and therefore in the level of analysis. Frank and Goodman (1986) stated that one of the main problems in attempting to analyse team games is the existence of a large number of potentially interacting variables in any game, which may be too complex for manually based systems to follow.

At the present, notation systems exist in various forms, depending on the coach's needs. Hand notation systems are the simplest form and have been used for many years. Various systems were developed to collect data and provide descriptive information related to play, e.g. Downey (1973) in tennis, and Reep and Benjamin (1968) in soccer. Reilly and Thomas (1976) pioneered work when they developed a motion analysis system to estimate the work-rates of professional soccer players. The system was designed to obtain data that could be interpreted in physiological terms e.g. distances covered or different intensities, exercise to rest ratios and so on.

Several investigators have used hand notation and computer analysis in combination for their studies. For example, Reilly and Thomas (1976) and Withers et al. (1982)

used hand notation for analysis of movement and work-rates. Reep and Benjamin (1968) and Hughes (1973) used hand notation systems for simple analysis of event outcomes, such as number of passes leading to goal and so on. Ali (1988), Bate (1988), Harris and Reilly (1988), Pollard et al. (1988), Partridge and Franks (1989, 1990), Hughes (1993), Yamanaka et al. (1993) and McGarry and Franks (1995) all used computer based systems for notational analysis. This focus was primarily analysis of tactics and pattern of play.

The newest system of entering data into the computer was generated by developments in computer software, i.e. the mouse and visual basic programming methods. These allowed a representation of the pitch and the relevant activities to be illustrated on the computer monitor. Then, by using the mouse and video recordings, the relevant information could be entered quickly and accurately. These developments addressed the main problems with hand notation systems, i.e. improved speed of producing results and greater ease of entering relevant information. With advanced technology, investigators should be able to produce results within minutes, allowing them to give immediate feedback to coaches and other team staff.

The latest computerised systems designed by Prozone (Leeds) permit the analysis of work-rates (discrete individual movements) and patterns of play (notation). The system utilises six camera placed on the stands side-on to the pitch and all linked to a common computer. The analysis is very expensive and is not generally available. Its advantage is that it combines motion analysis of all players on the field with a notation analysis of the pattern of team play.

In summary, the hand notation system represents the simplest form of behaviour analysis and has been used for many years. Various systems were developed to collect data and provide descriptive information related to playing football. Reilly and Thomas (1976) employed a motion analysis system in order to estimate the work-rates of football players. Since then, hand notation has been complemented by computerised methods of analysis for the rapid processing of data. For example, McGarry and Franks (1995) used a computer-based system for notational analysis to create models of the game and to identify winning tactics. The newest systems allow data to be entered into the computer directly using a representation of the pitch or relevant activities to be illustrated on the computer monitor. By using the mouse and video recordings, the relevant information can be entered quickly and accurately. These developments have addressed the main problems of hand notation systems, which were concerned with the ease of entering relevant information and the speed of producing results (Hughes, 1996).

There has been no serious attempt to design a definitive notation analysis system for assessing injury or injury risk in football, both by hand notation and computerised notation system, which Reilly (1993) claimed "analysis is also useful in identifying precursors of injury as errors. An error starts a chain of events leading to an accident, which sometimes causes an injury". A crucial aspect for the researcher is the identification of crucial events (or critical incidents) in this causal chain. As there is practically no research in this area in a sports context, this thesis represents an attempt to fill the gap.

2.3. MUSCULOSKELETAL STRENGTH IN SOCCER

2.3.1. Types of muscle actions

In order to appreciate how muscle can get damaged, it is appropriate to consider how muscles work. Muscle actions are classified into three categories according to the nature of the applied load or by the velocity and directions of change in the length of the muscle. The actions are referred to as isometric (static), concentric (shortening), and eccentric (lengthening) actions (Lieber, 1992).

In isometric, or static contractions, the muscle acts to develop tension against a fixed object or resistance. The distance between the origin and the insertion does not change, and no movement of the lever arm occurs. The development of tension during isometric action depends on the degree of voluntary effort exerted by the subject. In concentric contraction, which are described as isotonic (fixed load, changing angular velocity), the distance between the origin and the insertion of the muscle becomes shorter as it develops tension. In eccentric contraction, isotonic or "isokinetic", the muscle is forcibly lengthened while contracting, and the distance between the origin and the insertion increases.

Muscles can operate concentrically or eccentrically in an isotonic movement. Isokinetic or same velocity, refers to limb movement at a pre-set angular velocity. Such control is possible with the use of isokinetic equipment. Such machines are use for assessment of muscle function and for training during rehabilitation after injury.

2.3.2. Modes of testing muscle strength

The capacity of muscle to produce force can be assessed through either static or dynamic contractions. The modes of testing have been categorised into three types namely the isometric, isotonic (isoinertial) and isokinetic mode. The isometric mode of muscle strength assessment involves contraction against a fixed object and it measures a muscle's maximum potential to produce static force (fixed resistance and a fixed speed of 0 $rad.s^{-1}$). Early objective testing of isometric strength was performed with cable tensiometry for multiple joints, handgrip and back-lift dynamometry for specific muscle groups. The cable tensiometer, originally designed to measure the tension of aircraft control cables, was proposed as a tool for measuring the strength of various muscle groups by Clarke (1948).

The term isometric, when literally translated, means equal length. When a muscle is contracted without any appreciable change in length this is referred to as isometric contraction, which a muscle is contracted but cannot be said to be acting either concentrically or eccentrically. Hislop and Perrine (1967) described isometric contraction as muscular contractions against a load which is fixed or immovable or is simply too much to overcome.

Strength may be evaluated by static assessment (i.e. isometrically) measuring the force generated against a force plate or tensiometer. Static strength assessment is performed without joint movement. The peak value is expressed as maximum voluntary contraction (MVC). Due to the specific fixed joint angle and the muscle tested, these static tests are minimally functional but have high reliability. The utility of this assessment is improved when isometric tests are performed at multiple angles/positions through a joint's range of motion.

Isometric strength is possibly important in maintaining a player's balance on the pitch and also in contributing to ball control. Reilly (1996b) "stated that soccer players are generally found to be only a little above average in isometric muscle strength. This may reflect inadequate attention to resistance training in their habitual programme. Besides, isometric strength may not truly reflect the ability to exert force in dynamic conditions. It may also be a poor predictor of muscle performance in the game".

Isotonic testing involves a fixed resistance (constant load) and a variable speed. Isotonic strength can be measured dynamically with dumb-bells, barbells, and various commercial devices. Abernethy et al. (1995) stated that the term "isoinertial" is a more scientific word and should be used instead of isotonic. The strength of a particular muscle group is commonly determined by testing the maximum amount of weight that can be lifted through a joint's range of motion for either 1 repetition (1 RM) or 10 (10 RM).

The concept of isokinetic exercise, which was developed by James Perrine and introduced in the scientific literature by Hislop and Perrine (1967) and Thistle et al. (1967), is defined as dynamic muscular action when velocity of movement is controlled and held constant by a special isokinetic devise (fixed speed).

Isokinetic devices allow individuals to exert as much force as they can generate in movements up to a predetermined velocity.

2.3.3. History of isokinetic assessment

Musculoskeletal assessment is commonly evaluated using isokinetic dynamometry. The development and improvement of isokinetic technology has made objective quantification of muscle strength possible. Isokinetic assessment can be of major use in sports science to predict muscle performance and to assess performance factors, while in sports medicine it can be useful in preventing, diagnosing and rehabilitating injuries.

Muscle strength is a main part influencing the performance in the majority of sports. Numerous athletes therefore expend a lot of time in developing their muscle strength using different equipment. In recent years, the measurement of muscle force under conditions of constant velocity has become popular. Part of this popularity may be attributed to the facility by which isokinetic dynamometers provide information about dynamic muscular contractions; information that previously was not easily obtainable. Hill (1922) used a flywheel, a series of pulleys, and a hand tachometer to control and record velocity in calculating work and the mechanical efficiency of human muscles (Figure 2.3.1). Laird and Rozier (1979) reported that force, work, and power in dynamic exercise, where velocity is not controlled, are not easily measured because the changing mechanical advantage of the limb-lever system alters the force applied to the muscles through the range of motion employed.

The isokinetic assessment technique has been widely used in the last 25 years in hundreds of scientific research projects and it has been used also in testing and performance enhancement for over 30 years. The first articles regarding the use of isokinetic exercise were published in the late 1960s (Hislop and Perrine, 1967; Thistle et al., 1967; Moffroid et al., 1969). Since that time thousands of authors have reported isokinetic movements as part of their test methodology or use in training exercises.

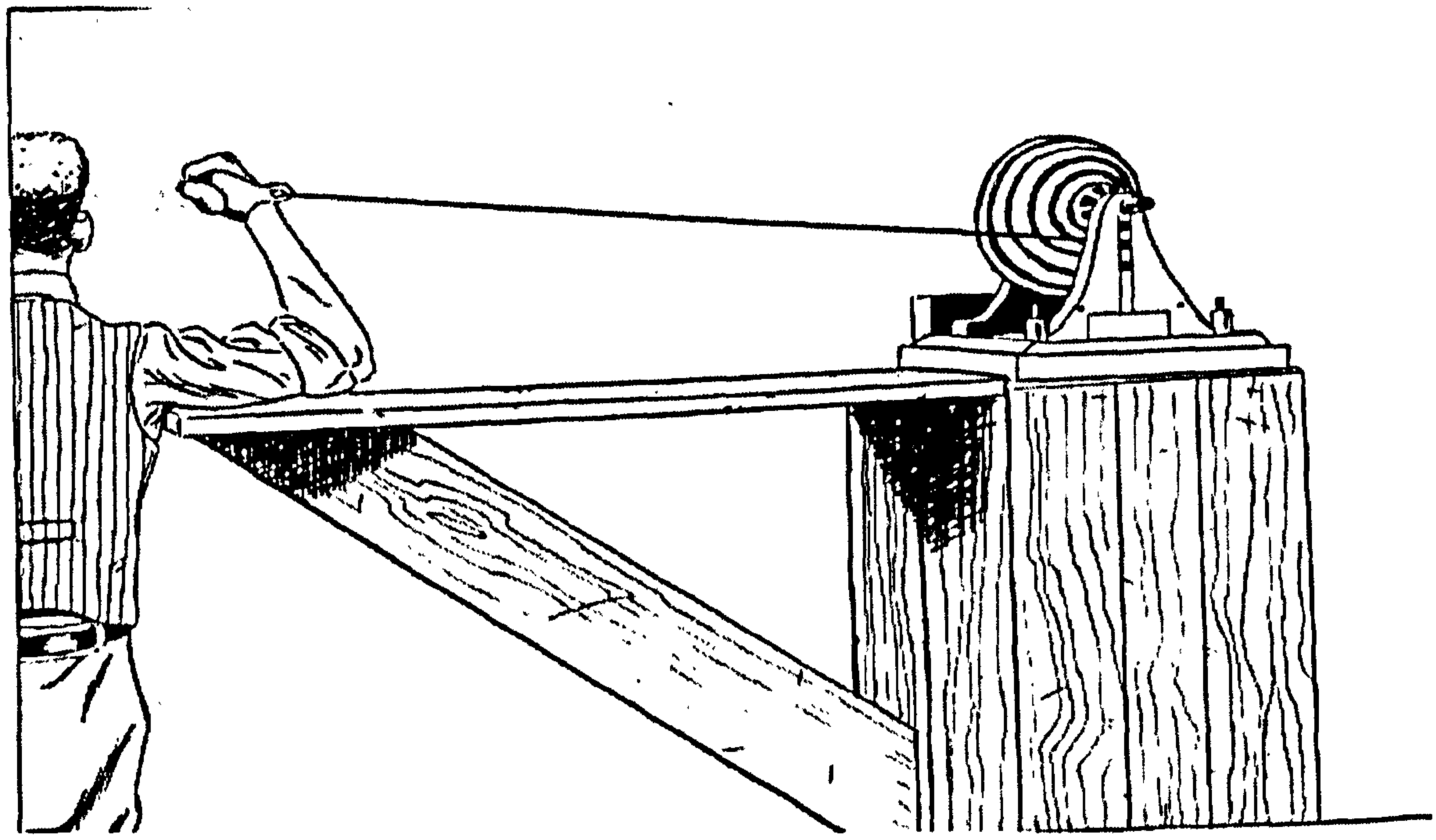


Figure 2.3.1. Flywheel and pulley apparatus used to calculate work and mechanical muscle (Hill, 1922).

Hill (1965) suggested that an instrument should be developed to record concentric and eccentric forces in human muscle. Komi (1969) introduced a dynamometer that measured forces at constant speeds during both concentric and eccentric exercise. The most used of the contemporary isokinetic dynamometers have been the Biodex (Biodex Medical system Inc.), the Cybex II machine (division of Lumex Inc.) introduced by Hislop and Perrine (1967), and by Thistle and co-workers (1967), Isosystem, Spark, the Kin-Com (Chattanooga Group Inc.), the Lido (Loredan Biomedical), and the Merac (Universal Gym Equipment Inc.). The Cybex II is an electrically driven devise, whereas the Kin-Com is hydraulically driven. The major differences in the dynamometers can be found in the maximum angular velocities they offer, and in the ability to test or exercise negative (eccentric) muscle actions. The most common dynamometers currently on the market are shown in Figures 2.3.2 to 2.3.7.

In the late 1960s, isokinetic machines included a simple computer program capable of comparing the information related to bilateral ratio, updated to enable the calculation of total work, power and endurance. The facilities, which are set up on dynamometer, can provide immediate feedback to the therapist and the patient too. Progression in terms of accessories has also provided more scale for muscle testing and rehabilitation. It is now possible to test all limbs. Recently, machines have been developed specifically for muscle training, such as an isokinetic cycle ergometer.

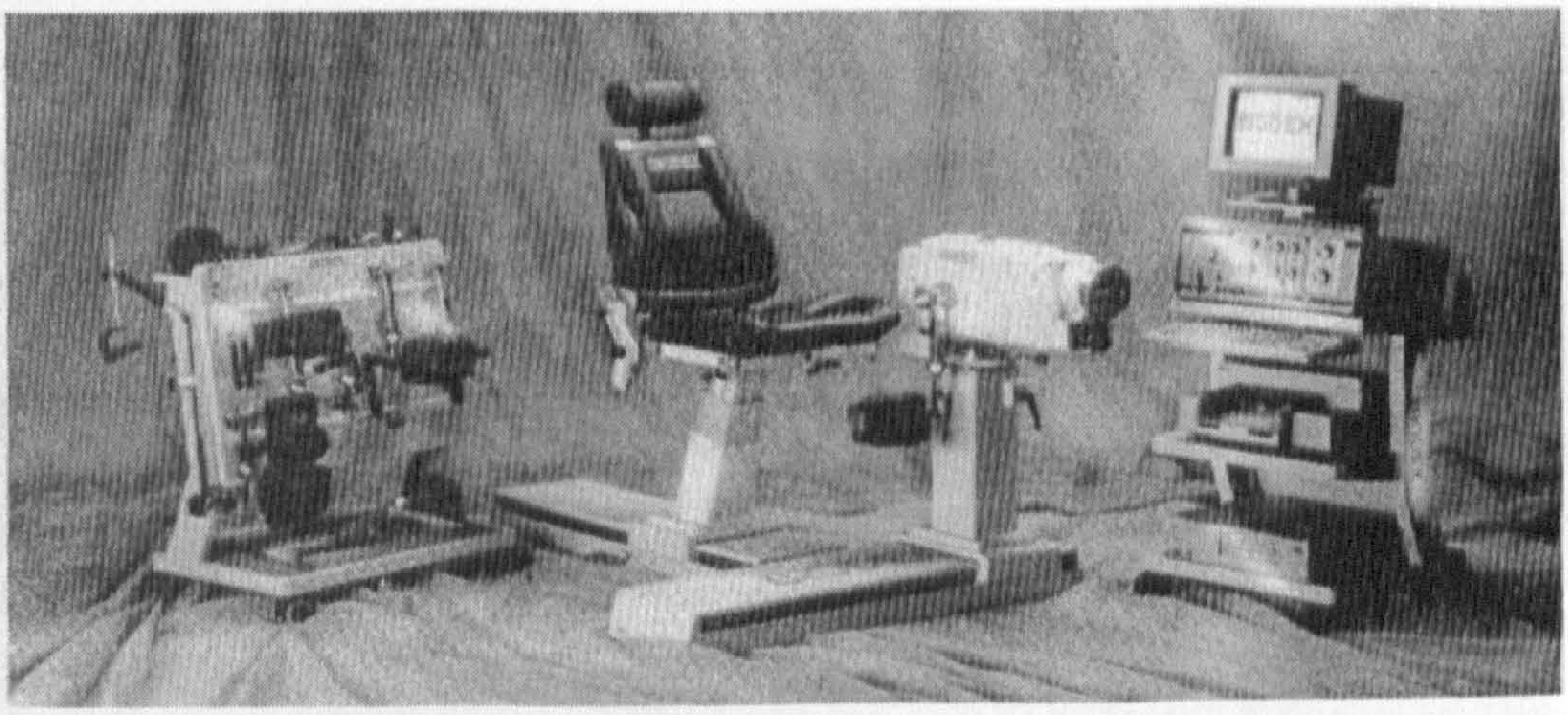


Figure 2.3.2. Biodex, Biodex Medical Systems, Shirley, New York.

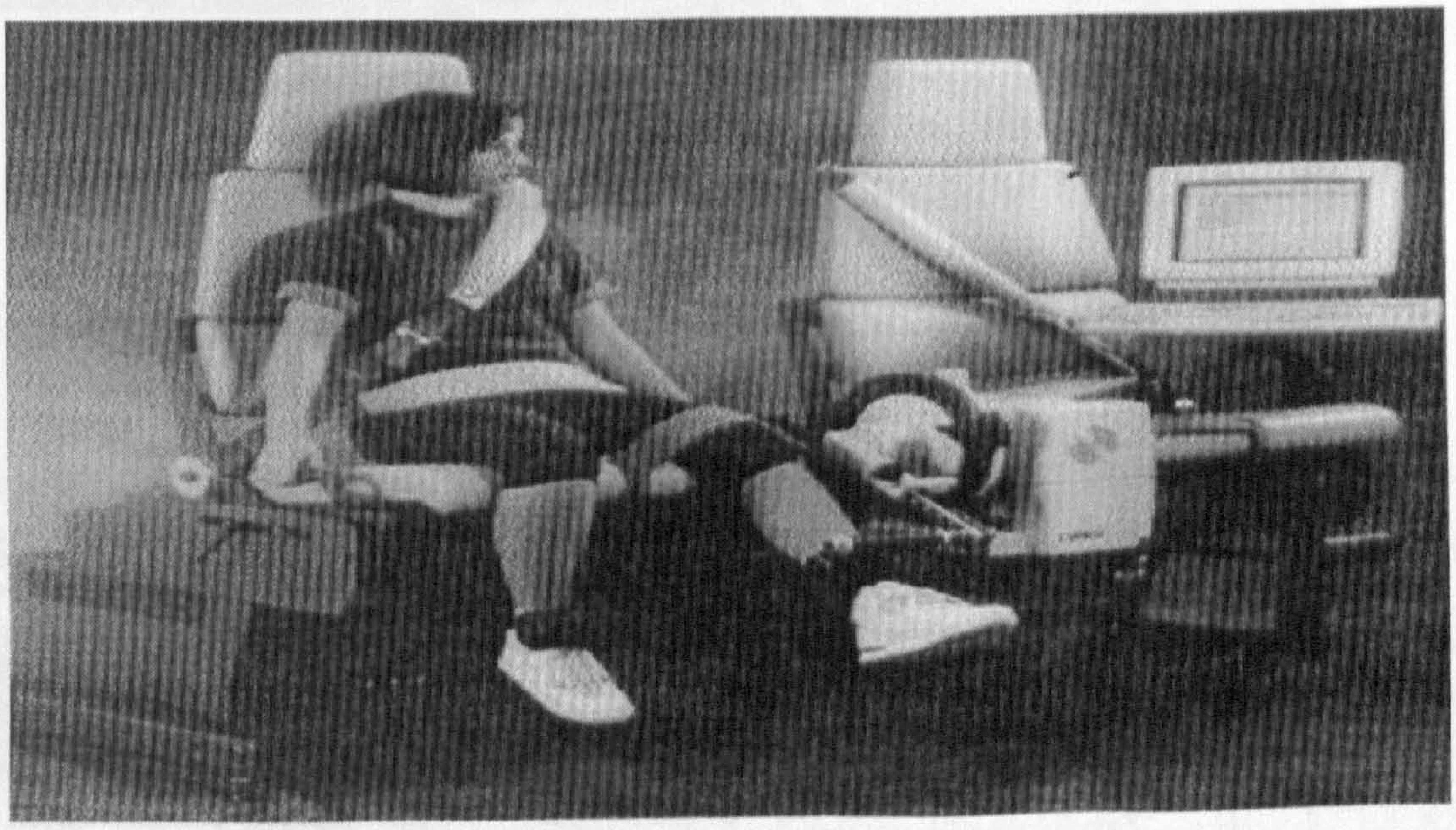


Figure 2.3.3. Cybex 6000, A Division of Lumex, Inc., Ronkonkoma, New York.

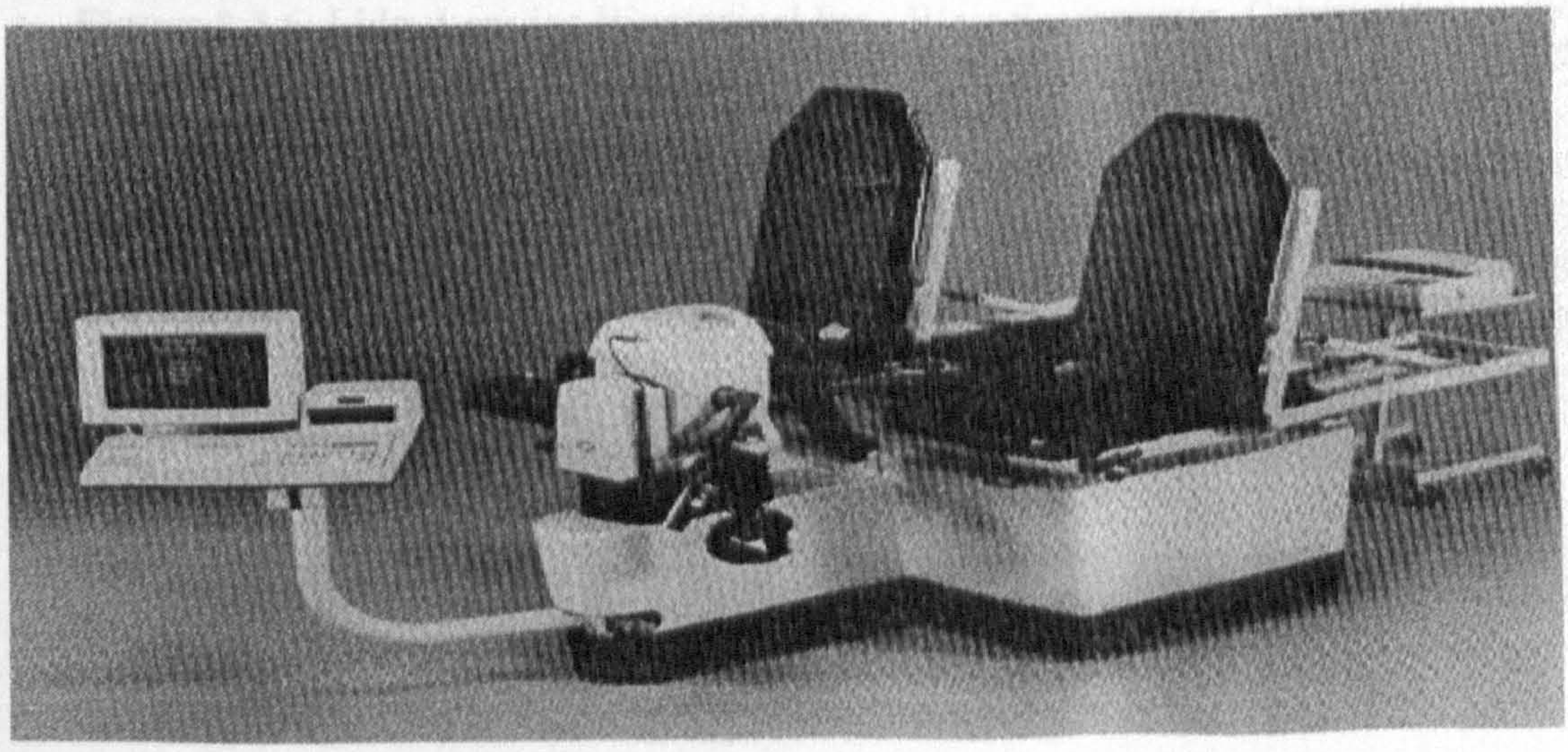


Figure 2.3.4. Kin-Com 500H, Chattanooga Group, Inc., Hixson, Tennessee.

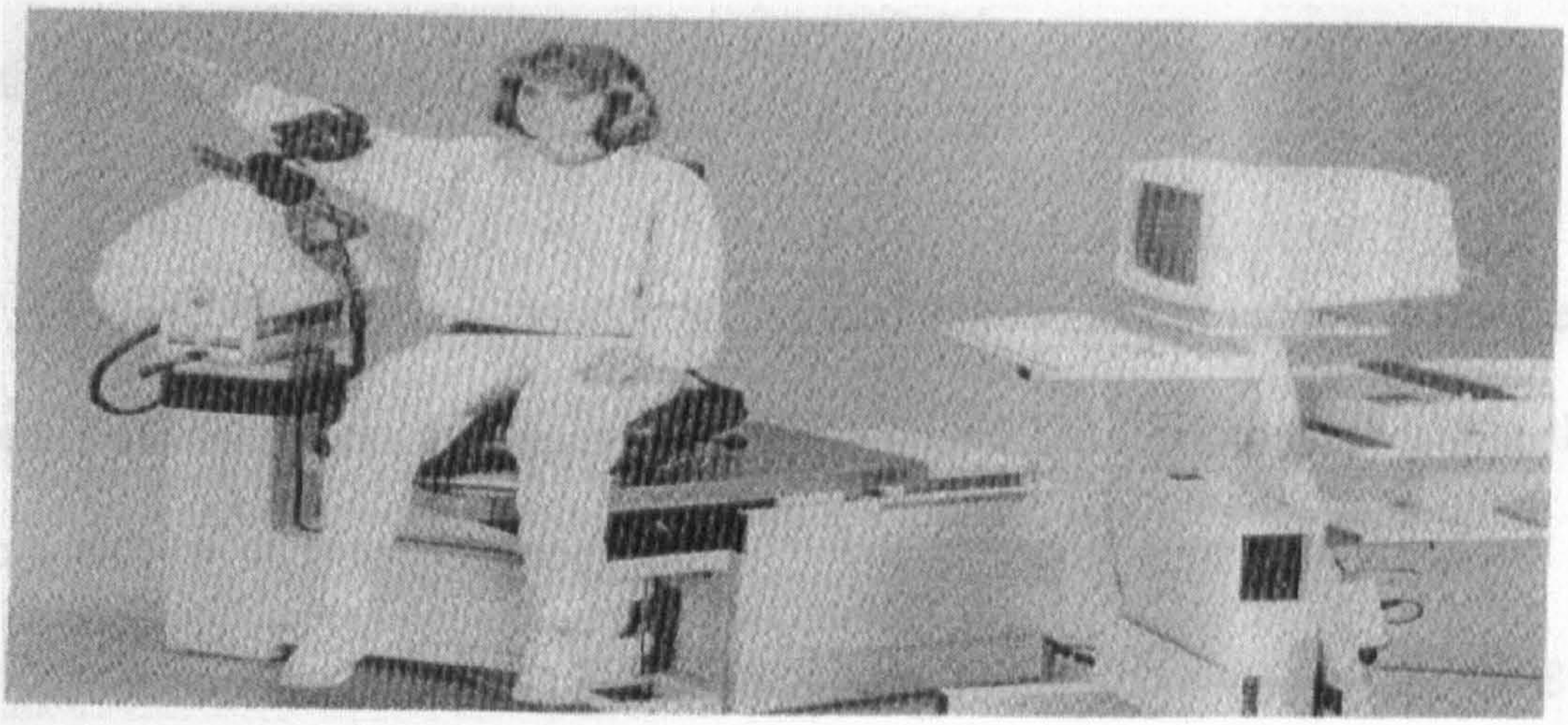


Figure 2.3.5. Kin-Com 125E, Chattanooga Group, Inc., Hixson, Tennessee.

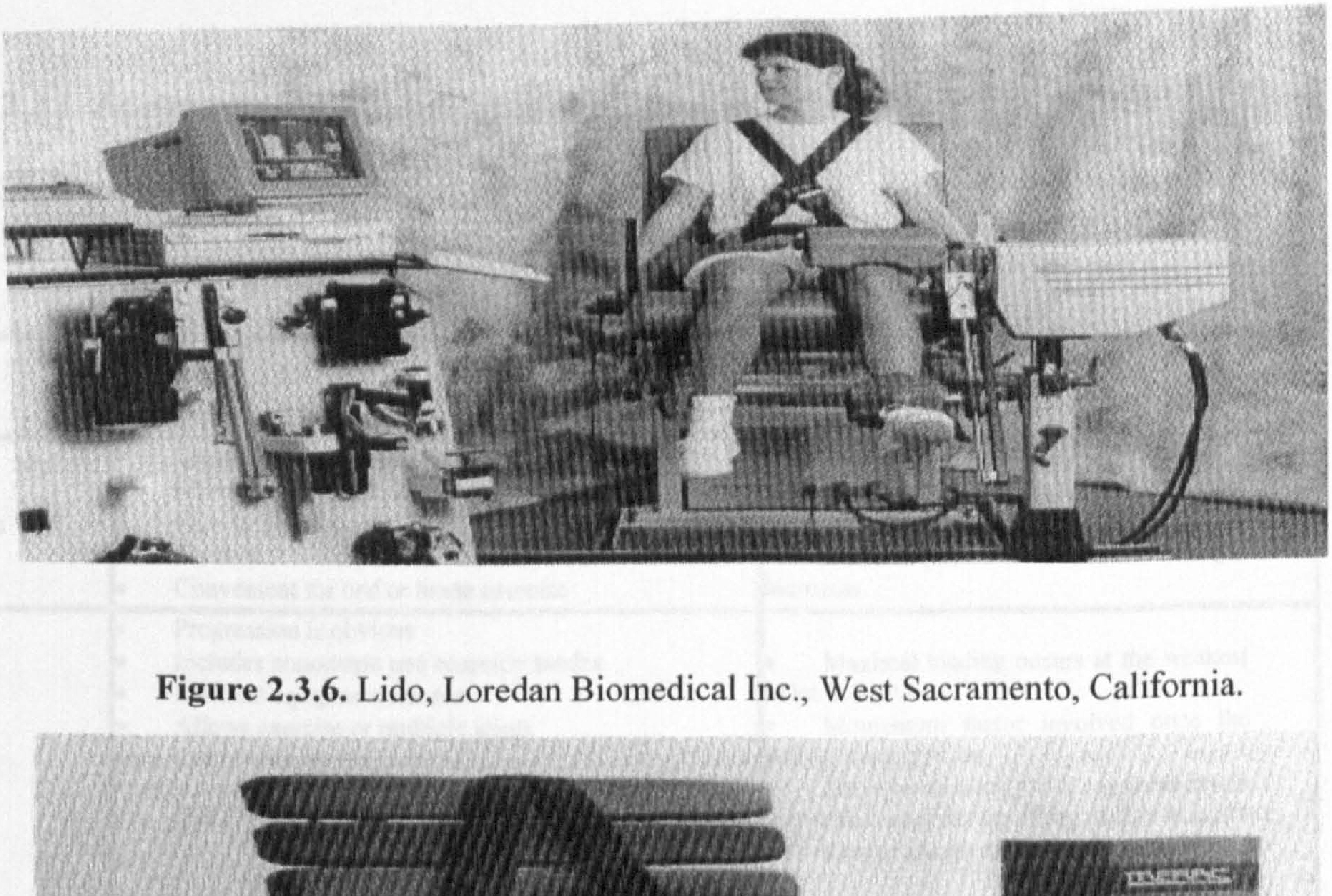


Figure 2.3.6. Lido, Loredan Biomedical Inc., West Sacramento, California.

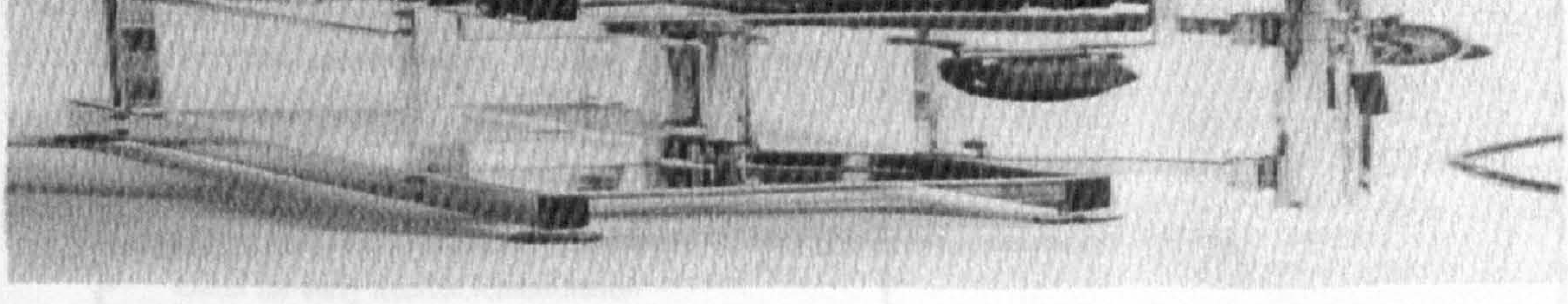


Figure 2.3.7. Merac, Universal Gym Equipment, Inc., Cedar Rapids, Iowa.

2.3.4. Comparison of isometric, isotonic, and isokinetic modes of muscle testing

Wilkie (1950) and Whitley and Smith (1965) stated that the use of cable tensiometers and others forms of static dynamometers has provided little information about the dynamic qualities of muscular contraction. Other types of apparatus designed to measure dynamic forces have been used only sparingly. Some of the main advantages and disadvantages associated with isometric, isotonic and isokinetic modes are summarised in Table 2.3.1.

Table 2.3.1. Advantages and disadvantages of the three modes of muscle testing (Perrin, 1993; Chan et al., 1996).

Modes	Advantages	Disadvantages
Isometric	• Useful if joint movement is painful • Minimal equipment required • Easy to perform • No cost • Convenient for bed or home exercise	• lack of dynamic functions • Strength increase in joint is largely angle-specific • Little objective feedback of strength increases
Isotonic	• Progression is obvious • Includes concentric and eccentric modes • Minimal equipment needed • Allows exercise or multiple joints • Convenient for home exercise	• Maximal loading occurs at the weakest point in ROM • Momentum factor involved once the weight starts moving • Stronger muscle groups can compensate for weaker ones during lifting of free weights • Can be unsafe on already injured joints
Isokinetic	• Maximal dynamic loading through muscles ROM • Objective, reproducible and quantifiable assessment • Provides speed-specific training through the velocity in a given range • Isolation of weak muscle groups by strapping and limiting ROM to a specific angle of movement • Accommodating resistance provides additional safety • Good for early muscle rehabilitation • Functional pattern training possible	• Time consuming • Require specially trained personnel • Cost of equipment

2.3.5. Important Isokinetic parameters relevant to soccer

2.3.5.1. Force-velocity relationship

The effect of the linear velocity during muscle shortening or lengthening on the force output has been examined extensively since the pioneering work of Hill (1938). The ability of a muscle to generate concentric force is greatest at slow isokinetic velocities and decreases non-linearly as the test velocity increases. These changes are compatible with the classical force-velocity relationship described by Hill (1938) and others. From the early study of Fenn and March (1935), Hill (1938, 1950), Katz (1939), and Wilkie (1950), in experiments on frogs, dogs, fishes, cats and other animals, it has been known that when the velocity of shortening (contraction) increased, the force exerted by the muscle decreased in a non-linear way.

In human subjects, the same results were observed (Moffroid et al., 1969; Thorstensson et al., 1976; Lesmes et al., 1978; Perrine and Edgerton, 1978; Campbell, 1979; Gregore et al., 1979; Barnes, 1980a; Osternig et al., 1983; Perrin, 1993) with muscular torque decreasing as the angular velocity of movement increased. This occurred because the number of cross-bridges formed, and the force they exert, are reduced. Barnes (1980b) suggested that the decline in torque output due to increasing angular velocity is a result of different neurological activation patterns of motor at different velocities. A higher output at faster angular velocities indicates a higher percentage of motor units in fast twitch fibres (Gregor et al., 1979). However, with an increase in linear velocity of muscle lengthening, the force exerted is increased (Wilkie, 1950; Chapman, 1976; Thorstensson et al., 1976).

Perrin (1993) later stated that the force-velocity curve produced during eccentric exercise is quite different from the curve resulting from concentric muscular contraction. For instance, while concentric force decreases with increases in contraction velocity, eccentric force remains the same, and sometimes even increases in force production are observed. This difference may be due to differences in the binding and interaction of actin and myosin within the muscle sarcomere.

The force-velocity relationship has been confirmed in isokinetic assessments of soccer players. Costain and Williams (1984) measured the quadriceps and hamstring torque levels of 16 high school soccer players using a Cybex II dynamometer at slow (0.54 $rad.s^{-1}$) and fast (3.24 $rad.s^{-1}$) speeds. They reported a significant decrease in peak torque in both muscle groups from the slow to the fast speed. In addition, Stafford and Grana (1984) assessed the knee extensors and knee flexors of 60 intercollegiate soccer players at functional angular velocities of 1.62, 3.24, and 5.4 $rad.s^{-1}$ on the Cybex II and found the same results.

In a comprehensive study, Oberg and colleagues (1986) tested the isokinetic torque of knee extension and knee flexion in three groups of Swedish male soccer players (national team players, n = 13; division I, n = 15; division IV, n = 180) and a group of non-soccer players (n = 32) at 0.54 and 3.24 $rad.s^{-1}$ angular velocities using a Cybex II devise. Torque values decreased with angular velocity. They also observed quite similar results in another study involving 180 soccer players (Oberg et al., 1984).

More recently, Cometti and co-workers (2001) investigated the isokinetic strength of 95 French soccer players in different level of players, including elite, sub-elite and amateur. The subjects were tested at different ranges from 2.16 to 5.4 rad.s^{-1} using an isokinetic ergometer (Biodex). The force-velocity curve revealed was consistent with previous studies (Moffroid et al., 1969; Scudder, 1980; Oberg et al., 1984, 1986; Ghena et al., 1991; Kannus, 1994; Mognoni et al., 1994). It should be noted that the rate of decline was greater at slow speeds compared to the faster speeds.

In summary, the studies cited tend to show a drop in peak isokinetic torque with increasing angular velocity of movement. An explanation for this phenomenon has been reported by Barnes (1980a) and this trend is explained also in most physiology texts. When velocity is fast there is not sufficient time to recruit all motor units. The suggestion is that there are different patterns of motor unit recruitment at different speeds and qualities inherent to isokinetic measurement, which cause reduced torque output at higher speeds. The reason for such a decline lies in the different recruitment capabilities of different muscle fibres (Grimby, 1985). At lower speeds, both type I and II fibres can be activated maximally while with increasing angular velocity it follows that the slow-twitch type I fibres will remain passive first followed by the fast-twitch type IIA fibres.

The type IIB fibres will be the last to be recruited, but usually at high angular velocities, the torque output becomes reduced (Kannus, 1994).

2.3.5.2. Quadriceps vs hamstrings

It is well documented in the literature that the quadriceps muscle group possesses higher mean torque values (20-40 % greater) than the hamstrings at all angular velocities (Goslin and Charteris, 1979; Wyatt and Edwards, 1981). Knee extension and knee flexion are used to measure these muscle groups. Stafford and Grana (1984) tested the quadriceps and hamstrings muscles of 60 intercollegiate soccer players at angular velocities of 1.62, 3.24, and 5.4 rad.s^{-1} by means a Cybex II. They reported that the quadriceps possessed greater torque than the hamstring muscles at all angular velocities, and the level of differences varied for different speeds (33 % at 1.62, 28 % at 3.24, 20 % at 5.4 rad.s^{-1}). In addition, Agre and Baxter (1987) investigated the musculoskeletal profile of 25 male collegiate soccer players at 0.54 rad.s^{-1} and found a greater value (40 %) in the quadriceps than in the hamstrings in their subjects. If the quadriceps strength greatly exceeds that of the hamstrings, the ability to resist knee extension is reduced which may result in a forced stretch of the hamstrings and consequent muscle damage (Fowler and Reilly, 1993). So, for minimising the injury risk, attention should be paid to keeping the hamstrings to quadriceps ratio closer to unity (Agre and Baxter, 1987; Fowler and Reilly, 1993).

2.3.5.3. Reciprocal muscle group ratio

The muscle groups on both sides of a joint necessarily act reciprocally to produce smooth and coordinated motion. When a muscle group produces a desired joint action it is the agonist for the observed motion. The muscle group producing the opposite joint action is the antagonist (Perrin, 1993). The reciprocal muscle group ratio has been thought to be an indicator of muscular balance or imbalance around the joint (Baltzopoulos and Brodie, 1989). Because of the important role of both muscle groups in knee stability, its ratio is one of the most important parameters used in isokinetic assessment.

Many optimal values for the strength ratio of the reciprocal muscle groups have been suggested in the literature (Moffroid, 1969; Gilliam, 1979; Goslin and Charteries,1979; Wyatt and Edward, 1981; Kannus, 1990). The hamstring/quadriceps strength ratio varies between 50 % and 62 % in healthy people (Moffroid et al., 1969; Coplin, 1971; Gilliam, 1979; Knapik and Ramos, 1980; Parker, 1982) while ratios for soccer players vary between 41 % and 81 % depending upon the angular velocity of movement. Gilliam (1979) showed that the knee flexion/extension ratio was 60% at 0.54 and 77% at 3.24 rad.s^{-1} for high school football players.

Coplin (1971) stated that an imbalance in strength between the knee extensors and knee flexors muscle groups is a factor which leads to an increase in the susceptibility to joint as well as muscle injury. Fowler and Reilly (1993) reported that the ratio between the strength of the knee extensors and knee flexors is of particular interest, a low ratio being associated with a risk of injury.

It is well documented that H/Q ratio increases with increasing velocity (Gilliam et al., 1979; Scudder, 1980; Davies et al., 1981; Wyatt and Edward, 1981; Stafford and Grana, 1984; Oberg et al., 1986). Oberg and colleague (1986) reported that the knee flexion/knee extension ratio (H/Q ratio) was significantly higher for soccer players than for the reference group, but there were no significant differences between the different groups of soccer players. Stafford and Grana (1984) found an increasing ratio with increasing angular velocity in soccer players. They also found that soccer players had a higher ratio than non-players. It seems that soccer training improves strength in the knee flexors. One hundred and fifteen high school football players were screened isokinetically for the knee extensors and flexors torque generating capabilities and muscle imbalances by Gilliam (1979) at 0.54 and 3.24 rad.s^{-1} angular velocities. They reported that flexion to extension ratio at the slow speed was greater for the linemen than the receivers and backs. It seems that linemen are less predisposed to hamstring injury than players in other positions. Cometti and co-workers (2001) reported that the H/Q ratios proposed with two different methods were significantly lower in the amateur group than in the elite group, except at 5.4 rad.s^{-1}. It can be noted that several years of soccer training and match-play at a high level improve the H/Q ratio in professional players and they are less to prone injury than the less skilled players.

The agonist-antagonist relationship for knee flexion and extension may be better described by the more functional ratio of eccentric hamstring to concentric quadriceps, known as the dynamic control ratio. It is thought that this functional H/Q ratio is more suitable to recognise the ability of the knee flexors in stabilising the knee joint than the conventional ratio. Ideally the hamstrings should be able to resist as much force as the quadriceps can produce, which equates to a DCR of 1.0. Due to characteristics of the force-velocity curve it is unlikely that this value will be attainable for all movement speeds, but it is important that a value of 1.0 is attained at movement speeds typical of placekicking. Cometti et al. (2001) reported that due to the importance of the hamstring muscles in some specific soccer activities and the need for stabilisation of the knee joint during critical events, it is recommended that trainers should pay more attention to eccentric actions and strength training in their training sessions, in order to minimise the likelihood of injury occurrence. In soccer, the knee flexors are used concentrically to flex the knee and extend the hip in preparation for a kick and are used eccentrically to control knee extension and hip flexion towards the end of the kicking action (Clarys et al., 1988). If the knee extensor strength greatly exceeds that of the hamstrings, the ability to resist knee extension is reduced which may result in a forced stretch of the hamstrings and consequent muscle damage (Fowler and Reilly, 1993).

2.3.5.4. Bilateral muscle group comparison (left/right ratio)

A lot of interest associated with isokinetic dynamometry lies in the determination of muscle imbalances either left/right or agonist-antagonist relationships because of the common belief that muscle imbalance is related to injury. One of the most common comparisons made by trainers and clinicians to assess patient progress is between contralateral limbs. Contralateral differences in measurements of muscle strength greater than 10-15 % are considered to represent significant asymmetries (Elliot, 1978; Gleim et al., 1978 Davies, 1984). Such inconsistency is thought to predispose to injury at or around the given joint (Kannus, 1994). Kannus (1994) classified bilateral discrepancy into three groups including normal (imbalance in strength of less than 10 %), possibly abnormal (imbalance in strength between 10-20 %) and probably abnormal groups (imbalance in strength greater than 20 %).

Grace and co-worker (1984) investigated the strength of quadriceps and hamstrings of 206 high school soccer players and the relationship between the bilateral asymmetry with occurrence of injury. They found no association between muscle imbalance of 10 % and frequency of injury.

Ekstrand and Gillquist (1983) indicated that an imbalance in muscle strength between limbs may predispose a player towards musculoskeletal injury. Bender et al. (1964) reported that 806 cadets who had differences greater than 10 % in quadriceps strength between limbs were more likely than normal to get knee injuries in the weaker limb. It has been suggested that subjects with an imbalance of greater than 15 % were 2.6 times more likely to suffer injury in the weaker leg (Knapik et al., 1991). In a later study, Fowler and Reilly (1993) reported a 20 % difference in muscle strength in professional soccer players prone to injury.

Mognoni and co-workers (1994) tested the knee extensors of 24 junior soccer players using an isokinetic dynamometer (Cybex II) at 1.05, 3.14, 4.19 and 5.23

rad.s^{-1}. At all speeds the torque values of knee extensors were higher in the non-dominant limb and the differences were significant at 3.14 rad.s^{-1} (4.2 %), at 4.19 rad.s^{-1} (6.2 %) and at 5.23 rad.s^{-1} (6.2 %). The strength of the knee extensors turned out to be somewhat higher in the non-dominant limb than in the dominant limb. A possible explanation for this is that during kicking the knee of the non-dominant limb is bent so that its extensor muscles support both the weight of the body and the reaction of the torque developed by the opposite limb. This biomechanical situation may possibly act as a training stimulus.

Chin and colleague (1994) measured the isokinetic muscle strength of 21 elite junior Hong Kong soccer players at 1.08 and 4.32 rad.s^{-1} angular velocity using a Cybex II isokinetic dynamometer. They did not find a significant bilateral difference in the knee extensors (except the absolute peak torque measured at 1.08 rad.s^{-1}). Their results were consistent with findings of other groups (Oberg et al., 1986; Rhodes et al., 1986, Rochcongar et al., 1988). These data provided strong evidence that the strength capabilities of soccer players were similar in both legs at least in this group. For the knee flexors, the dominant leg scored significantly higher results than the non-dominant leg at both speeds. This may be due to the difference in muscle involvement in the ball kicking action. Olson and Hunter (1985) reported that the quadriceps strength of both kicking and non-kicking legs are important for leg swing action in ball kicking, while only the kicking (dominant) leg flexor is important in the action which cause deceleration of the leg and foot following the kick.

Early studies have shown that a contralateral strength difference of 10 % or greater may be a contributing factor to injury (Wyatt and Edwards, 1981; Grace et al., 1984). Chin and co-workers (1994) stated that there were respectively eight and twelve out of twenty one subjects who had contralateral hamstrings imbalance ratios greater than 10 % when measured at slow and fast isokinetic speeds.

Kirkendall (1985) indicated that soccer players were within clinical norms (10 %) in contralateral muscle balance. Therefore, specific weight training is required where appropriate for correcting of the subjects' contralateral muscle imbalance in order to avoid sports injuries.

In spite of the importance attributed to muscular imbalance, the extent to which such imbalance in contralateral limb symmetry predisposes an athlete to injury is still questionable (Osternig, 1986). The relationship between bilateral muscle imbalance and the occurrence of injury is still unclear.

2.3.5.5. Fast-speed/slow-speed ratio

Oberg and co-workers (1986) investigated the dynamic muscle strength of the quadriceps and hamstrings in Swedish male soccer players in different divisions including the national team players (n = 13); division I (n = 15); division IV (n = 180) and a group of nonsoccer players (n = 32) at 0.54 and 3.24 rad.s^{-1} angular velocity using a Cybex II devise. They reported a relatively greater fast-speed/slow-speed ratio in national players compared to other two groups of soccer players (0.64 vs 0.58). The reference group showed a higher fast-speed/slow-speed ratio for knee extensors than did division I and division IV players (0.67 vs 0.58). They reported also that the fast-speed/slow-speed ratio for the knee extensors was lower for most of the soccer players than for the non-players. This observation suggests that soccer training has more of an effect on slow than on fast movements. In an other study of muscle strength exhibited by soccer players in different positions, Oberg and colleagues (1984) did not find any significant differences. Soccer training might be improved if more practice in fast-speed movements was added.

2.3.5.6. Eccentric vs concentric

Eccentric actions develop greater tension than concentric muscle actions performed at the same angle, and might be more effective in improving muscle strength (Albert, 1995) and several studies have confirmed this view point (Komi and Rusko, 1974; Ghena et al., 1991; Kannus, 1994, Cometti et al., 2001). Westing and Seger (1989) investigated the eccentric and concentric torque-velocity characteristics in twenty subjects. Quadriceps and hamstring strength of subjects were tested at 1.08 to 6.48 rad.s^{-1} using the Spark system. They reported that mean concentric torque was significantly lower than the corresponding eccentric torque. They observed that mean eccentric torque did not change significantly with increasing eccentric velocity for either the quadriceps or hamstring muscles. At each test velocity, the concentric H/Q ratio was significantly lower than the corresponding eccentric H/Q ratio.

From a clinical point of view, it has been suggested that there is no relationship between isokinetic concentric strength of individual muscles and injuries in soccer players (Paton et al., 1989), but it has also been suggested that poor eccentric muscle strength of the hamstring group may cause hamstring strains (Stanton and Purdam, 1989). Worrell et al. (1991) did not find any differences in either concentric or eccentric lower limb muscle torque between injured and uninjured athletes. Eccentric actions produce greater loading of the elastic component of skeletal muscle, which may help to improve sprinting and jumping performance, and may be useful in the rehabilitation (Kellis and Baltzopoulos, 1995). If the risk of strains and tears is to be reduced, the ability of the muscle to resist forces should be improved (Bennett and Stauber, 1986).

2.3.5.7. Playing position and muscle strength

Since fitness demands tend to vary with positional roles, muscle strength values may depend on the player's position (Reilly, 1996b). Oberg et al. (1984) reported that goalkeepers and defenders have higher knee extension torque at 0.52 rad.s^{-1} than midfield players and forwards, but when the result was corrected for body size, the positional effect was not observed. Togari et al. (1988) in a study on Japanese soccer league players reported that, the goalkeepers were significantly stronger than forwards at slow (1.05 rad.s^{-1}) speeds and midfield players being intermediate. When the angular velocity was raised to 3.14 rad.s^{-1}, the positional effect disappeared. This may be due to the specific nature of training for goalkeepers compared to the players in other positions.

2.3.5.8. Reliability of muscle function tests

A major prerequisite for measurement of muscular performance is reliability. Reliability is defined as consistency of a measurement when all conditions are thought to be held constant (Rothstein, 1985). The mechanical reliability of the Lido dynamometer for torque measurement at different speeds has been established and supported by Aitkens et al. (1987). They reported a regression line slope of 1.01 for observed/expected torques, which led the authors to conclude that the internal calibration is very accurate, through a wide range of loads. Isokinetic testing of knee flexion and extension bilaterally at 1.05 rad.s^{-1} and 4.18 rad.s^{-1} on 17 normal, healthy subjects with a mean age of 29 years on this dynamometer produced high intra-class correlation coefficients (0.83- 0.94) which supports the reliability of measuring muscular strength based on torque and work values (Lord et al., 1987). Patterson and Spivey (1992) investigated the validity and reliability of the Lido active Isokinetic system and reported that this system is both valid and reliable for assessing muscle strength (mean correlation coefficient relating observed to expected torques was = 0.98). It can be concluded that the isokinetic dynamometer is a reliable research tool. In the later study, Coldwells et al. (1994) reported a significant test-retest correlations ($p < 0.001$, $r = 0.80$) for leg strength and back strength ($p < 0.001$, $r = 0.91$) with using a computer-controlled dynamometer (Lido Active, Davis, CA).

In summary, the previously mentioned aspects of musculoskeletal strength in soccer, namely, type of muscle actions, types of modes of testing muscle, strength, history of isokinetic assessment, comparison of isometric, isotonic, and isokinetic modes of muscle testing, force-velocity relationship, quadriceps vs hamstrings, reciprocal muscle group ratio, bilateral muscle group comparison, fast-speed/slow-speed ratio, eccentric vs concentric, provide such information on musculoskeletal strength in soccer.

The assessment of muscle function has become increasingly important as it is realised that there is a large variation in this human attribute, which is affected by both individual and environmental factors. The identification of asymmetric weakness or laxity within an individual player may be more important than comparison between team members (Reilly and Howe, 1996). Isokinetic dynamometry can be used to assess strength as it allows the comparison of hamstrings/quadriceps strength ratio, left /right leg ratio and fast-speed to slow-speed ratio to identify any muscle imbalance and deficit in specific muscle groups.

Elite players are likely to have elevated levels of muscle strength due to the requirements of a high performance level and freedom from injury. Yet in the course of their habitual training they may develop imbalances and tightness not evident in those playing at a lower level. Therefore, this aspect of musculoskeletal function needs to be investigated.

2.4. FATIGUE

A muscle called upon to contract repeatedly, or hold a given force level, will show a fall-off in force. Fatigue represents a reduction in the capability of muscle to generate force. Fatigue can be described as either central or peripheral fatigue. Central fatigue is typically associated with lack of motivation, impaired spinal cord transmission, or impaired recruitment of motor units. Central fatigue occurs proximal to the motor axons and leads to a failure of voluntary activation and thus a decrease in maximal voluntary force. Generally peripheral fatigue refers to impairment of peripheral nerve transmission, neuromuscular junction transmission, impaired processes of activation of fibres, and impaired actin-myosin interactions. Peripheral fatigue is distal to the site of stimulation and is seen as a decrease in twitch or tetanic force generated by the stimulus (Taylor et al., 2000).

Muscular fatigue is often evident in the course of a soccer game, notably towards the end of play (Reilly, 1996a). As the game nears its end, general muscle fatigue may occur as result of the activities previously performed in the match. Players are able to continue to exercise at lower intensities but have a reduced ability to perform maximally. Such a decrease in performance has been related to a reduction in muscle glycogen levels (Bangsbo, 1994b). Nutritional conditions may have a main role as low muscle glycogen levels affect the player's capacity to keep a high work-rate over the 90-min duration. Reilly (1994) and Taylor et al. (2000) stated that the fatigue is indicated by a reduction of maximal force or power associated with sustained exercise and is reflected in a decline in some aspects of performance. In high level soccer, a fatigue effect has been confirmed in the second half as a drop in the work-rate (Reilly and Thomas, 1976). Van Gool and colleagues (1988) reported that Belgian University players covered, on the average, a distance of 444 m more in the first half than in the second half of the game. In an investigation of professional players, Bangsbo et al. (1991) reported a 5 % greater distance covered in the first half. Whilst the decline in work-rate has been attributed to a reduced glycogen content in the thigh muscles of players (Saltin, 1973), other factors such as dehydration and physiological changes within the muscle cell (Karlsson and Saltin, 1971; Saltin, 1973; Jacobs et al., 1982; Bangsbo, 1994b) may also be implicated. Fluid carbohydrate intake has been shown to address both the dehydration and muscle glycogen (through blood glucose availability) problems dealing with fatigue. However, further research into the role of carbohydrate intake in attenuating fatigue is warranted.

Reilly and Thomas (1976) found a relationship between the fall in work-rate and aerobic fitness, in terms of maximal oxygen consumption for individual players. They also reported significant differences between playing position in this respect, with central defenders and forward players covering significantly reduced distances in each half compared with the midfield players and fullbacks. Midfield players and full-backs did not show such a pronounced drop in performance and possessed higher maximal oxygen consumption values than the other positions.

Fatigue may also be expressed in other indices of play besides work-rate. Reilly (1994) noted that the vast majority of goals are scored during the final 10-minute period of games. This trend may be related to the decline in work-rate observed during the second half of match-play, as fatigued players would make more errors or through inadequate marking.

The reduction in muscle force due to fatigue is likely to be due to a decrease in the number of fibres that can be recruited to generate force as fibres already recruited begin to fail (Bangsbo, 1994a). The fatigue produced by any activity can be assessed by comparing the force of maximal voluntary contraction pre-exercise and post-exercise. The onset of fatigue is more difficult to determine (Taylor et al., 2000) particularly in intermittent exercise, such as a soccer game. Essen (1978) reported that the muscle fibres that are most frequently recruited in performance and have the lowest capacity to restore glycogen may become depleted of glycogen first and this probably reduces the number of fibres that can be recruited to compensate for a loss in muscle force. This arguably would happened within the two 45 min halves. Therefore the muscle may not be able to generate enough force during the high intensity exercise periods. In a later study, Bangsbo (1994a) reported that fatigue during prolonged intermittent exercise may also be caused by changes in the function of the sarcoplasmic reticulum.

Gleeson and co-workers (1995) investigated the effect of a fatigue task (30 reciprocal maximal voluntary actions of the knee flexors and extensors) on isokinetic leg strength in eleven female collegiate soccer players using an isokinetic dynamometer (Lido) at angular velocity of 3.14 rad.s^{-1}. They reported that this fatigue protocol reduced the ability of knee flexors and extensors to generate force by 20 % to 60 % during concentric muscle actions at 3.14 rad.s^{-1} angular velocity.

Kawakami and others (1993) assessed concentric and eccentric muscle strength of ten youth subjects before, during and after a fatigue protocol (50 consecutive maximal trials) using a specially made dynamometer at angular velocities of 0.21, 0.52, 1.05

and 3.14 rad.s^{-1}. They reported a decline in concentric and eccentric muscle strength of 27 % to 40 %. These protocols produce fatigue relatively quickly and are unsuitable as models for studying the phenomenon of fatigue as it occurs in soccer.

A decline in body water content or other factors may also be involved in the fatigue process. Soccer is an intermittent high-intensity team sport in which high sweat losses can be expected. Ekblom (1986) and Rico-Sanz et al. (1996) have reported that during a soccer match, a player may run between 8 to 13 km in 90 min at an intensity requiring 75 to 80 % of $\dot{V}O_{2\,max}$, increasing thermal strain in the process. The sweat glands can produce between 12 to 30 g of sweat per minute depending on the environmental conditions and intensity of exercise, and this sweat loss can lead to a decrease in exercise performance (McGregor et al., 1999). Typical sweating rates for athletes range from 1 to 3 l.h^{-1} depending on temperature (Rehrer and Burke, 1996) and for soccer player rates of 1.5 l.h^{-1} have been reported (Kirkendall, 1993). This impacts directly on performance, making the effects of fatigue more likely at an earlier stage of the game. So, further research into the role of rehyderation in attenuating fatigue is warranted.

Lieber and Friden (1988) and Davis and Bailey (1997) suggested that muscle fatigue is a factor which can lead to injury. Further a loss of concentration may compound the potential for injury especially later in the game. This is evidenced by a greater injury incidence in the second half, particularly during the last quarter of the match compared to the first half (Hawkins et al., 2001). This aspect of injury risk merits further research.

In summary, muscle fatigue can involve multiple sites and multiple factors. The actual fatigue mechanisms depend on the exercise intensity, duration, subject's physical fitness, muscle composition, and nutritional and behavioural status. Whilst the investigations mentioned earlier provide valuable data related to physiological and metabolic responses to laboratory-based intermittent exercise protocols relevant to the work-rate of soccer, there is a lack of any documented isokinetic strength changes during a fatigue-inducing intermittent exercise task. So, research related to muscle fatigue during exercise simulating the work-rate of competitive play is warranted.

2.5. ELECTROMYOGRAPHY

Electromyography (EMG) refers to the study of the electrical signals originating from the muscle (Basmajian and De Luca, 1985). Muscles produce electrical activity during the course of each contraction. The main target of EMG is to analyse the function and co-ordination of muscles under different movement conditions (Jonsson, 1978).

2.5.1. Factors which affect the EMG signal and force produced by a muscle

One of the most difficult aspects of the surface EMG signal is that when rectified and sufficiently smoothed, its amplitude is related to the torque around a joint, but more often than not, an accurate quantitative relationship is not definable. The reason for this quandary is that the EMG signal is the result of many physiological, anatomical and technical factors. The effect of some of these factors may be managed by proper detection methods, but others are not easily regulated with current technology and their potential effect on the signal may only be summarised and considered (De Luca, 1997).

De Luca (1997) stated that the factors which control the EMG signal can be classified into the following categories: causative, intermediate and deterministic factors. The causative factors have a main effect on the signal. These are separated into two groups: extrinsic and intrinsic. The extrinsic factors are those related to the structure of the electrode and its placement on the muscle. They include: the area and shape of the electrode detection surfaces; the distance between the electrode detection surfaces; the location of the electrode with respect to the motor points in the muscle; the orientation of the detection surfaces with respect to the muscle fibres which affects the value of the measured conduction velocity of the action potentials and, consequently, the amplitude and frequency content of the signal. The influence of the electrode's location on the amplitude and frequency spectrum of the signal is displayed in Figure 2.5.1.

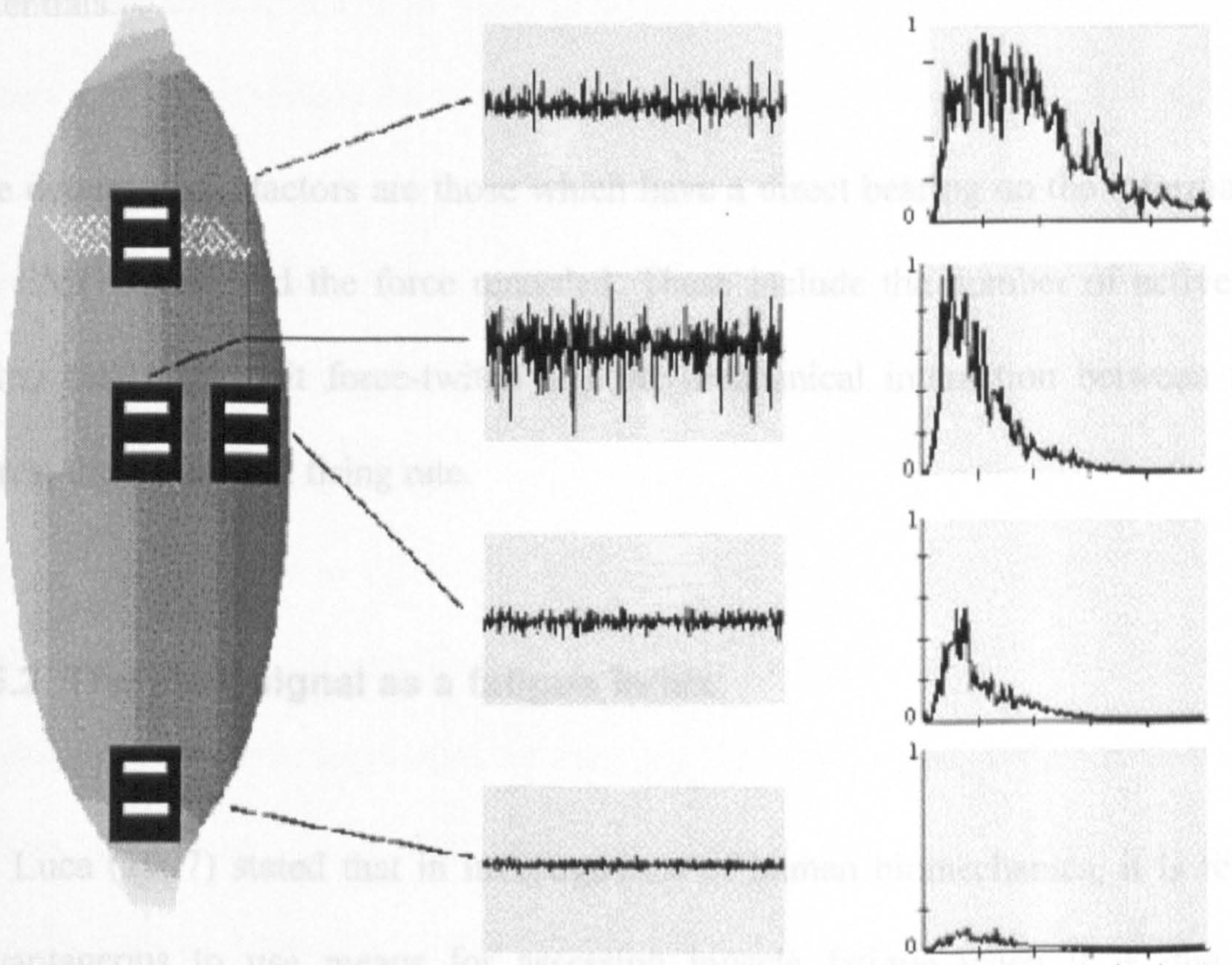


Figure 2.5.1. The amplitude and frequency spectrum of the EMG signal are affected by the location of the electrode with respect to the innervations zone (top electrode), the myotendonous junction (bottom electrode) and the lateral edge of the muscle (middle right electrode). The preferred location is in the midline of the belly of the muscle between the nearest innervations zone and the myotendonous junction. In this location the EMG signal with the greatest amplitude is detected (De Luca, 1997).

The intrinsic causative factors are the physiological, anatomical and biochemical characteristics of the muscle. Due to limitations of current knowledge and technology they cannot be controlled. They include the number of active motor units, the fibre type composition of the muscle, the blood flow in the muscle; the fibre diameter and the depth and location of the active fibres within the muscle (De Luca, 1997).

The intermediate factors represent physical and physiological phenomena. These include:- the band-pass filtering aspects of the electrode; the detection volume of the electrode; superimposition of action potentials in the detected EMG signal which include crosstalk from nearby muscles; the conduction velocity of the action potentials.

The deterministic factors are those which have a direct bearing on the information in the EMG signal and the force recorded. These include the number of active motor units, the motor unit force-twitch and the mechanical interaction between muscle fibres; the motor unit firing rate.

2.5.2. The EMG signal as a fatigue index

De Luca (1997) stated that in investigations of human biomechanics, it is regularly advantageous to use means for assessing muscle fatigue when it is due to the performance of a task. Physiologists used to apply the muscle force output as the index of muscle fatigue. In particular, the point at which a contraction can no longer be maintained has been defined as muscle fatigue. This approach implies that fatigue occurs at a specific point in time, a notion that is inconsistent with the concept of fatigue accepted by engineers and physical scientists. Application of the failure point has some inherent practical disadvantages. For example, fatigue would be detected only after it had occurred. This approach would have little use in clinical and ergonomics applications where it is useful to have indications that precede failure so that appropriate remedies may be taken.

The spectral modification may be monitored and quantified by tracking some characteristic indicators of the frequency spectrum, such as the median, mean or mode frequency of the spectrum. De Luca (1997) indicated that the median frequency is one of the best methods, because it is less sensitive to noise and signal aliasing. In addition, in most cases it is more sensitive to the biochemical and physiological factors that occur within the muscles during sustained contractions. The estimate of the median frequency is more variable, largely due to the instability of the EMG signal spectrum at lower frequencies. The spectral modification events described above are represented graphically in Figure 2.5.2.

One type of fatigue is systemic, affecting the person as a whole. Examples of contributing factors involved in systemic fatigue would be high levels of heat or cold, aerobic requirements, lactic acid, or even psychological stress (Hermans et al., 1984). Fatigue also occurs on a local level within the body. This is true particularly in musculoskeletal exertions. Typical externally visible symptoms are loss of force production capabilities, localised discomfort and pain. This type of fatigue has become known as localised muscle fatigue (Chaffin, 1973). Localised muscle fatigue continues to be of concern in the ergonomic assessment of jobs. Muscle exertion levels do not necessarily need to be high to cause localised muscle fatigue. Electromyographic analysis has been proposed as one method of evaluating localised muscle fatigue during repeated or locally stressful activities.

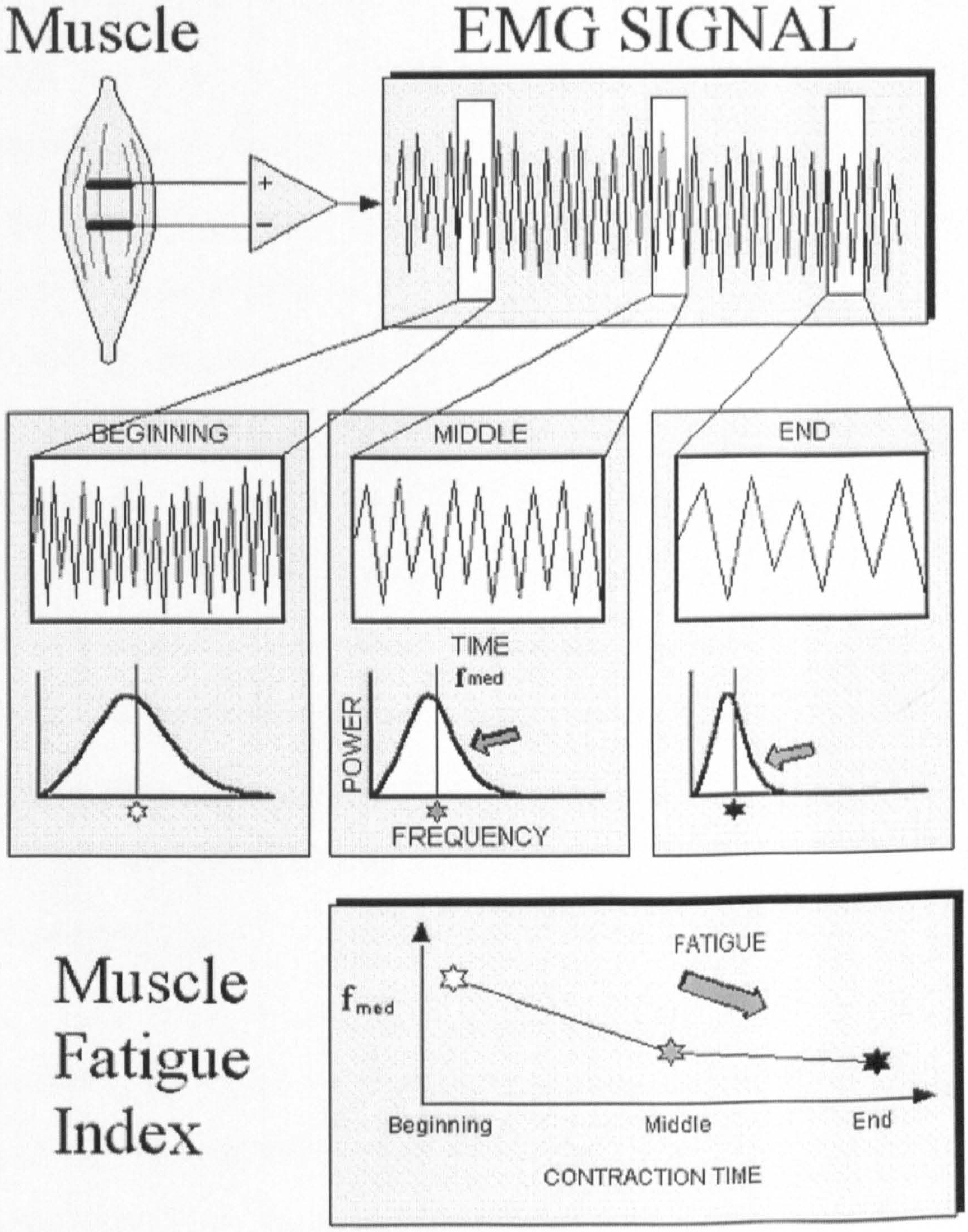


Figure 2.5.2. A diagrammatic explanation of the spectral modification which occurs in the EMG signal during sustained contractions. The muscle fatigue index is represented by the median frequency of the spectrum (De Luca, 1997).

2.5.3. Localised muscle fatigue and the EMG signal

During localised muscle fatigue, changes occur in the surface EMG signal that is recorded. Two of the most commonly cited changes are a shift in the frequency content of the signal toward the low end and an increase in the amplitude (Basmajian and De Luca, 1985). Figure 2.5.3. graphically demonstrates this effect during sustained, isometric contraction. Note that the level of force decreases for a given EMG level and the power spectrum shifts from time a to time b. Lindstrom et al. (1970) and De Luca (1979) contended that these two phenomena are related. They stated that tissue filtering characteristics act as a low-pass filter. As the frequency content of the signal shifts to the lower frequencies, more energy is transferred through the tissues to the electrodes. This energy transfer, in turn, increases the amplitude of the recorded signal. Two often used measures of the spectral changes are the median power frequency and a ratio of high to low frequencies. The cause of these changes has been attributed to motor unit recruitment, firing rate, synchronisation, and action potential shape.

The median power frequency method of analysis is the most widely used measure of spectral shift resulting from fatigue. The median frequency is defined as that frequency about which the power is distributed equally above and below. It is calculated as any median of a distribution. Median frequency decreases over time, some times as much as 50 % during prolonged isometric contraction (Lindstrom et al., 1970, Lindstrom et al., 1977; Petrofsky and Lind, 1980; Hagberg, 1981). Some researchers have also observed a reliable decrease in the median frequency during dynamic contractions (Cross et al., 1979; Komi and Tesh, 1979). The rate at which the shift in the median power frequency occurs over time is dependent on the level of the contraction (Figure 2.5.4). The higher the tension level exerted, the faster the median power frequency shifts to lower frequencies. This is expected because muscles under greater tension will fatigue more rapidly. The total decrease is dependent on the muscle under investigation and on some subject variability.

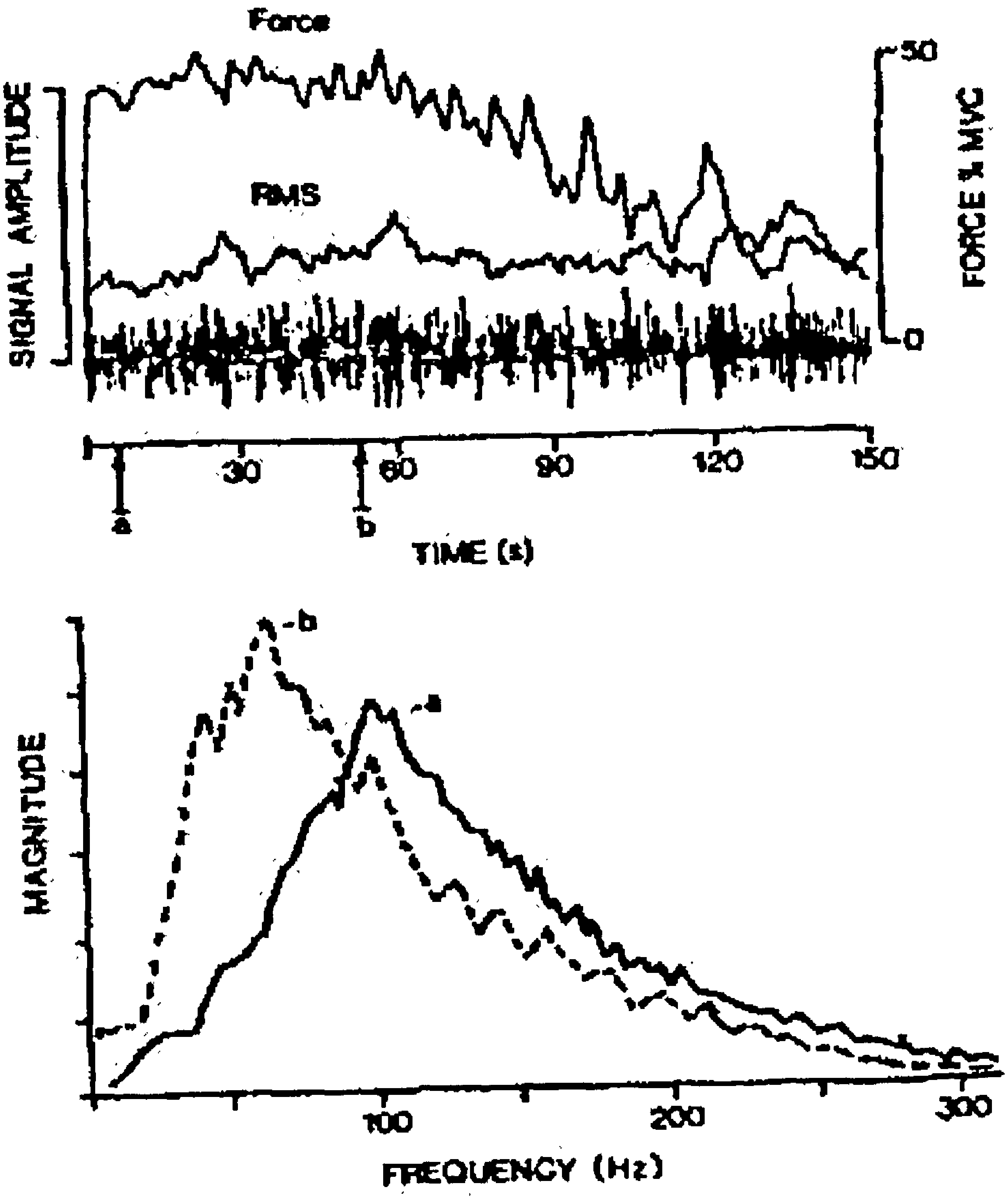


Figure 2.5.3. Amplitude changes (Top) and frequency spectral shifts (bottom) resulting from local muscle fatigue during a sustained, isometric contraction of the first dorsal interosseous muscle (Basmajian and De Luca, 1985).

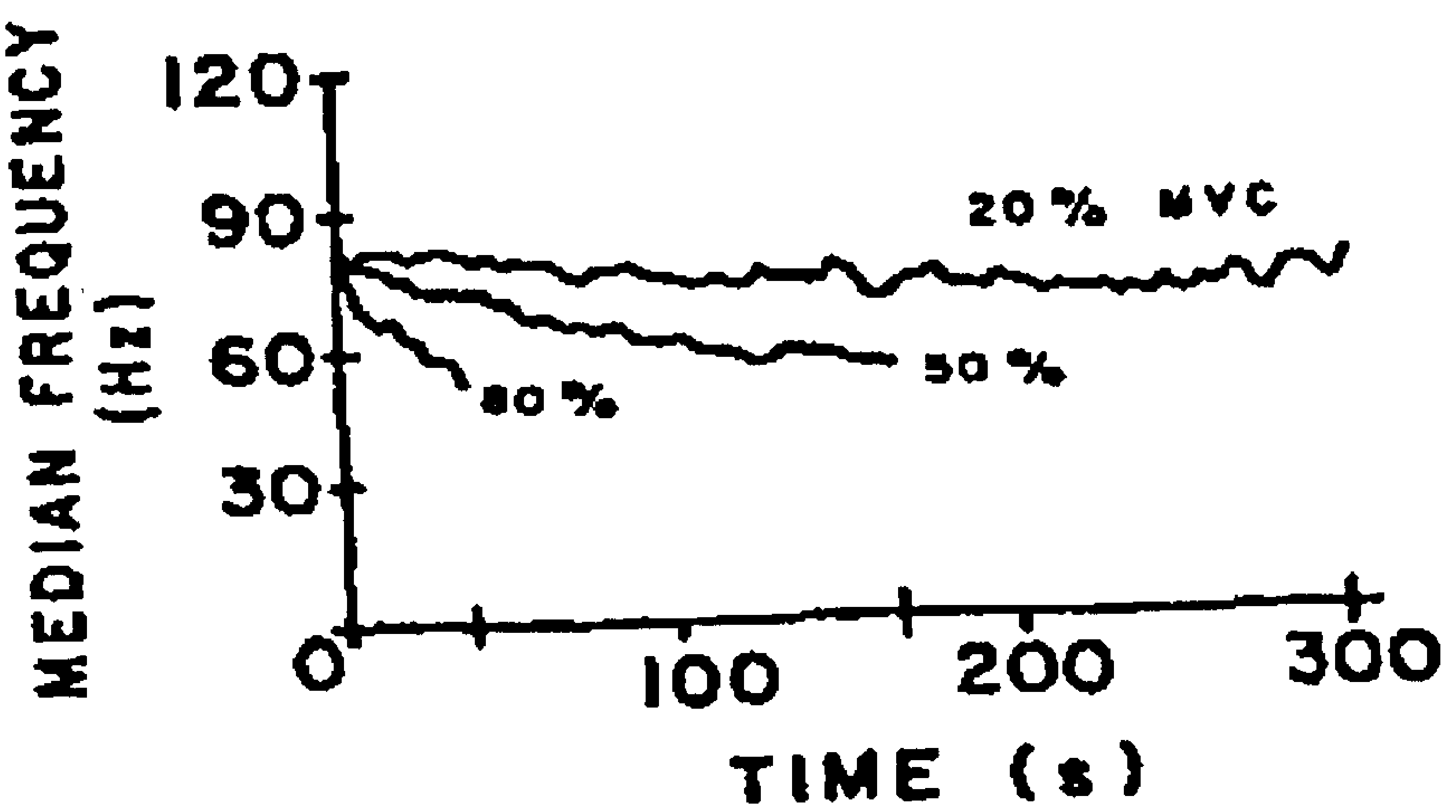


Figure 2.5.4. The affect of tension level on the rate of change of the median power frequency (Basmajian and De Luca, 1985).

Christensen and Fuglsang-Frederiksen (1988) investigated the EMG changes during experiments in a laboratory environment as a comparison to occupational work. They analysed the surface EMG of the quadriceps muscle of 16 subjects during 2 experiments including 1) 10 % maximal voluntary contraction (MVC) sustained for 1 h; and 2) 20 % MVC for 1 h and 20 % MVC was sustained until exhaustion. In the latter the endurance time decreased with increasing MVC. They reported a decrease in mean power frequency following the fatigue task.

Naeije (1984) studied the correlation between surface electromyograms and the susceptibility to fatigue of the human masseter muscle. He tested 17 healthy male subjects' EMG activity at 50 % of the maximum activity. The endurance time was used as an indicator of the muscle's resistance to fatigue. There was a significant positive correlation between the endurance time and the root mean square value of the EG signal the mean power frequency values.

Hansson et al. (1992) investigated the electromyographic fatigue in neck/shoulder muscles and endurance in women with repetitive work. They recorded the EMG with surface electrodes from the trapezius and deltoid muscle during a static endurance test at approximately 20 % of maximal voluntary contraction. The localised muscular fatigue was derived from the time course of the RMS and mean frequency of the EMG recordings. The most pronounced sign of fatigue for trapezius muscle was an increase in the RMS values, while for deltoid muscle it was a decrease in the median frequency values. This most pronounced sign of fatigue could be explained by the different functions of the two muscles.

Svantesson et al. (1998) compared the development of fatigue during pure concentric actions with eccentric-concentric actions in a standardised isokinetic movement. The concentric test was performed on 10 healthy subjects with the same number of cycles as in the eccentric-concentric test, which was performed until exhaustion. A significant decrease in median frequency was only evident in the eccentric-concentric test. No changes in RMS were observed.

Later, Yeung et al. (1999) investigated the effects of fatigue on the temporal neuromuscular control of vastus medialis in 19 young male subjects. The EMG activities of vastus medialis and the force generation capacities of the quadriceps muscle group were monitored before and after a fatigue protocol (30 isometric maximal voluntary contractions). They reported a significant decrease in peak torque force and an increase in the RMS value, but a significant reduction in the median frequency.

Esposito et al. (1998) investigated the electromyogram changes in fresh and fatigued muscle during sustained contraction in men. In seven subjects the EMG was recorded from biceps brachii during sustained isometric effort at 80 % of the maximal voluntary contraction (MVC), before and 10 min after a fatiguing exercise. From the time and frequency domain analysis of the signals, the RMS and the median frequency were calculated. The result showed that the mean MVC was greater in fresh than in fatigued muscle and also the mean RMS increased from test 1 to 2.

More recently, Linnamo et al. (2000) investigated the force and EMG power spectrum during and after eccentric and concentric actions inducing fatigue. The eccentric and concentric force and median frequency were measured during and immediately after maximal eccentric and concentric exercise. When comparing maximal eccentric and concentric actions before the exercise, the average force was higher in eccentric than in concentric but the average RMS values were the same with the two types of action. The median frequency of biceps brachii decreased during both eccentric and concentric actions.

In summary, there are several, factors which affect the EMG signal and force produced by a muscle such as fatigue. The EMG signal can be used as an index for localised muscle fatigue. The research has showed that median frequency and RMS are good indices for determining the occurrence of fatigue.

2.5.4. Electromyographic studies

A review of electromyographic studies in sports by Clarys and Cabri (1993) has highlighted that a number of Olympic sports disciplines have received great attention. These include swimming, cycling, running and skiing. Other sports have received only a little attention and many sports no attention at all (Table 2.5.1).

The popularity of soccer is not reflected in scientific investigations using EMG. The studies reviewed by Clarys and Cabri (1993) were concerned with the levels of skill of kicking and are considered here.

Muscular synchronisation and the importance of antagonist and eccentric work during a standard soccer kick have been monitored via EMG investigations by different research groups (Bollens et al., 1987; De Proft et al., 1988). They reported that informative and descriptive data allow for specific training applications. They suggested that in soccer players, agonists must be trained concentrically, antagonists eccentrically. In addition, they indicated that establishing a strong equilibrium between agonists and antagonists with a balance between concentric and eccentric strength is likely to reduce the incidence of injuries, improve the neuromuscular pattern of the kick and improve kick performance.

Table 2.5.1. Number of studies of sport-specific EMG research interest (Clarys and Cabri, 1993).

Sport	Number	Sport	Number	Sport	Number
Swimming	33	Rowing	3	Bowling	1
Cycling	22	Judo	3	Cricket	1
Running	17	Windsurfing	2	Fin swimming	1
Skiing	13	Archery	2	Handball	1
Tennis	8	Volleyball	2	Rifle shooting	1
Gymnastics	8	Baseball	3	Sailing	1
Weightlifting	7	Water polo	2	Skiff	1
Triple, high, long jump	5	Javelin	2	Shot put	1
Golf	5	Kayak	2	Softball	1
Speed kating	4	Badminton	1	Synchro-swimming	1
Soccer	3	Basketball	1	Wrestling	1

McCrudden and Reilly (1993) compared EMG findings in punt kicking of a soccer ball with drop kicking and they reported similar muscle activity. Bollens et al. (1987) divided the soccer kick into six phases and measured EMG activity for six muscles in the kicking leg during these phases. They called their phases: (1) first step; (2) second step; (3) loading phase; (4) swinging phases; (5) ball impact; (6) follow-through. They found that vastus medialis and vastus lateralis contractions were maximal during the loading phase, at which time the knee was still flexing. They called this part of the "soccer paradox" that a substantial amount of muscle work appears to be done eccentrically during soccer kicking. This corresponds to the "wind-up" phases in the above description of punt kicking, where maximal quadriceps activity was also found.

In the last two decades, analysis of the surface EMG has become an important tool in the study of local muscle fatigue. During maximal voluntary contraction several changes are observed. The integrated EMG or root mean square EMG shows a gradual decrement (Milner-Brown and Stein, 1973; Bigland-Ritchie et al., 1983;

Moritani et al., 1985;). The median frequency shows a rapid shift to a lower frequency during sustained maximal voluntary contraction (Milner-Brown and Stein, 1973; Kranz et al., 1983).

Masuda et al. (1999) investigated the changes in surface EMG parameters during static and dynamic fatiguing contractions in healthy subjects. They examined the median frequency of surface EMG in the vastus lateralis of 19 healthy male adults. The subjects performed knee extension both statically and dynamically until they were exhausted. Median frequency decreased 22.4 % from initial value during the static contraction. A similar tendency was observed during the dynamic contraction, in which median frequency decreased 15.2 % from the initial value.

Kay et al. (2000) investigated the different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. Twelve athletes performed isometric, concentric and eccentric maximal voluntary contractions and 100-s endurance trials on an isokinetic dynamometer. Raw EMG data were recorded throughout each trail from the rectus femoris of the right limb. In concentric and eccentric, integrated electromyography was maintained, whereas integrated electromyography for isometric decreased to 38 % of initial values. The greatest reduction in percentile frequency shifts occurred in concentric compared to isometric and eccentric. They concluded that eccentric activity was largely fatigue resistance, whereas isometric and concentric contractions displayed different neuromuscular fatigue profiles.

Linnamo et al. (2000) investigated the force and EMG power spectrum during and after eccentric and concentric fatigue. Eight physically fit males performed maximal eccentric and concentric exercise consisting of 100 maximal eccentric and concentric actions with elbow flexors during two separate exercise sessions. The average eccentric force decreased by 53.3 % after eccentric exercise and by 30.6 % after concentric exercise, while the average concentric force decreased by 49.9 % after concentric exercise and by 38.4 % after eccentric exercise. The median frequency of biceps brachii in eccentric action decreased during both eccentric exercise and concentric exercise. In concentric action median frequency of biceps brachii decreased during concentric exercise, while no changes were observed in eccentric exercise. On the absolute scale, the eccentric force in eccentric exercise decreased more than the concentric force in concentric exercise. Fatigue response was action type specific as seen in the greater reduction in the force of the exercise type. Median frequency decreased immediately after both exercises, which may be at least partly related to elevated blood lactate concentration. Decreased median frequency after eccentric exercise may be indicative of selective damage of fast twitch fibres in this type of exercise.

Miller et al. (2000) studied the reciprocal coactivation patterns of the medial and lateral quadriceps and hamstrings during slow, medium and high speed isokinetic movements. Fourteen athletes performed six continuous isokinetric knee extension and flexion movements at 1.08, 3.24 and 5.4 rad.s^{-1} to examine muscular fatigue patterns. They reported that the RMS activity of the vastus medialis showed a higher degree of coactivation than the vastus lateralis and the biceps femoris showed approximately three times the coactivation level of the medial hamstrings. The median frequency of the vastus lateralis and medial hamstrings shifted downward as the repetitions progressed with no changes for the vastus medialis or for the biceps femoris.

The reduction in muscle torque during consecutive isokinetic efforts has been investigated extensively (Barnes, 1981; Gray and Chandler, 1989; Tesch et al., 1990). This decrease in muscle torque has been attributed to both contractile failures (Tesch et al., 1990) and the availability of energy sources within the muscle (Kellis and Baltzopoulos, 1995). Though the studies are fewer in number, the changes in EMG activity have also been monitored during consecutive dynamic muscular contractions as a way in which to describe the effects of fatigue on maximum strength production (Komi and Tesch, 1979; Oberg, 1995; Potvin and Bent, 1997). Overall, two primary changes in the EMG signal appear to take place during exhaustive, repetitive exercise: (1) the power spectrum of the EMG signal and median frequency shifts toward the lower band, which is thought to be caused by a decrease in the conduction velocity of muscle actions during sustained fatiguing contractions (Ament et al., 1993; Potvin and Bent, 1997; Masuda et al., 1999) and, (2) the amplitude of the EMG increases (Oberg, 1995; Kellis, 1999; Masuda et al., 1999).

In summary, most studies of neuromuscular activity and fatigue have been conducted using isometric contractions. Isometric contractions may not be representative of muscle activity and fatigue development during human locomotion (Green, 1995). Indeed, available data suggest that the development of fatigue may be specific to contraction type, activity and duration (Tesch et al., 1990; Enoka and Stuart, 1992). Despite this, it appears that no study has previously compared neuromuscular fatigue profiles during prolonged exercise such as a soccer game; to established if the profiles during these types of muscle activity are different.

2.6. SUMMARY

Injury prevalence in soccer has been the subject of many investigations. Available data suggests that soccer is associated with a high injury rate. From both performance and an economic point of view, injury prevention is a better option than injury management or treatment. In this respect more research is required on how to prevent soccer injuries. The principle of injury prevention based on the elimination of predispositions to injury has received little attention in the literature.

In relation to developing an injury prevention programme, the first step is to identify and control the risks of injury (as opposed to the actual injuries). There are numerous methods including both hand notation and computerised system for recording and analysing the work-rate in soccer. However, there are no immediate and adequate methods for assessing injury risk in soccer.

There are few data related to muscle function that can be used to compare elite and sub-elite English soccer players. Some important issues related to musculoskeletal strength have been highlighted in the literature but further data and information in this respect are therefore needed.

It is thought that fatigue may be is a factor that increases injury risk. Fatigue represents a reduction in the capability of muscle to generate force and it reduces the work-rate in soccer, especially toward the end of the game. The data available on the effects of fatigue are concerned exclusively with work-rate and neglect the muscle strength changes that may occur during a soccer match. Investigations are needed to evaluate changes in muscle function in the course of an intermittent exercise performance.

Electromyography has been used in various sport activities, with an analysis on identifying precursors of fatigue. Soccer has received only isolated interest and also there is little known about EMG activity in the main muscle groups of soccer players, especially as fatigue develops during a match.

The intention is that the studies proposed for this thesis would help make good these deficiencies in our knowledge.

CHAPTER THREE

INJURY RISK ASSOCIATED WITH PLAYING ACTIONS DURING COMPETITIVE SOCCER

3.0 INJURY RISK ASSOCIATED WITH PLAYING ACTIONS DURING COMPETITIVE SOCCER

3.1. INTRODUCTION

Soccer is a vigorous sporting activity and, in the course of play and contesting possession of the ball, leads to relatively high injury incidence rates (17-24 injuries per 1000 playing hours) compared to many other sports (McMaster and Walter, 1978; Ekstrand, 1982; Engstrom et al., 1991; Hawkins and Fuller, 1998, 1999). From an economic point of view, the costs of injuries to soccer players are enormous. The cost of treatment and loss of production through time off work as a result of soccer injuries has been estimated at about £1 billion in Britain each year (Ball, 2000). In order to minimise the number of injuries and the associated costs, avoid the early retirement of professional soccer players, and provide a safe and healthy sports environment, preventive programmes are recommended. These preventative programmes require information on injury and the risk of injury associated with different aspects of the game.

There has been a great deal of research undertaken on soccer injuries and a number of issues with regard to their nature, causative mechanisms and characteristics have been established. For example, with regard to the nature of injuries, over 75% of injuries for professional players are strain, sprain and contusion injuries (Ekstrand, 1982; Lewin, 1989; Anglietti et al., 1994; Inklaar, 1994; McGregor and Rae, 1995). Lower extremity injuries represent 60-85% (Inklaar, 1994b) of the total injuries incurred by soccer players for both sexes, with the most susceptible joint being the knee, followed by the ankle (Fried and Lioyd, 1992; Inklaar, 1994b; Tucker, 1997). Injury severity is usually classified as minor, moderate or major depending on the length of time needed for recovery with over 65% soccer injuries being minor, 25% moderate and 10% serious (Anglietti et al., 1994). With regard to the mechanisms of injury, it is found that around half of the injuries arise from player-to-player contact, including tackling, being tackled, and collisions, and the remainder (non-contact) arise from actions such as running, shooting, turning and heading (Hawkins et al., 2001). Although most researchers have claimed that the playing position does not influence the occurrence of injury (Ekstrand, 1982; Hoff and Martin, 1986; Nielsen and Yde, 1989; Engstrom et al., 1991; Hawkind and Fuller, 1998), Hawkins and Fuller (1996) found that defenders had greater risk of injury compared to other players, suggesting that playing position may be an influential factor. With regard to other characteristics, the final quarter of each half is known as a period with high injury occurrence and the second half has a greater risk of injury than the first half (Sandelin and et al., 1985; Arnason et al., 1996; Hawkins and Fuller, 1996). Most epidemiological studies indicate that injuries to soccer players are about three times more likely in competition compared to training (Lewin, 1989; McGregor and Rae, 1995; Hawkins et al., 2001).

The majority of injuries are thought to be unintentional, resulting from an error on the part of the player concerned or by another player. The error may cause an accident and some of these accidents lead to injury (Reilly, 1993, 1997; Reilly and Howe, 1996). While the risk of injury is influenced by various factors, it is conventionally assessed by the injury incidence rate, defined in terms of the number of injuries and the exposure to injury, usually determined in terms of time. However, injury risk is an expression of risk to players for the game as a whole, and it does not detail the risk associated with specific actions, which may lead to injury. For example, the number of injuries, which are caused by a tackle, has been reported (Hawkins et al., 2001), but not the number of tackles from which these injuries occurred. Thus, the injury risk associated with tackles is based on a count of the tackles which have led to injury and not the incidence of injury from tackles (defined as the number of injuries from tackles divided by the total number of tackles made). Further, there are many actions which take place in the game which do not frequently lead to injury, but have some potential risk associated with them depending on the vigour, context and nature of the action. There is a risk associated with these non-injury generating actions, which is generally ignored in the literature. Consequently, to understand fully the risk of injury that a player is exposed to during soccer play, it is necessary to analyse the actions executed in a game and to relate these actions to the risk they may possess and the subsequent injuries which may result from them. This approach to the assessment of injury risk is fundamentally different from previous studies, as it attempts to express injury risk in terms of the actions used in play and the potential these actions have for injury. It therefore provides a more detailed understanding of injury risk, which will have importance for designing appropriate injury prevention and rehabilitation programmes.

There are several factors which are thought to be related to injury risk in addition to the type of playing action used, such as location on pitch, period of play, and whether playing at home or away. Since the role of playing actions before the actual occurrence of the injury event has not previously been investigated, the purpose of this study was to assess the exposure of players to injury risk during English Premier

League soccer matches in relation to a number of selected factors which may influence that risk.

3.2. METHODS

3.2.1. Matches selected

In order to assess the injury risk in soccer performance with respect to (i) types of playing action (ii) periods of the game (iii) zones of the pitch and (iv) playing either at home or away, 10 games from the English Premier League 1999-2000 were chosen for analysis. A complete list of all notated matches is shown in Table 3.2.1.

In the Research Institute for Sport and Exercise Sciences there were 18 videotapes available of matches from the FA Carling Premier League 1999-2000. From these videotapes, firstly each team that had only one home and one away game was chosen for the analysis (n=7) and then other teams that had games with the mentioned teams were chosen, so that altogether there were 20 teams and 10 games. No team was included more than twice (1 Home + 1 Away) so as to not bias the selection. Although not random, the selection (from what was available) was considered to be representative of Premier League play. Actions, zones of the pitch, periods of the game, injury potential, and actual injury were considered in the analysis.

Table 3.2.1. List of matches that were notated for this study.

	Home Teams	Away Teams
1	Manchester UTD	Liverpool
2	Leicester	Sunderland
3	Middlesborough	Manchester UTD
4	Leeds	Arsenal
5	Liverpool	Bradford City
6	Tottenham	Middlesborough
7	Bradford City	Leeds
8	Derby County	Leicester
9	Everton	Newcastle
10	Wimbledon	Everton

3.2.2. Apparatus

In order to assess injury risk and performance, a new hand notation method and a compatible computer notation and analysis system were designed.

3.2.2.1. Description of hand notation technique

3.2.2.1.1. Part 1: Definition of measurement categories

The hand - notation method was developed which took into consideration the following:

- **Period:** Playing time was divided into six periods of 15 minutes each. These are shown in Table 3.2.2.

Table 3.2.2. Playing time broken down into 6 periods of 15 minutes each.

Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
0-15 min	15-30 min	30-45 min	45-60 min	60-75 min	75-90 min

Information about each period was recorded on individual sheets, e.g. information about the first 15 minutes was recorded on separate sheets for period 1 and so on.

In relation to periods 3 and 6, the problem of extra time was dealt with in two ways. Firstly, these periods included the extra time when all factors were compared between home and away teams without respect to period. Secondly where the difference between home and away teams was significant and where comparisons were made for injury potential, injury and actions per period, the extra time was not taken into account, i. e. the playing period of concern was kept to 15 min.

- **Zone:** The field of play was divided to 18 equal zones (Figure 3.2.1). These consisted of six horizontal and three vertical areas. All of the actions and the frequency of each action per zone were recorded by hand during periods 1-6 on a special sheet.

In relation to the field of play it should be noted that this was dependent on the direction of play for home and away teams. For example where a home team played from the left to the right side (Figure 3.2.1a) the defending zones were 1, 2 and 3 while the attacking zones were 16, 17 and 18. The zones were reversed for the away team which played in the opposite direction (Figure 3.2.1b).

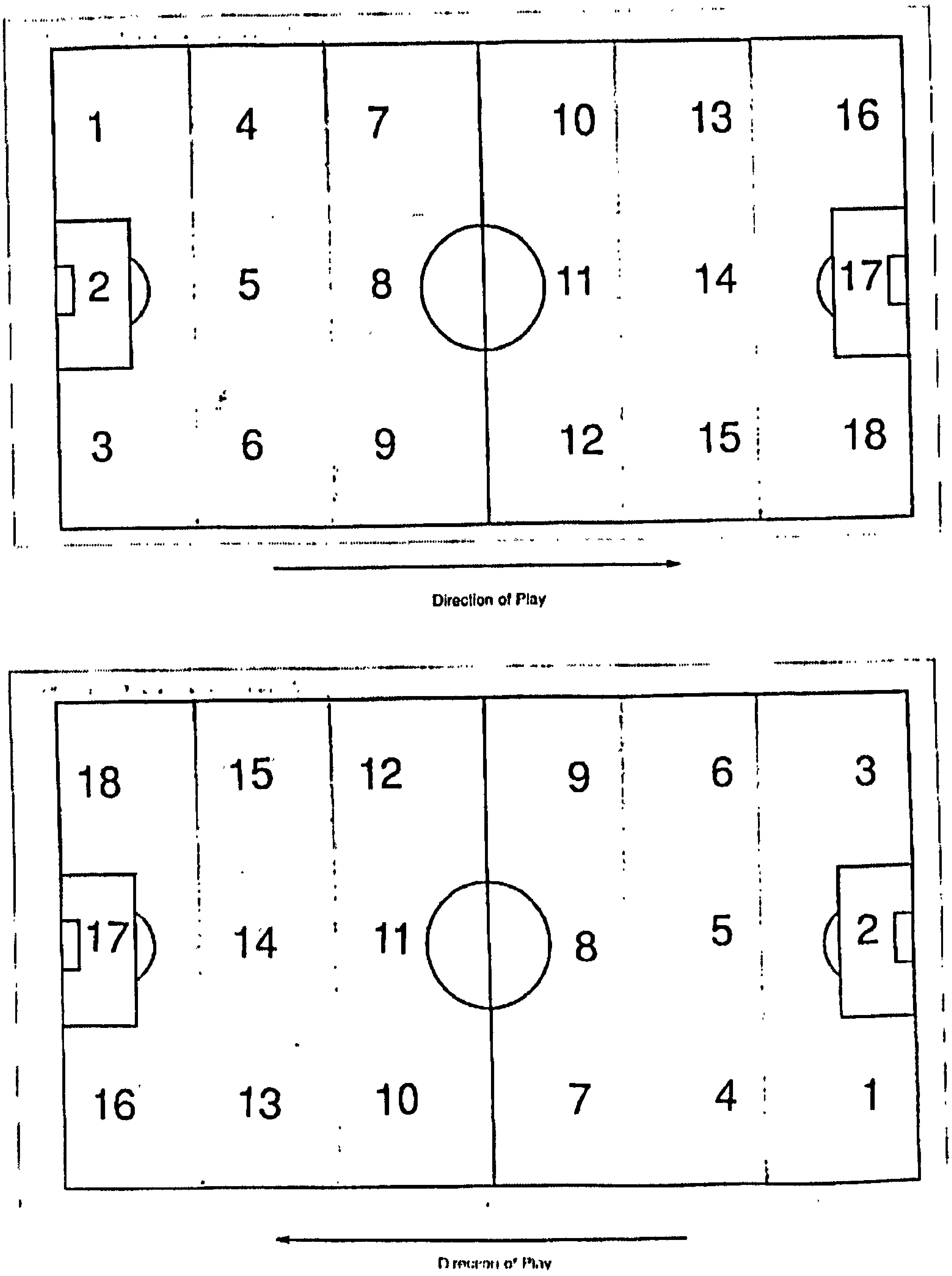


Figure 3.2.1. The field of play broken down into 18 separate sections.

- **Injury risk:** Each playing action was classified into one of three categories depending on its likelihood for causing an injury. These categories were "no injury potential", "injury potential" (both assessed subjectively on the likelihood of the actions producing on injury) and "actual injury" (defined as receiving medical treatment on the pitch). The "no injury potential" category was used for actions, such as an easy pass to a team player, where there was no discernible likelihood of injury. The "injury potential" category was divided into three subcategories: - grade 1 was a mild (small) possibility of injury, for example when receiving a ball unchallenged; grade 2 was a moderate possibility of injury, for example when making a long kick or jumping to head the ball; grade 3 was a high possibility of injury, for example when making a vigorous tackle or a receiving a hard "charge". The "actual injury" category was divided into three subcategories:- grade 1 was a minor injury where there was evidence of injury and the player received "first aid" inside the field of play (but without any additional treatment); grade 2 was a moderate injury when the player received treatment off the field of play but continued for the remainder of the game; grade 3 was a major injury when the player received treatment and left the field for the remaining part of the game. These descriptions of minor, moderate and major injuries do not correspond to general definition of injury severity used in the literature, as information on the subsequent effect of the injury was not available.

In order to quantify the injury risk associated with a playing action, the Playing Action Injury Risk Incidence (PAIRI) was defined as the number of actions with some level of injury risk plus all actual injuries in a specific playing action category, divided by the total number of actions made in that category, expressed as a percentage. In this study it was decided to use the sum of moderate and high (Grade 2 and 3) injury potential to express the genuine risk of injury as a level of mild risk is accepted as a part of the game. Playing Action Injury Incidence (PAII) is defined as the number of actual injuries in a specific playing action category divided by the number of actions made in that category as a percentage. All data were collected by the author and in a pilot study analysis was shown to be reliable ($r = 0.99$). The data were analysed using chi-square to compare between categories and a level of $P< 0.05$ was used to indicate statistical significance.

- **Playing actions:** All of the playing actions and movements used in the game were divided in to 16 categories. Some of categories were divided into subcategories. Complete lists of all playing actions are shown in Table 3.2.3.

Category 7 included; corner kick, penalty kick, bicycle kick, and volley kick. Category 8 included trips, kick on opponents, foul tackle from behind, tripping using the leg and tripping by stopping in front of the opponent. Category 9 included pushing, pushing an opponent and also a fair charge.

The analysis in this study was limited to actions involving the ball. Although some movements without the ball (i.e. running) have been reported as causes of injury in soccer (Hawkins et al., 2001), these were not included because the games were recorded from television broadcasts and attention was focused on activity around the ball. As such, movements of all players on the pitch are rarely visible. In order to cover all the movements made in play, other methodologies would be necessary and were beyond the scope of this study.

Table 3.2.3. The list of playing actions that recorded in during the game.

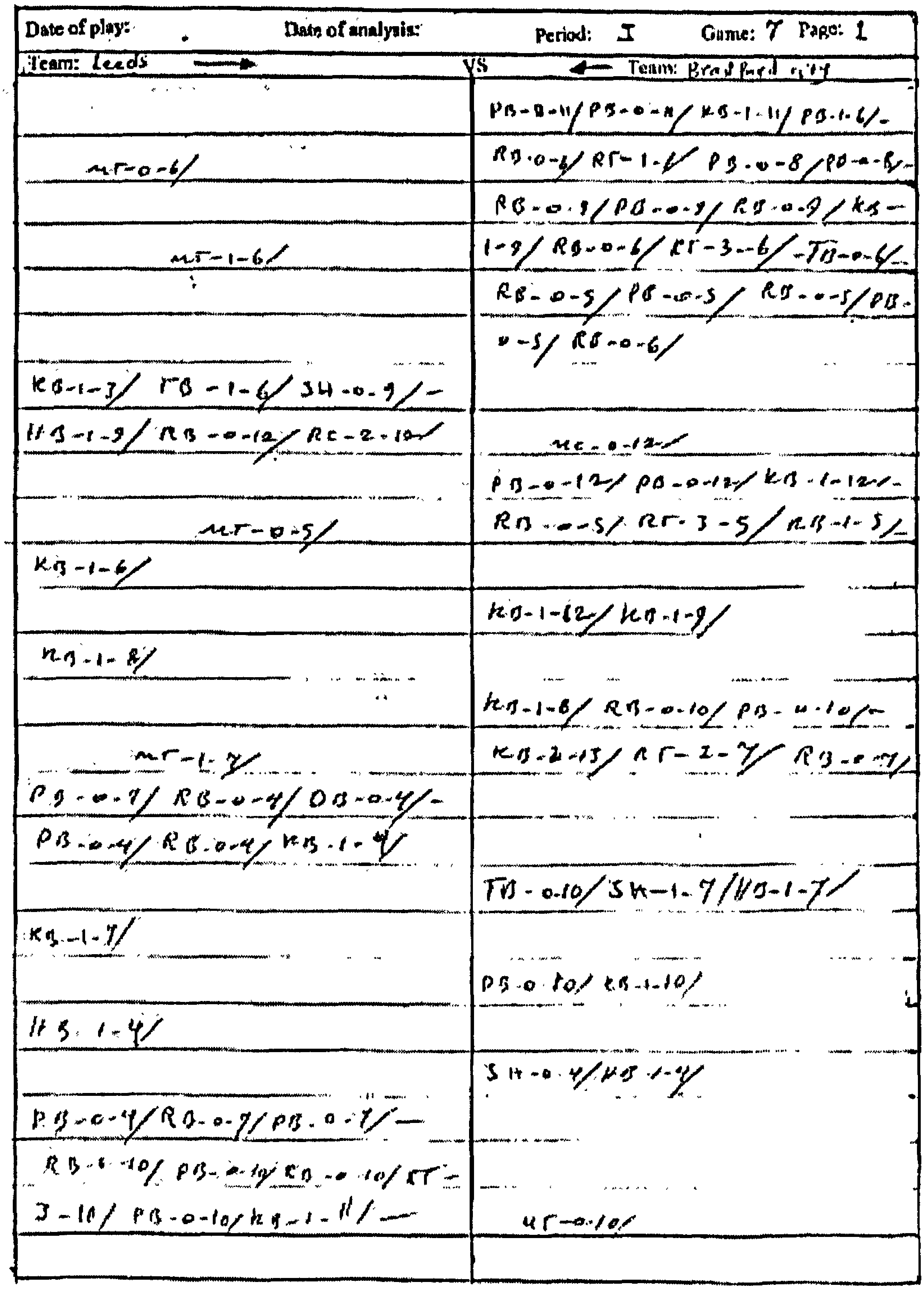
Abbreviation	Actions	Definitions
1. DB	Dribbling the ball	With close control to take the ball past on opponent using the foot with 3 or more touches.
2. GC	Goal catch	Goalkeeper catches and holds onto the ball.
3. GP	Goal punch	Goalkeeper punches the ball and doesn't keep possession.
4. GT	Goal throw	Goalkeeper distributes the ball by throwing the ball towards a team-mate.
5. HB	Heading the ball	Player makes direct contact with the ball using the forehead.
6. JH	Jumping to head	Player leaves the ground prior to making direct contact with the ball with the forehead.
7. KB	Kicking the ball	Player makes direct contact with the ball with the foot.
8. MT	Making a tackle	Player actively moves his body or limb towards the ball when the ball is in the possession of an opponent.
9. MC	Making a charge	Player makes physical contact with opponent during a tackle.
10. PB	Passing the ball	Player plays the ball with the foot with the intention of a team-mate receiving it.
11. RB	Receiving a ball	Player receives and controls ball with any part of the body.
12. RT	Receiving a tackle	An opponent tackles a player in contact with the ball.
13. RC	Receiving a charge	Player in possession receives physical contact by opponent.
14. SG	Shot on goal	Any attempt made by an attacking player with a shot (kick) directly towards the goal.
15. SK	Set kick	A free kick situation anywhere on the pitch.
16. TB	Throw-in the ball	Restart of the game with hands following the ball going outside the touchline.

3.2.2.1.2. *Part 2: Recording data*

A TV monitor and a video recorder (Panasonic NV- HD 685) were used to view the games and enable notation of events to take place. The video was paused after every event that occurred (for both home and away teams) and the action, location and time were notated manually onto paper.

As an example of data recording, consider a player who has received a hard tackle in zone 10. Data were recorded as (RT-3-10), i.e. RT, was the abbreviation for 'received tackle', 3 was related to the injury potential and 10 was the zone of the pitch where the action happened. When a player made a hard tackle, data were recorded as (MT-2-10), i.e. MT, was the abbreviation for make tackle, 2 was related to the injury potential and 10 was the zone of the pitch where the tackle was made. Actions by home and away team players were recorded in a separate column. A typical recording sheet is shown in Figure 3.2.2

On completion of a game, the hand-notated notes were transferred onto the computer system. When the game was transferred onto the computer database, the results and summaries broken down by game and team were put into Excel. This procedure allowed further analysis by action, injury and so on. Also data were entered into 'Minitab' for some statistical techniques.



Date of play: Date of analysis: Period: I Game: 7 Page: 1

Team: Leeds →	VS ← Team: Bradford city
	PB-0-11/ PB-0-8/ KB-1-11/ PB-1-6/-
MT-0-6/	RB-0-6/ RT-1-6/ PB-0-8/ PB-0-8/-
	RB-0-9/ PB-0-9/ RB-0-9/ KB-
MT-1-6/	1-9/ RB-0-6/ RT-3-6/ TB-0-6/-
	RB-0-5/ PB-0-5/ RB-0-5/ PB-
	0-5/ RB-0-6/
KB-1-7/ TB-1-6/ SH-0-9/-	
HB-1-9/ RB-0-12/ RC-2-10/	MC-0-12/
	PB-0-12/ PB-0-12/ KB-1-12/-
MT-0-5/	RB-0-5/ RT-3-5/ RB-1-5/
KB-1-6/	
	KB-1-12/ KB-1-9/
KB-1-8/	
	KB-1-6/ RB-0-10/ PB-0-10/-
MT-1-7/	KB-2-13/ RT-2-7/ RB-0-7/
PB-0-7/ RB-0-4/ OB-0-4/-	
PB-0-4/ RB-0-4/ KB-1-4/	
	TB-0-10/ SH-1-7/ HB-1-7/
KB-1-7/	
	PB-0-10/ KB-1-10/
HB-1-4/	
	SH-0-4/ HB-1-4/
PB-0-4/ RB-0-7/ PB-0-7/—	
RB-1-10/ PB-0-10/ RB-0-10/ RT-	
3-10/ PB-0-10/ KB-1-11/—	MT-0-10/

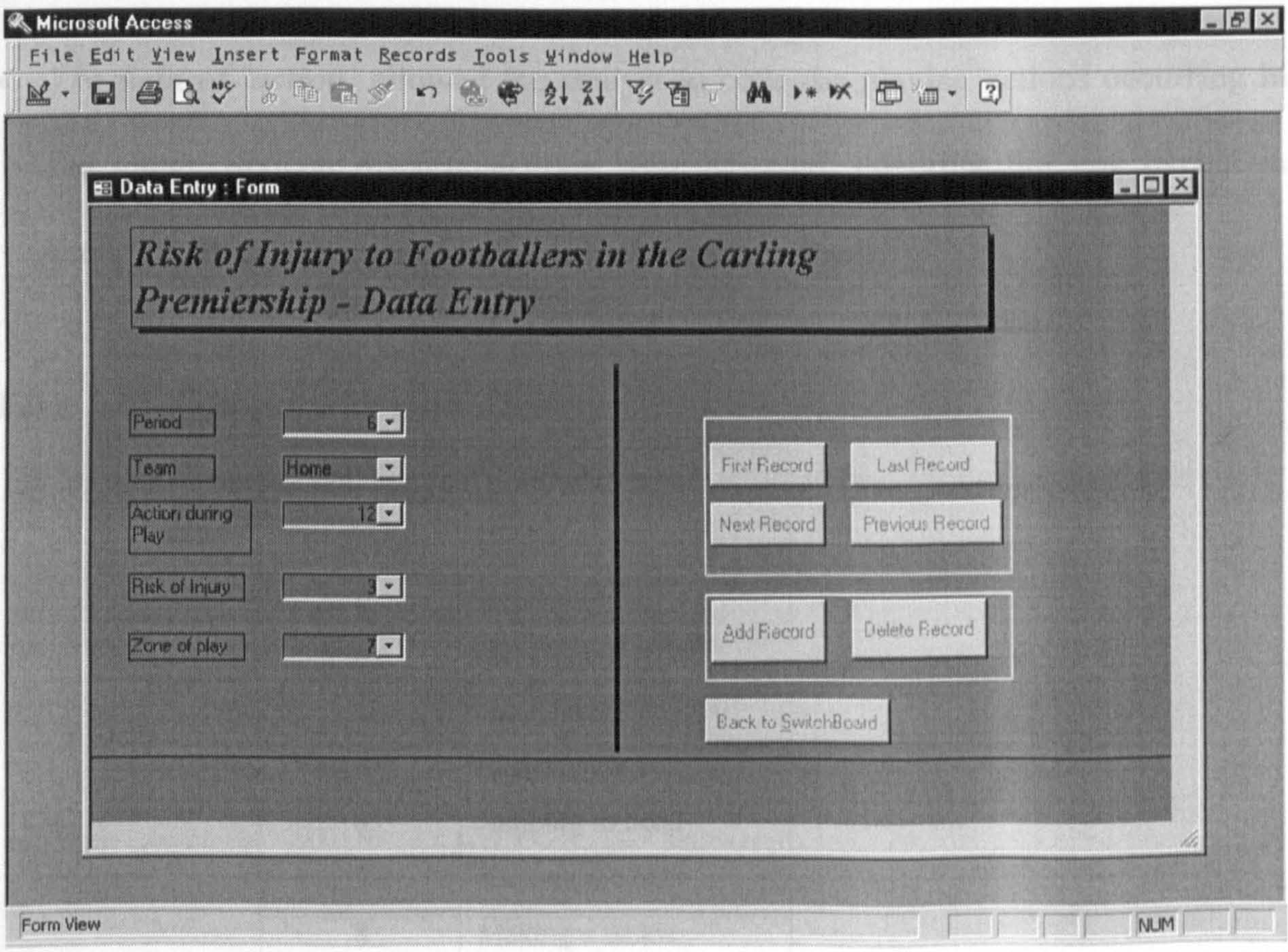
Figure 3.2.2. A typical recording sheet that used for recording data.

Figure 3.2.3. Picture of a TV, Video recorder (Panasonic NV- HD 685), and Computer as employed in data collection.

3.2.2.2. The Computerised notation and analysis system

3.2.2.2.1. Description of the computerised notation and analysis system

The computerised system, which was designed in Microsoft Access, was subdivided into the following categories: period; team; playing actions; risk of injury and zone of the pitch. These options are illustrated in the window shown in Figure 3.2.4.



Risk of Injury to Footballers in the Carling Premiership - Data Entry

Period: 6
Team: Home
Action during Play: 12
Risk of Injury: 3
Zone of play: 7

Figure. 3.2.4. Data entry form of the computerised system.

- *The field designated as 'period'* allowed the analyst to code the playing actions occurring in different periods of the game. Six discrete periods relating to the time during the match can be used and are shown in Table 3.2.4.

Table 3.2.4. Codes used for period of the game.

Code	1	2	3	4	5	6
Period	0-15 min	15-30 min	30-45 min	45-60 min	60-75 min	75-90 min

- *The field referred to as 'team'* allowed the analyst to indicate whether the team was playing at home (0) or away (1) (Table 3.2.5).

Table 3.2.5. Codes used for home and away team.

Code	Definitions
0	team is playing at home.
1	team is playing at away of home.

- *The field of 'action'* allowed the analyst to code the playing actions occurring in the game. Sixteen discrete actions were selected, covering the key events in football games. These are shown in Table 3.2.6.

Table 3.2.6. Codes used for playing actions.

Code	**Definitions**
1	Dribbling the ball
2	Goal catch
3	Goal punch
4	Goal throw
5	Heading the ball
6	Jumping to head
7	Kicking the ball
8	Making a tackle
9	Making a charge
10	Passing the ball
11	Receiving the ball
12	Receiving a tackle
13	Receiving a charge
14	Shot on goal
15	Set kick
16	Throw-in

- *The field of 'risk of injury'* allowed the analyst to code each playing action with regard to the likelihood of it causing injury (defined the injury potential) and also when injuries result, the severity of the injury. Six categorises of injury risk are shown in Table 3.2.7.

Table 3.2.7. Codes used for risk of injury.

Code	Definitions
0	No injury potential
1	Mild injury potential
2	Moderate injury potential
3	High injury potential
4	Evidence of injury, and the player received first aid inside the pitch (minor injury)
5	Received treatment on the pitch but continued for the remanding of the game (moderate injury)
6	Received treatment on the pitch, and subsequently came off the pitch (major injury)

- *The field called 'zone' of play'* allowed the analyst to code the playing actions with respect to 18 different zones on the pitch. (Table 3.2.8).

- *The other fields:*

When each field had been completed, clicking on **'Add Record'** enters the data into the main table. The data can be viewed at any time by opening the table and using the other buttons to move forwards and backward through all of the records entered (Figure 3.2.4).

Table 3.2.8. Codes used for zone of play.

Code	Definitions
1	zone 1 that consist of left defending area.
2	zone 2 that consist of centre defending area.
3	zone 3 that consist of right defending area.
4	zone 4 that consist of left defending area.
5	zone 5 that consist of centre defending area.
6	zone 6 that consist of right defending area.
7	zone 7 that consist of left midfield area.
8	zone 8 that consist of centre midfield area
9	zone 9 that consist of right midfield area.
10	zone 10 that consist of left midfield area.
11	zone 11 that consist of centre midfield area
12	zone 12 that consist of right midfield area.
13	zone 13 that consist of left attacking area.
14	zone 14 that consist of centre attacking area.
15	zone 15 that consist of right attacking area.
16	zone 16 that consist of left attacking area.
17	zone 17 that consist of centre attacking area.
18	zone 18 that consist of right attacking area.

3.2.2.2.1.1. Using the computer notation and analysis system

- *Tables:*

The database is stored in Microsoft Access and is composed of a number of tables, queries and forms. The principle table is **'Main'** in which all of the data are stored. The other tables such as **'Action'**, **'Game'**, **' Injury'**, **'Period'**, **'Team'**, **'Zone'** and **'Match Information'** which define the choices available (as described above) are set up in the system (Figure 3.2.5).

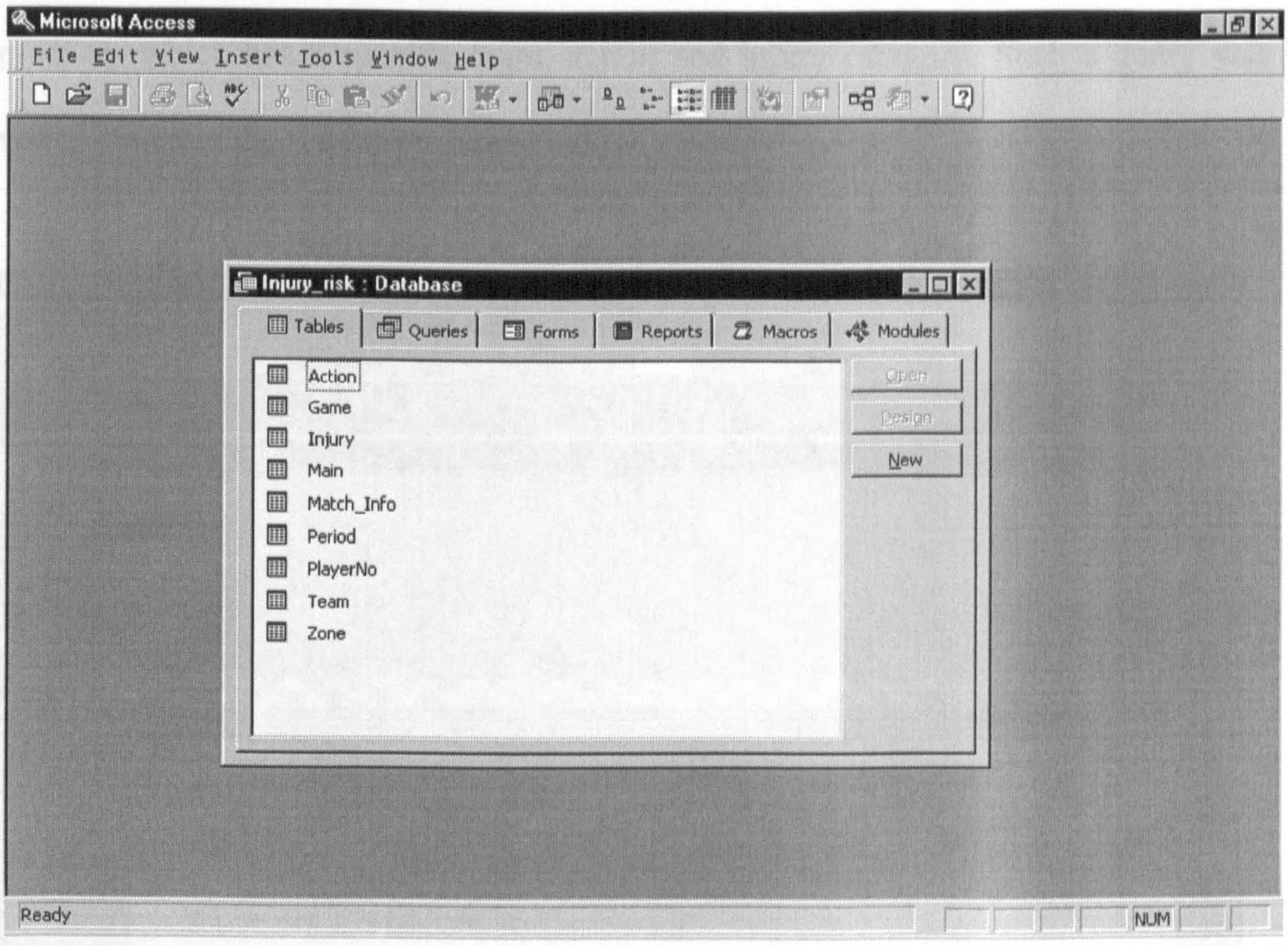
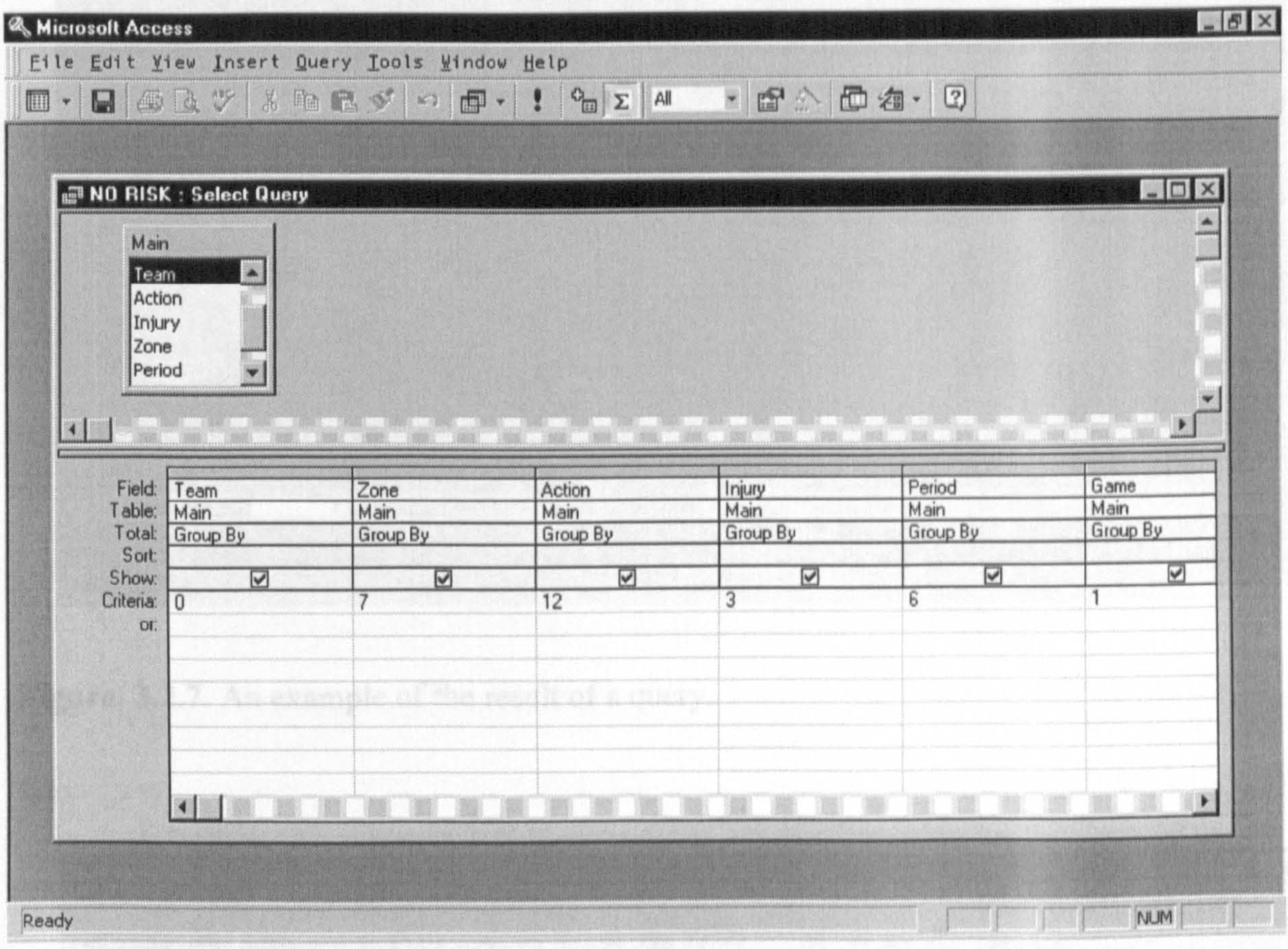


Figure. 3.2.5. Tables used in computerised system.

- *Queries*

Queries were constructed to extract the data in relevant ways. For example, Figure 3.2.6 shows a query that will summarise the data based on the 0 (Home team), ‘zone 7’ where the ‘action’ was 12 (Receiving a tackle) with an ‘injury potential’ of 3 (High injury potential) in ‘period 6’ (Last 15 minutes of the game) in ‘game 1’ (Manchester United vs Liverpool F.C.). The result of this query is shown in Figure 3.2.7. It can be seen there was just one occurrence matching the specified criteria.

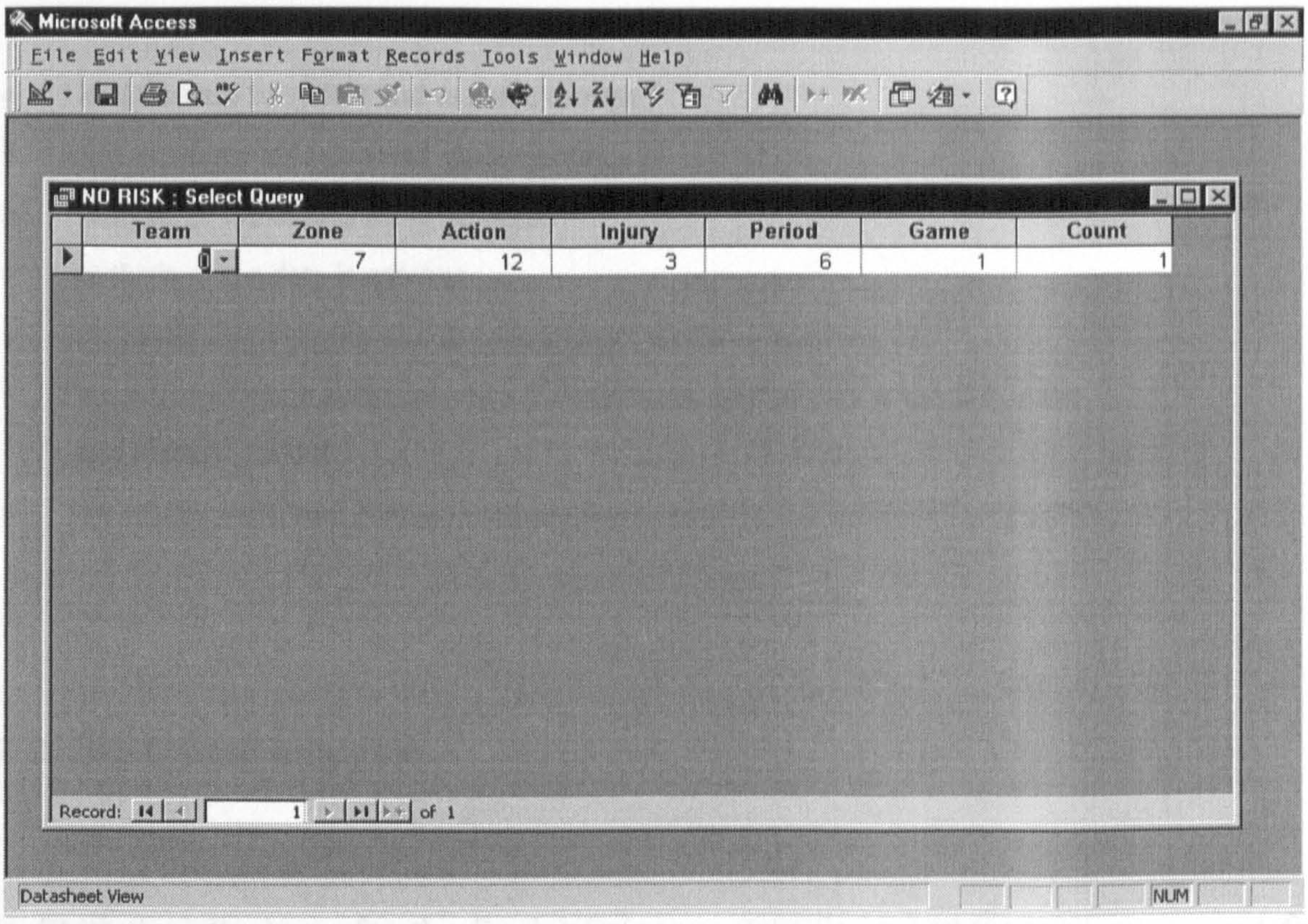
A query can be constructed which has fewer categories. For example, a query could be set up which has a specific team, action and injury category. Such a query was used to generate the results presented below.



Field:	Team	Zone	Action	Injury	Period	Game
Table:	Main	Main	Main	Main	Main	Main
Total:	Group By	Group By	Group By	Group By	Group By	Group By
Sort:						
Show:	☑	☑	☑	☑	☑	☑
Criteria:	0	7	12	3	6	1
or:						

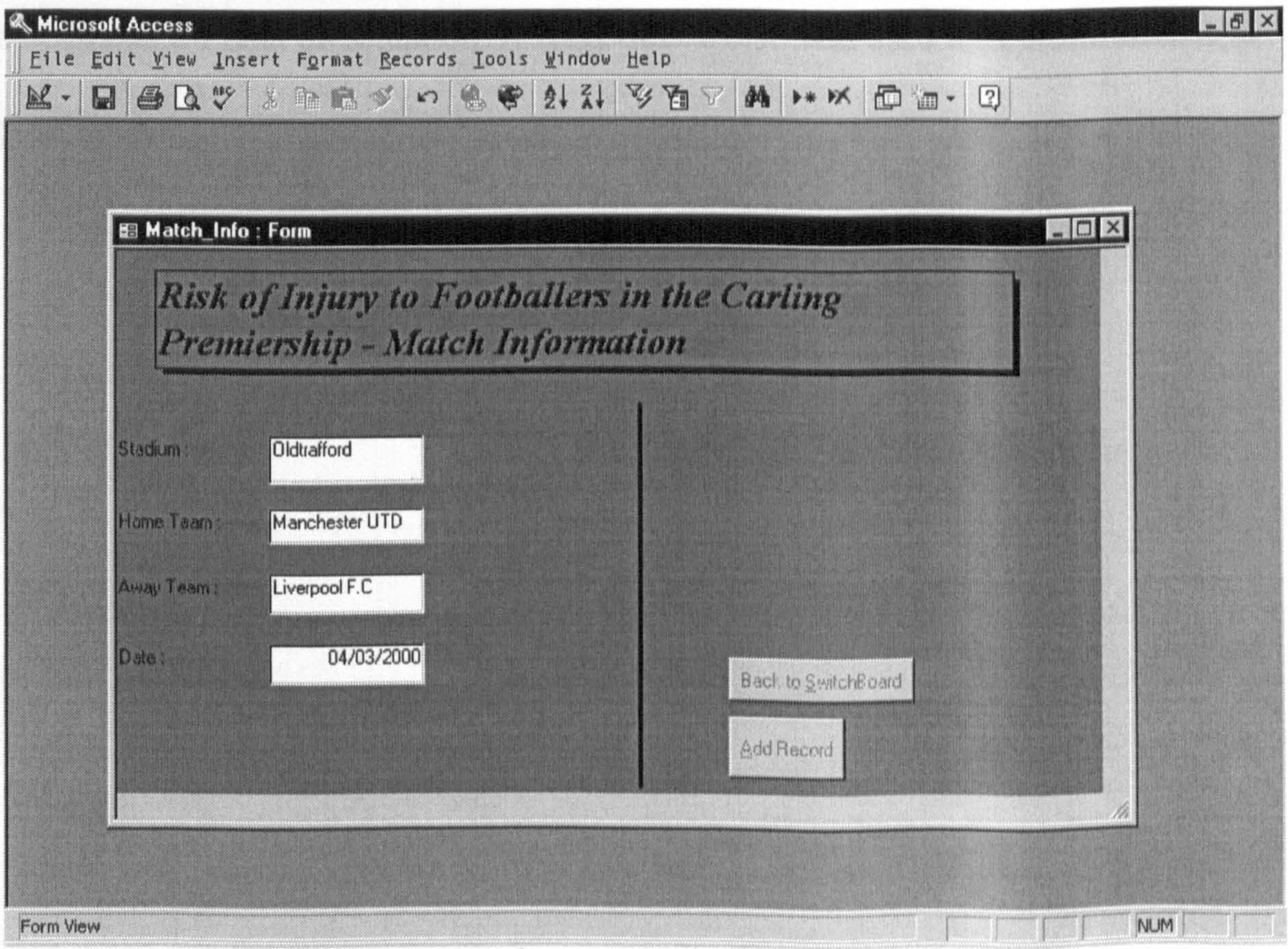
Figure. 3.2.6. An example of a query.

- *Form.* There are two forms used which include the data entry form (Figure 3.2.4) and the match information entry form (Figure 3.2.8).



Team	Zone	Action	Injury	Period	Game	Count
0	7	12	3	6	1	1

Figure. 3.2.7. An example of the result of a query.



Risk of Injury to Footballers in the Carling Premiership - Match Information

Stadium : Oldtrafford

Home Team : Manchester UTD

Away Team : Liverpool F.C

Date : 04/03/2000

Figure. 3.2.8. Mach information entry form.

3.2.2.2.2. The advantages of the computerised system are that:

- Data are easy to update and to make change.
- Data are more secure stored on computer.
- Analysis of the data is more flexible.
- Analysis of the data is quicker.
- It is easier for someone else to follow the procedures involved.
- Extraction of some necessary data from between a lot of data is too fast in the computerised system.
- The results generated from a query are more accurate in a computerised system.

3.2.3. Statistical analysis

The Statistical Package for the Social Sciences (SPSS) and "Minitab" were used for data analysis. The data were entered into "SPSS" and 'Minitab' for the application of statistical techniques. These included chi- square for data analysis and bar graphs or pie diagrams for data presentation. A level of $P < 0.05$ was used to indicate statistical significance.

3.3. RESULTS

The total number of playing actions recorded was 17,877. Altogether, 7667 actions were judged to have possessed some level of injury potential and 20 actions resulted in actual injuries (an average of 2 injuries per game) (Fig 3.3.1). The total exposure in terms of player-hours was 374 (22 players, 10 games, 1.7 hours match-play). The injury frequency rates (as defined by Hawkins and Fuller, 1996, 1998) for minor, moderate and major injuries were 27, 16 and 11 per 1000 hours played, respectively. The overall injury frequency rate was calculated to be 53 injuries per 1000 hours played.

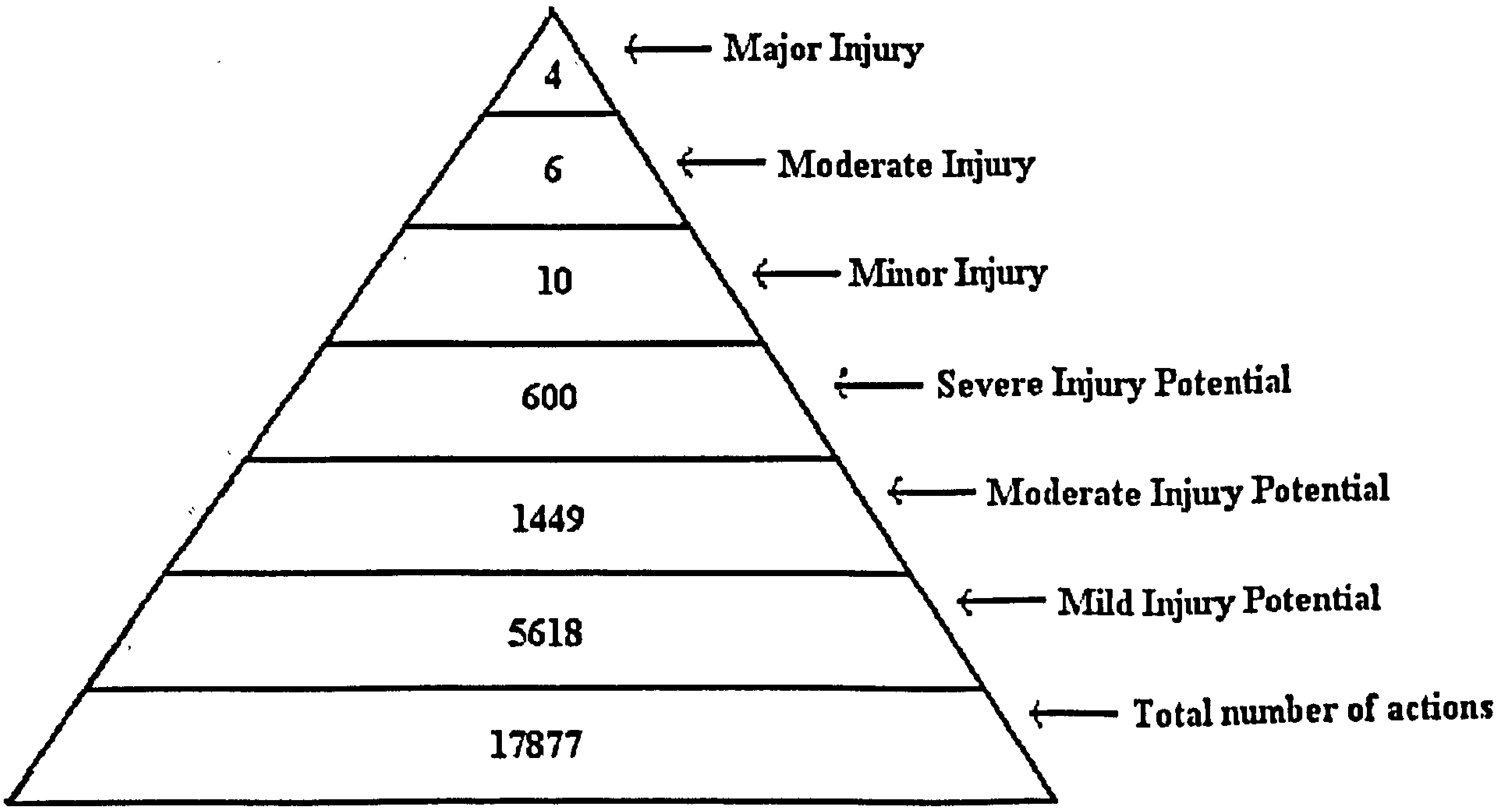


Figure 3.3.1. Total actions that were notated with the number of events in the injury potential and actual injury categories.

3.3.1. Playing actions

With regard to injuries (Table 3.3.1), the minor injuries were caused by receiving a tackle (50 % of all minor injuries), making a tackle (20 %), receiving a "charge", kicking the ball and catching the ball (10 % each). The moderate injuries resulted from receiving a tackle (83 % of all moderate injuries) and making a tackle (17 %). The major injuries were all attributable to receiving a tackle. The PAII values for actions leading to injury were 1.54 % (receiving a tackle), 0.43% (goal catch), 0.33% (making a tackle), 0.17% (receiving a charge) and 0.04% (kicking the ball).

The total numbers of occurrences with injury potential for each playing action are given in Table 3.3.1. A significant difference (χ^2 = 1101.6, P= 0.001) was found between the playing action categories. Those with more than 50 % of actions judged to have some degree of injury potential were categorised in terms of risk. Actions which were classed as having mainly a mild injury risk (because they had their highest percentage of actions with injury potential in the mild category) were kicking the ball (89 % of all kicking the ball actions), set kick (83 %), heading the ball (68 %) and shot on goal (73 %). Actions which were categorised as having a predominantly moderate injury risk were receiving a "charge" (72 %), making a tackle (49 %) and goal punch (47 %), while one action (receiving a tackle, with 54 % of all tackles received) was categorised as having a predominantly high injury risk.

Moderate and high injury risk are also expressed by the Playing Action Injury Risk Incidence (PAIRI) which for the four playing actions identified above were receiving a tackle (95.5 %), receiving a charge (82.2 %), making a tackle (50.4 %) and goal punch

(60 %). Of these only one (goal punch) did not lead to injury. Two playing actions had low PAIRI values but led to an injury and these were kicking the ball (4.5 %) and goal catch (20.4 %). The former may have occurred because of the high number of kicking actions made while the latter did not figure in any injury risk category and may be a chance occurrence.

Table 3.3.1. The frequency of injury potential (IP) and actual injury (AI) for each type of playing action (PA).

Playing Actions	Total. Events	Mild. IP	Moderate. IP	High. IP	Minor. AI	Moderate. AI	Major. AI	PA Injury Risk Incidence, %*	PA Injury Incidence, %**
Dribbling the Ball	157	47	1	0				0.6	0
Goal Catch	230	62	39	7	1			20.4	0.43
Goal Punch	43	11	20	6				60.4	0
Goal Throw	81	29	0	0				0	0
Heading the Ball	1723	1177	17	0				0.9	0
Jumping to Head	1225	496	9	3				0.9	0
Kicking the Ball	2330	2070	96	7	1			4.5	0.04
Making a Tackle	910	451	443	13	2	1		50.4	0.33
Making a Charge	585	68	5	3				1.36	0
Passing the Ball	4145	295	8	1				0.2	0
Receiving the Ball	3688	55	11	8				0.5	0
Receiving a Tackle	910	37	366	493	5	5	4	95.9	1.54
Receiving a Charge	583	97	420	58	1			82.2	0.17
Shot on Goal	82	69	4	0				4.8	0
Set Kick	676	563	6	0				0.8	0
Throw-in the Ball	509	91	4	1				0.9	0
Total	17877	5618	1449	600	10	6	4	11.6	0.11

* Playing action injury risk incidence % defined in text

** Playing action incidence % defined in text

3.3.2. Periods of the game

The number of actual injuries per period is illustrated in Figure 3.3.2. No significant difference ($\chi^2 = 1.58$, $P > 0.05$) was found between the six 15-min periods of the game. The greater number of actual injuries occurred in the first 15 min of the first half (N= 5) and the first 15 min of the second half (N= 4). The first half tended to have more actual injuries than the second half (accounting for 11 and 9 incidents, respectively), but this difference was not significant ($\chi^2 = 0.04$, $P > 0.05$).

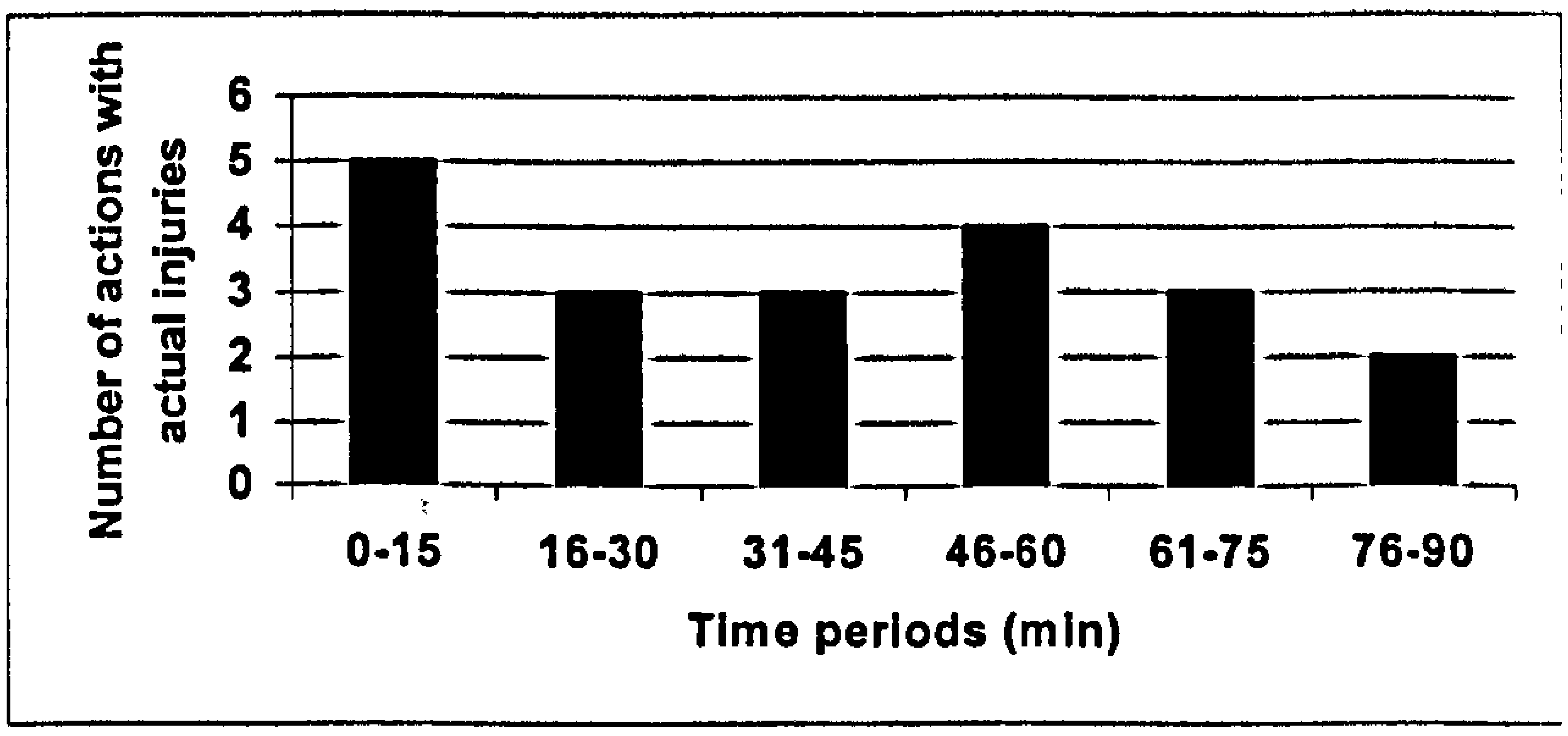
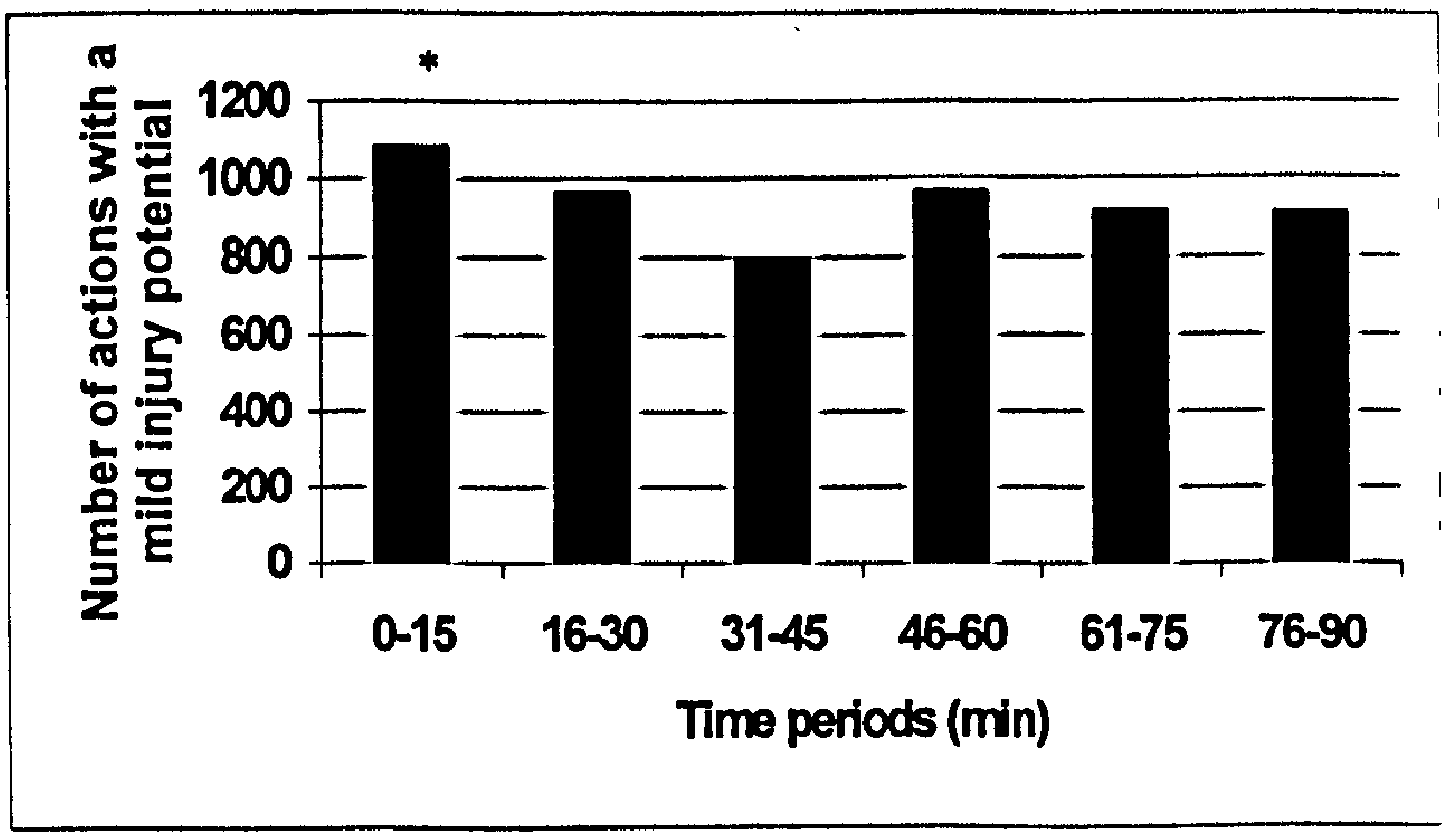


Figure 3.3.2. Number of actions with actual injuries per period

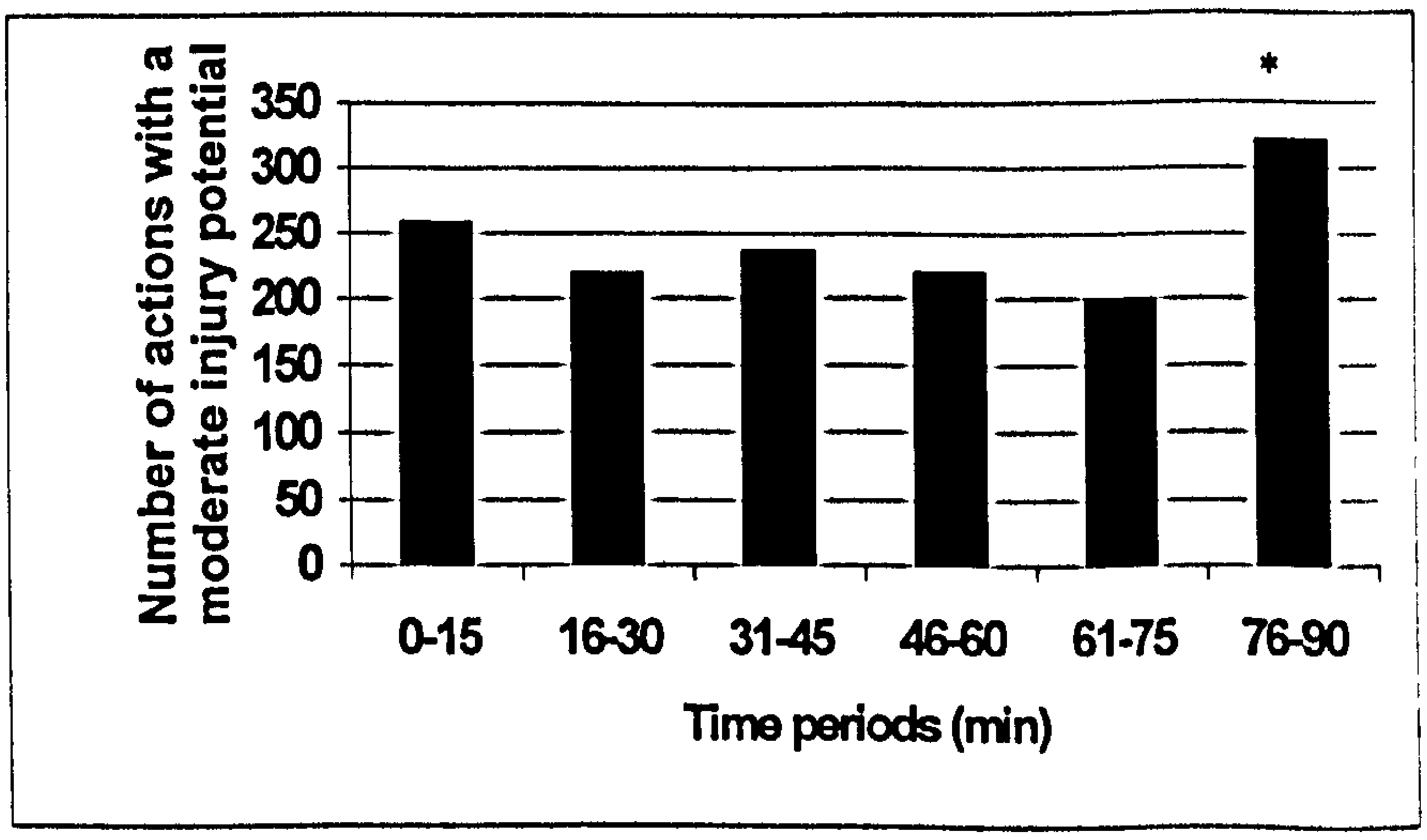
(Total over 10 games).

The number of actions with mild, moderate and high injury potential per period is illustrated in Figures 3.3.3, 3.3.4 and 3.3.5. A significant difference was found in mild and moderate injury potential between halves, with the first half having more actions with injury potential ($\chi^2 = 9.59$, $P = 0.008$, $\chi^2 = 10.47$, $P = 0.005$, respectively). The number of actions with high injury potential was similar between halves (51 % vs. 49 %). A significant difference between periods ($\chi^2 = 39.79$, $P = 0.001$) was found in mild injury potential, the first 15-min period having significantly more actions with mild injury potential than any other period of the game. With regard to actions with moderate injury potential, a significant difference ($\chi^2 = 25.08$, $P = 0.001$) was found; the last 15-min period had significantly more of those actions than any other period of the game. With regard to the actions with high injury potential, although the first and last 15-min periods had more occurrences than other periods, they were not significantly different (P > 0.05).



* denote significant difference between the first 15-min period and any other period of the game

Figure 3.3.3. Number of actions with mild injury potential per period (total over 10 games).



* denote significant difference between the last 15-min period and any other period of the game

Figure 3.3.4. Number of actions with moderate injury potential per. period (total over 10 games).

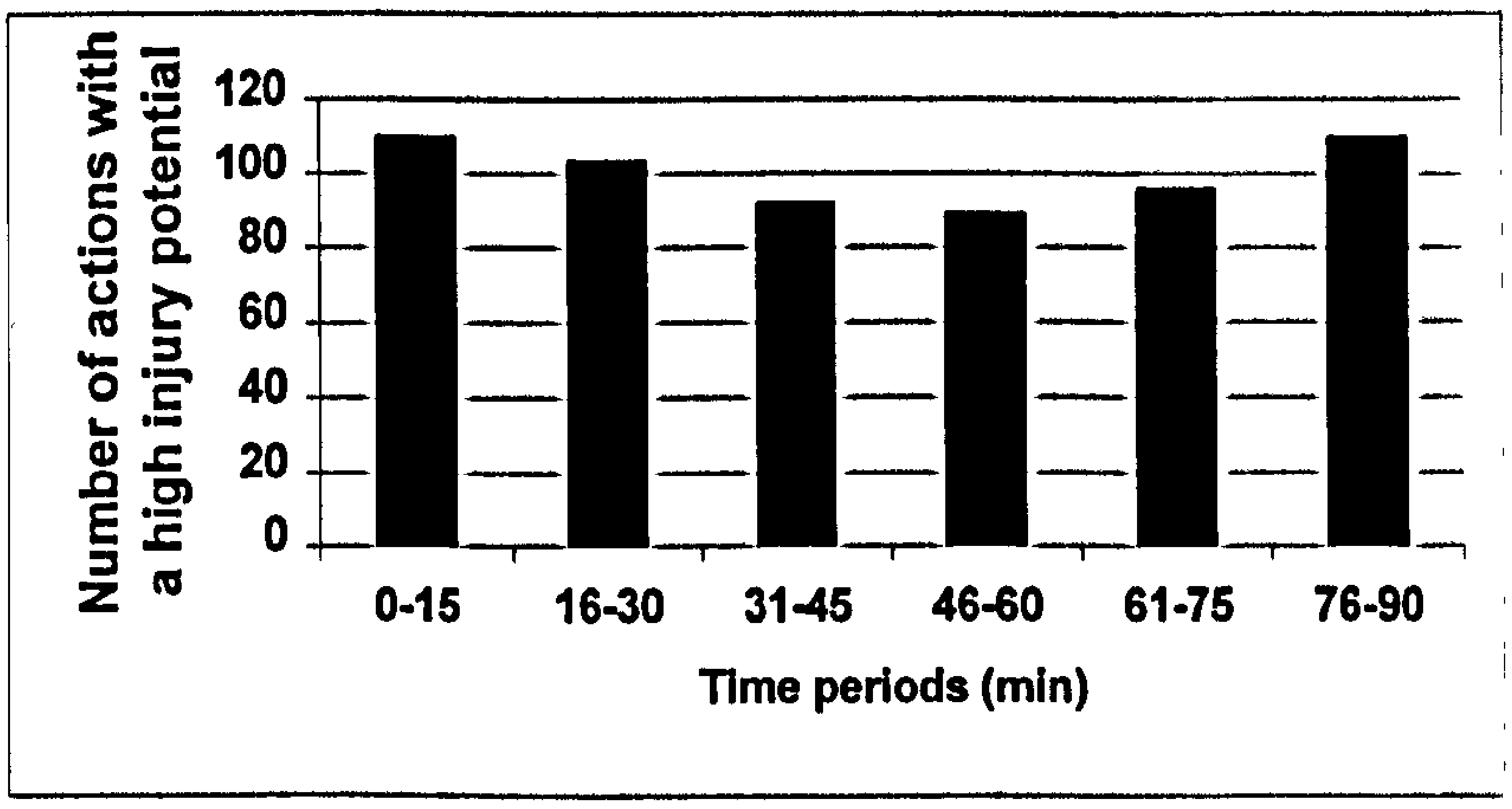


Figure 3.3.5. Number of actions with high injury potential per period (Total over 10 games).

3.3.3. Zones of the pitch

The number of actual injuries observed was small so it was not possible to analyse these formally per zone. Altogether, 40 % of injuries occurred in the midfield area, 30 % in the defending area and 30 % in front of the main attacking area (Table 3.3.2).

There was a significant association (χ^2 = 517, P = 0.001) between the number of actions with injury potential and the zone of play (Table 3). The higher number of actions with mild injury potential occurred in the attacking zones (14, 17), defending zones (2, 5) and midfield zones (7, 12) with around 60 % of all events with mild injury potential occurring in these six zones (Figure 3.3.6). The number of actions with moderate and high injury potential also occurred in the same attacking and defending zones, with around 40 % of all events with moderate injury potential and around 44 % of all events with high injury potential occurring in the four zones numbered 5,7,12 and 14 (Figures 3.3.7 and 3.3.8). Furthermore, it can be noted that 38 % of events with injury potential occurred in the midfield area, 31 % in the attacking area and 31 % in the defending area.

Table 3.3.2. Injury potential (IP) and actual injuries (AI) per zone.

Zone	Mild. IP	Moderate. IP	High. IP	Actual. Injury	Total IP+AI
1	124	21	11		156
2	633	146	36	1	816
3	143	28	15	1	187
4	187	41	18		246
5	538	140	66	2	749
6	169	64	21	2	256
7	463	141	56	1	661
8	305	92	37	2	436
9	306	87	32		425
10	321	109	42	1	473
11	234	72	31		334
12	397	114	50	4	565
13	164	44	13		221
14	595	142	87		824
15	188	37	21		246
16	86	26	13	3	128
17	638	124	32	3	797
18	127	21	19		167
Total	5618	1449	600	20	7687

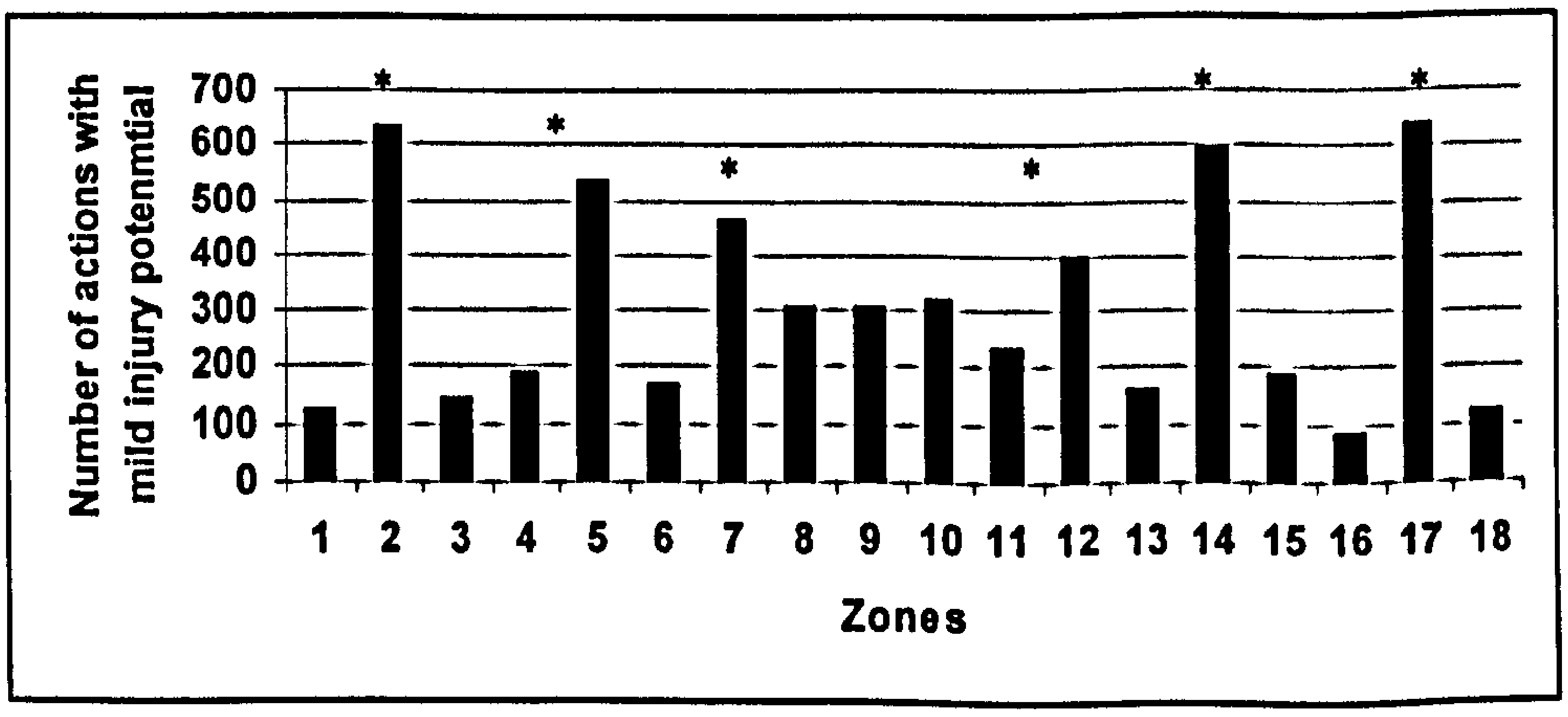


Figure 3.3.6. Number of actions with mild injury potential per zone (Total over 10 games).

* denote significant differences between the zones

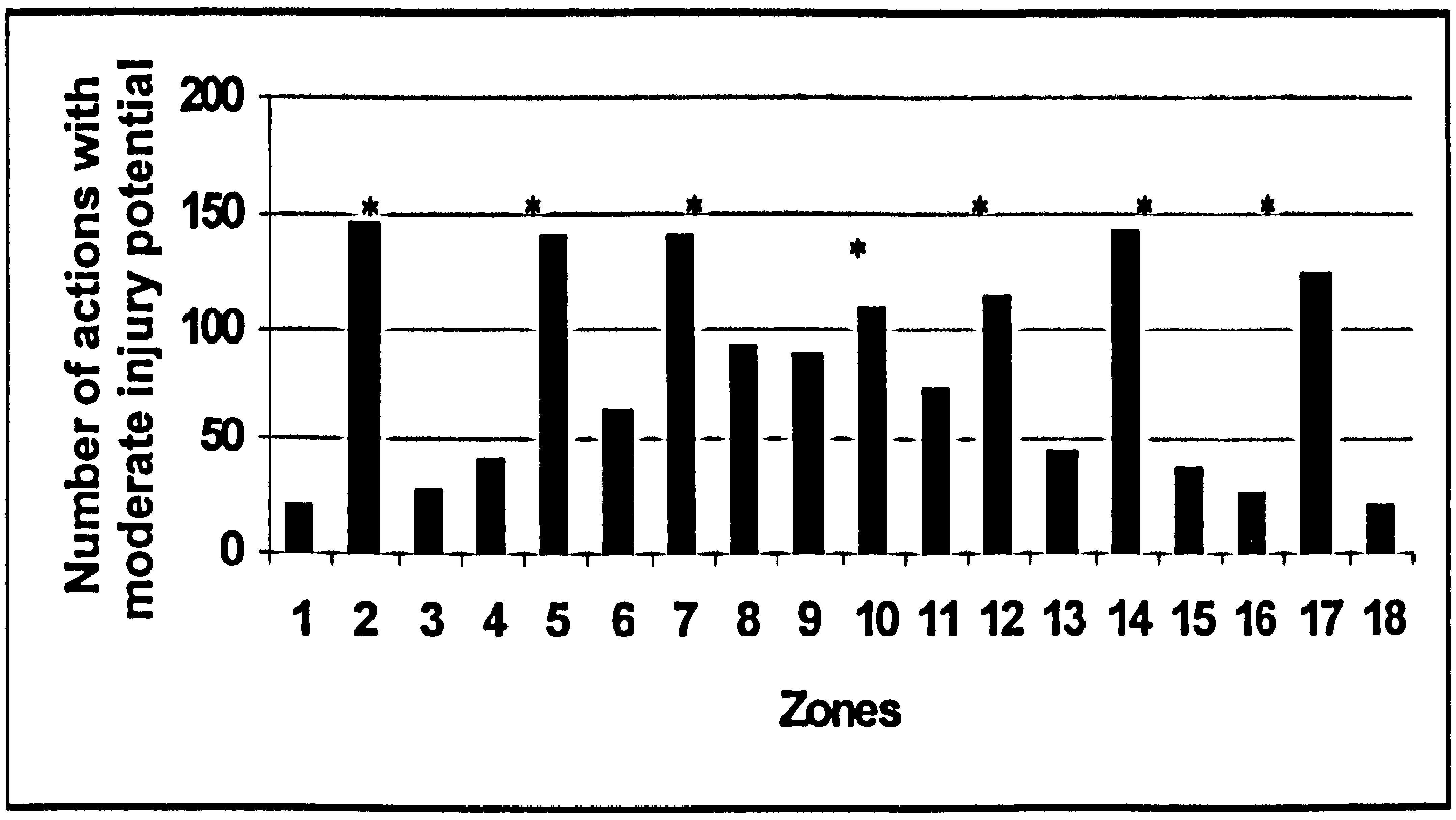


Figure 3.3.7. Number of actions with moderate injury potential per zone (Total over 10 games).

* denote significant differences between the zones

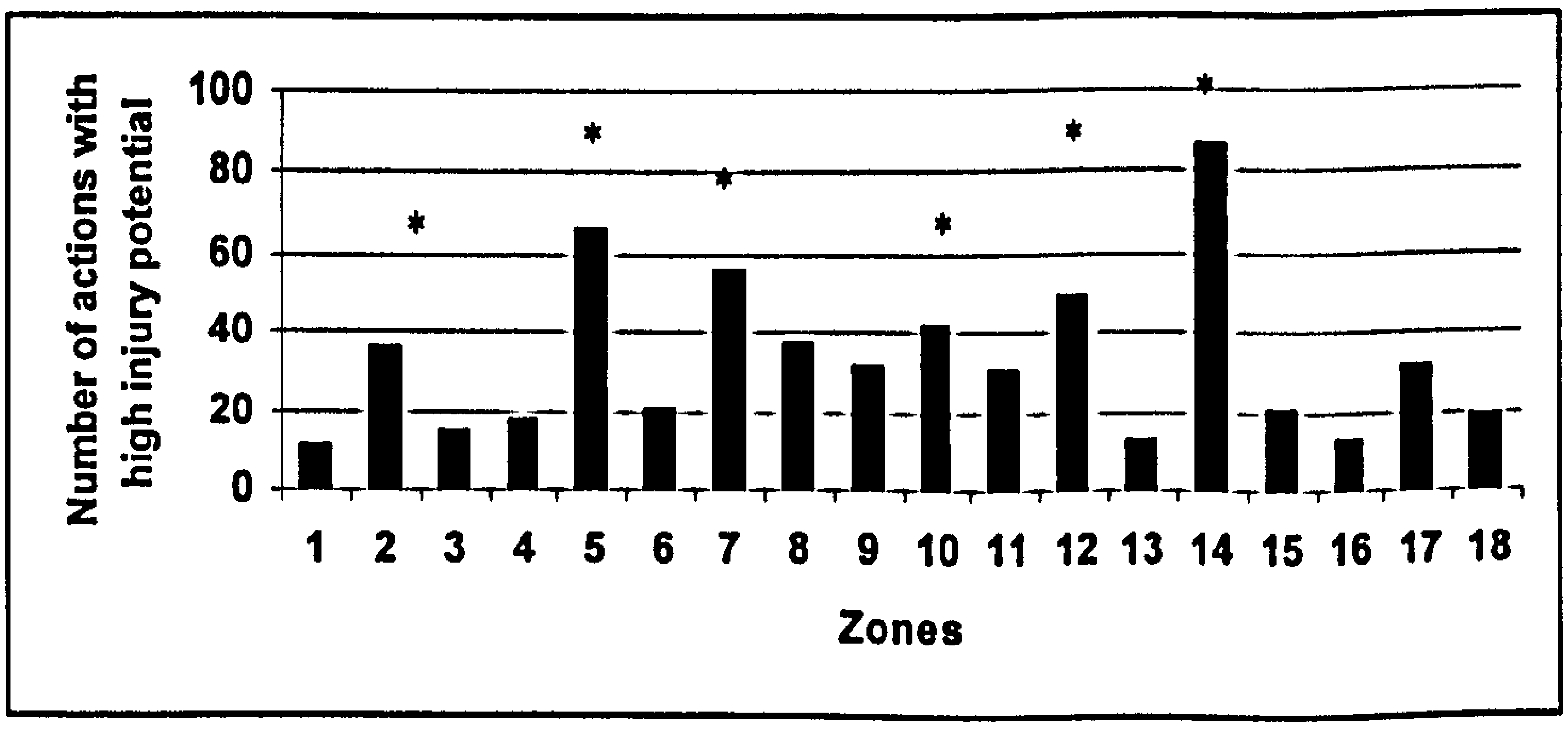


Figure 3.3.8. Number of actions with high injury potential per zone (Total over 10 games).

* denote significant differences between the zones

3.3.4. Playing either at home or away

The number of actual injuries for away teams (13) exceeded that for home teams (7), but the difference between them was not significant ($\chi^2 = 1.8$, P = 0.12). The actions with mild, moderate and high injury potential also were not significantly different between home and away teams (Figure 3.3.9).

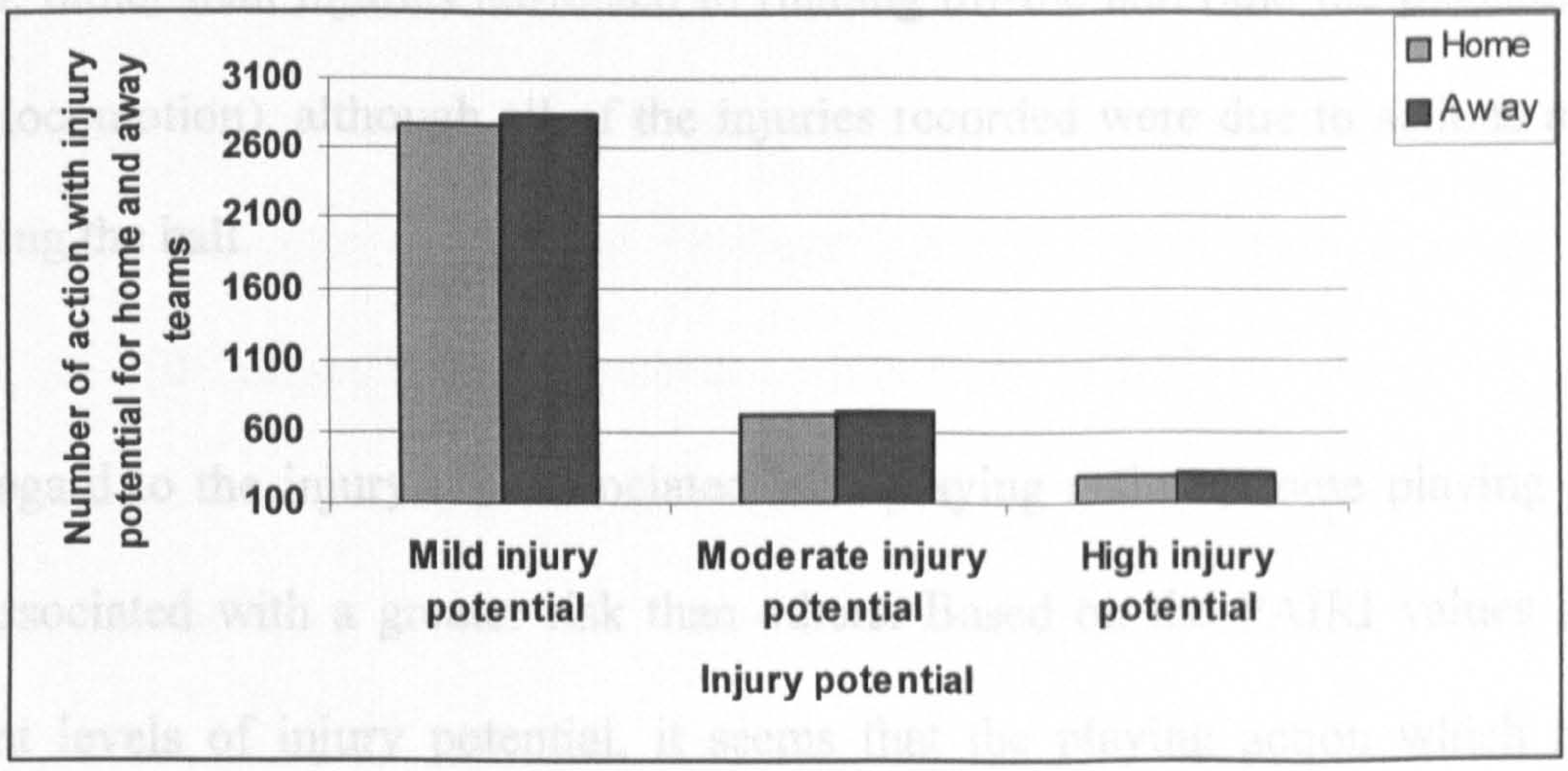


Figure 3.3.9. Number of actions with mild, moderate and high injury potential for home and away teams (Total over 10 games).

3.4. DISCUSSION

The aim of the present investigation was to assess the exposure to injury risk during competitive English Premier League matches, by identifying the most common critical incidents and the injury potential and actual injury associated with them. Injury potential and actual injuries were assessed with respect to playing actions, periods of the game, zones of the pitch and playing at home or away. The overall injury frequency rate in the current study was found to be 53 per 1000 hours played which is higher than reported by Inklaar (1994b) and Arnason et al. (1996) probably due to the method of defining injury used in this study.

Unlike the previous work referred to, the present study was focused on the thousands of events observed over the 10 games analysed, and the small numbers of actual injuries occurring would not allow inferences about injury to be drawn. It should be noted that the concern of this study was with injury risk associated with actions around the ball, rather than injuries attributed to running off-the ball (and the associated risk due to locomotion), although all of the injuries recorded were due to actions made in contesting the ball.

With regard to the injury risk associated with playing actions, some playing actions were associated with a greater risk than others. Based on the PAIRI values and the different levels of injury potential, it seems that the playing action which had the greatest level of injury risk is receiving a tackle. Receiving a charge and making a tackle should also be considered as having substantial risk associated with them. Playing actions such as goal catch, goal punch and kicking the ball, including shot at goal and set kick, and heading the ball all have a significant risk of injury. Other playing actions have a much smaller risk associated with them. Making a "charge" appears to be relatively low-risk compared to receive a charge, presumably due to the planned nature of the event by the player doing the charging. Since some actions have a higher injury risk than others, more attention should be paid to these by the coach in planning training, by the referee while judging a match and by players who may also need to practice avoidance manoeuvres to protect themselves in such instances. Inspection of the data in Table 2 shows that some playing actions (such as kicking the ball) are characterised by a large number of "low injury potential" occurrences while others (such as making and receiving a tackle and receiving a charge) are characterised by a smaller total number but a higher occurrence in the moderate or high injury potential category. In both cases these can lead to actual injuries. In the former case an injury might occur simply because the large number of events increases the chance of one of those events becoming a critical incident (as illustrated in Figure 2). In the latter case the higher level of risk associated with certain actions means that they are more likely to lead on to a critical incident or injury. An exception to this appears to be the goal catch which has a low number of actions and has a predominantly low injury potential but generated one injury. However, in any action there is always some element of risk depending on context and it may be that this particular action represents a chance event because of the small but important number of events with high injury potential.

A significant difference was found between periods of the game with respect to injury risk. The opening 15 minutes had significantly more actions with mild injury potential than any other period of the game. The contest is arguably at its most intense in the initial period of play, compared with later in the game, because the players are fresh and more energetic and wish to "register their presence" with the opposition. The closing 15 minutes of the game had the most frequent actions with moderate injury risk. This may be the result of a fatigue effect on the muscles and other body organs as muscle glycogen stores near depletion (Saltin, 1973) and players become hypohydrated (Reilly, 1997). At this stage of the game the players are tired but the contest may still be intense. The consequence may be that predisposition to injury is exposed as fatigue sets in or damage incurred earlier in the game becomes more evident as play is sustained. More attention should be paid by game officials and players (and the team's medical staff) to the first and last periods of the game if actions including some risk of injury are not to lead on to actual injury.

In relation to actual injury per period of the game, no significant difference was observed largely because of the small numbers involved. The highest number of actual injuries occurred in the first 15 minutes of the first half. This observation may be due to the fact that this is the period in which greatest effort occurs. The first 15 minutes of the second half of the game again had a relatively high number of injuries. In this instance the players may not have warmed up properly after the half-time intermission. These results differ from those of Hawkins et al. (2001) who reported that a greater number of injuries was observed during the final 15 minutes of the first half and the final 30 minutes of the second half. These differences may be caused, in part, by differing definitions of injury (they classified injury severity by the length of time that a player was subsequently absent from training or competition), methods of data collection, observation periods, study designs, and sample characteristics (Jung and Dvorak, 2000). There was no significant difference between the two halves of play in terms of frequency of actual injury, accounting for 11 (55 %) and 9 (45 %) incidents respectively. Hawkins and Fuller (1999) found that the number of injury incidents in the second half was significantly greater than the first half (57% v 43 %), although Ekstrand and Gillquist (1983) have shown some similarities to the current research (i.e. a greater number of injuries at early stages of a games).

A significant difference in injury risk was observed between zones of the pitch. More actions with mild injury potential occurred in the goal area (zones 2 and 17) and more actions with moderate and high injury potential occurred in zones adjacent to the goal area (zones 5 and 14). This pattern is likely to be due to intense actions occurring as a result of efforts to obtain goals by forward players and the protection of the goal area by opponents. Relatively high injury risk also occurred in zones 12 and 7, which are asymmetrical zones of the pitch. This may be due to a tendency of players to attack on the right side of the pitch (see Figure 1). Zone 12 represents the right hand side of the pitch when attacking while zone 7 represents the opponents' right hand side of the pitch when they attack. Therefore more attention should be paid by referees to play in these zones (14, 17, 2, 5, and 12) with regard to judging play. In relation to actual injury per zone, it is noted that just 50 % of injuries occurred in the attacking zones 16, 17 and 12. This finding is linked to the attempts by forward players to score and by defenders to protect the goal area from the opponents. The low number of actions in zone 16 suggests that this is the weaker side of the field for players, who are therefore at increased risk. In defence, zones 3 and 6 are also high-risk locations due to the high number of injuries in relation to the low number of actions.

In soccer, home advantage has always been a very important factor in determining the outcome of a game (Pollard, 1986; Silva and Andrew, 1987) but in the present study no significant difference was observed between the home and away teams regarding their exposure to risk. The total number of actual injuries for away teams was only marginally more than that for home teams and this difference was not significant. The higher number of actual injuries for away teams may be due to psychological factors such as stress and lack of acquaintance with the opponent's playing surface, and may contribute to the phenomenon of home advantage but seemingly not to injury risk or injury occurrence.

In conclusion, data available from this investigation suggest that some playing actions were associated with higher injury risk than others. In particular, receiving a tackle, making a tackle and receiving a charge, were actions with a substantial risk of injury. The first and last 15 min of the game contained the highest risk, although the greatest number of injuries tended to be in the first period of each half. Exposure to injury risk was concentrated on those parts of the pitch where possession of the ball is most vigorously contested, being specific attacking, defending and midfield zones. Playing at home or away does not affect a player's risk of injury.

CHAPTER FOUR

A COMPARISON OF MUSCULOSKELETAL FUNCTION IN ELITE AND SUB-ELITE ENGLISH SOCCER PLAYERS

4.0 A COMPARISON OF MUSCULOSKELETAL FUNCTION IN ELITE AND SUB-ELITE ENGLISH SOCCER PLAYERS

4.1. INTRODUCTION

Effective musculoskeletal function is important in soccer, both for enhancing performance and minimising injury. Impairment in muscle function is reflected in strength imbalance and insufficiency and poor flexibility in the lower extremities. These are influential in soccer specific movements such as sprinting, jumping, tackling, changing direction and kicking, whereas during heading and tackling, strength in trunk and upper body muscles is also utilised.

Ekstrand and Gillquist (1983) indicated that an imbalance in muscle strength between limbs may predispose a player towards musculoskeletal injury. Bender et al. (1964) reported that 806 cadets who had differences greater than 10 % in quadriceps strength between limbs were more likely than normal to get knee injuries in the weaker limb. Knapik et al. (1991) suggested that subjects with an imbalance of greater than 15 % were 2.6 times more likely to suffer injury in the weaker leg. In a later study, Fowler and Reilly (1993) reported a 20 % difference in muscle strength in professional soccer players prone to injury.

A gross imbalance in strength between the quadriceps and hamstrings muscle groups has also been suggested as a factor which leads to an increase in the susceptibility to joint as well as muscle injury (Coplin, 1971). The ratio between the strength of the knee extensors and knee flexors is of particular interest, a low ratio being associated with a risk of injury (Fowler and Reilly, 1993). The hamstring/quadriceps strength ratio varies between 50 % and 62 % in healthy people (Knapik and Ramos, 1980) while ratios for soccer players vary between 41 % and 81 % depending upon the angular velocity of movement. The agonist-antagonist relationship for knee extension and flexion may be better described by the more functional ratio of eccentric hamstring to concentric quadriceps, known as the dynamic control ratio (Aagaard et al., 1998).

Besides this asymmetry in muscle strength, risk usually manifests itself as muscle weakness and poor co-ordination of muscle activation. Generally, it is the disproportionately weaker muscle group that is prone to injury (Burkett, 1970). Players who carry muscle weaknesses into competition are likely to experience situations where the muscle may fail and injury occurs (Reilly and Howe, 1996). Individuals with well developed strength capabilities are less prone to musculoskeletal strain, sprain injuries and back fatigue than their weaker counterparts when placed in physically demanding activities (Chaffin et al., 1978).

Muscular tightness which restricts the range of motion is also thought to predispose the muscle to injury and to impair performance in sports where flexibility is important. In soccer, around 17% of injuries have been attributed to muscle tightness (Ekstrand and Gillquist, 1983). The hamstring muscles (knee flexors and hip extensors) are one of the most commonly strained muscle groups in soccer: one of the possible causes of this injury is a lack of flexibility in the joints they act across. Athletes with a history of injury to the hamstrings have more tightness in those muscles than do their counterparts (Noonan et al., 1994).

The assessment of muscle function has become increasingly important as it is realised that there is a large variation in this human attribute which is affected by both individual and environmental factors. The identification of asymmetric weakness or laxity within an individual player may be more important than comparison between team members (Reilly and Howe, 1996). Isokinetic dynamometry can be used to assess strength as it allows the comparison of hamstrings/quadriceps strength ratio, left/right leg ratio and fast-speed to slow-speed ratio to identify any muscle imbalance and deficit in specific muscle groups.

Elite players are likely to have elevated levels of muscle strength due to the requirements of a high performance level and freedom from injury. Yet in the course of their habitual training they may develop imbalances and tightness not evident in those playing at a lower level. The aim of this study therefore was to compare musculoskeletal function between elite and sub-elite soccer players. A subsidiary aim was to identify the influence of body size on this comparison.

4.2. MATERIALS AND METHODS

4.2.1. Participants

Twenty-eight soccer players (14 elite and 14 sub-elite) were studied. Elite players were classed as those who were signed for a professional club (full-time professional players with an English Premier League club). Sub-elite players were classed as those who were not signed for a professional club but were playing regularly for local and University teams.

Participants recruited were not injured or rehabilitating from injury at the time of testing. All participants were aged between 18-25 years. Informed consent was obtained from all subjects before data collection, and ethical approval for the study was obtained from the University's Human Ethics Committee.

Participants were tested during the 2000-2001 English competitive soccer season. All the tests were scheduled for the same time of day (10:00 hours) to remove the effects of any circadian variation on the variables being measured (Reilly and Brooks, 1986). Measurements for each participant were in four categories: anthropometric (height and mass), muscle strength profiling, flexibility of hamstrings, and vertical jump height. The procedures in each category are described in turn. Table 1 shows the descriptive statistics for age, height and mass of the participants.

Table 4.2.1. Mean (± SD) age, height and mass of elite and sub-elite soccer players.

Groups	N	Age (years)	Height (m)	Mass (kg)
Elite	14	23.7 (4.3)	1.82 (0.06)	85.5 (9.2)
Sub-elite	14	23.1 (3.1)	1.79 (0.06)	75.2 (8.1)

4.2.1.1. *Anthropometric profiling*

Each participant's body mass (kg) was determined using a calibrated precision weighing scales (Hotline, Hamburg, Germany). A cursor placed on the participant's head was used to help measure height (m) (Seca, MeB-und Wiegetechnik, Vogel and Halke, Hamburg, Germany).

4.2.1.2. *Muscle strength profiling*

Strength of knee flexors and extensors (dominant and non-dominant legs) was measured on an isokinetic dynamometer (Lido Active, Loredan, Davis, CA), which is a reliable research tool for assessing muscle strength (Patterson and Spivey, 1992). Each subject visited the laboratory and was tested with the same protocol on two separate occasions. The first visit entailed familiarisation with the dynamometer and the experimental procedure (Figure 4.2.1).

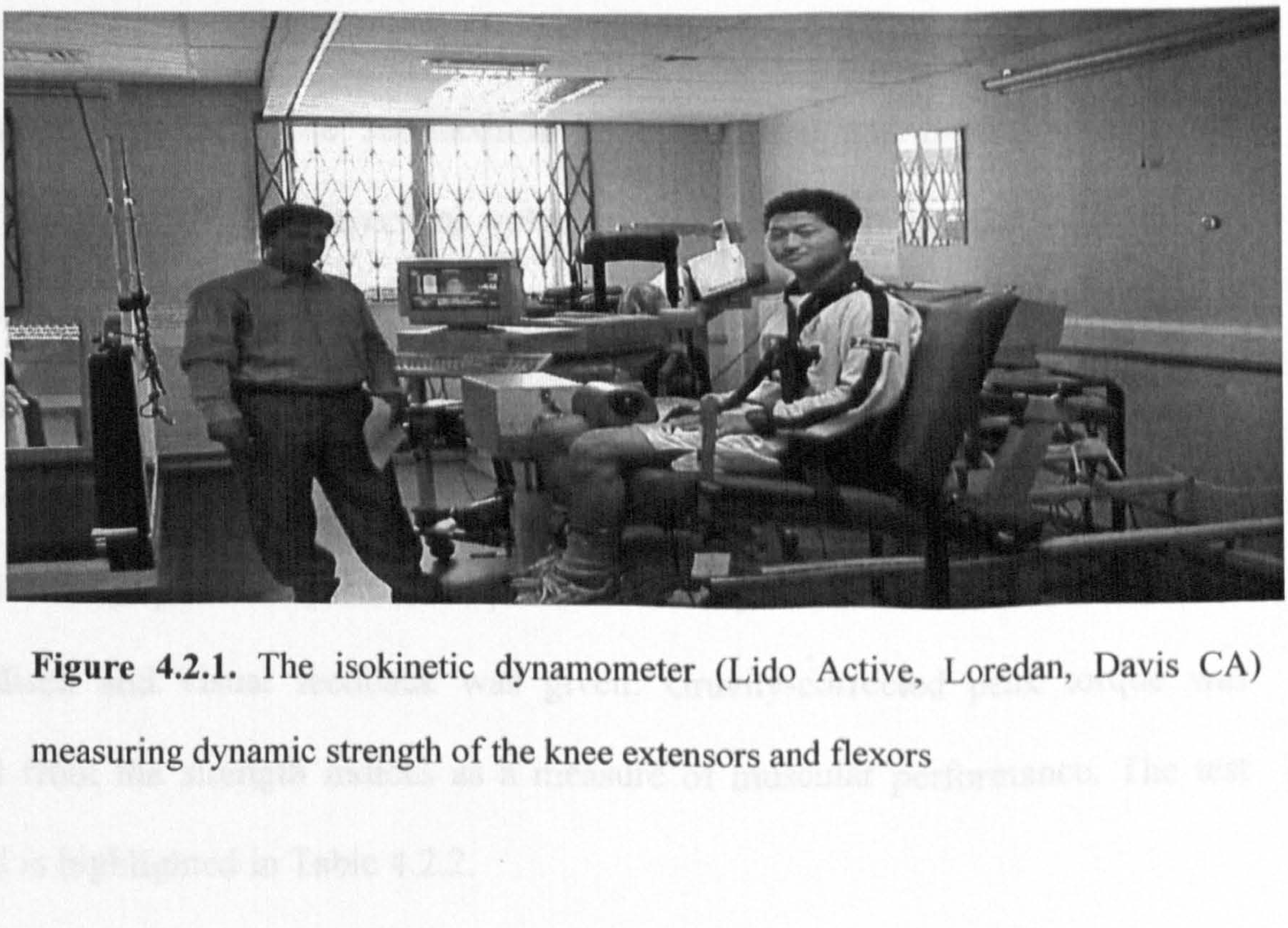


Figure 4.2.1. The isokinetic dynamometer (Lido Active, Loredan, Davis CA) measuring dynamic strength of the knee extensors and flexors

A standardised warm-up was initially performed on a Monark cycle ergometer for 5 min with no resistance at 60 rev.min^{-1} prior to the experimental protocol. This exercise was followed by 10 min of static stretching of the relevant muscle groups, which were concentrated on the lower extremities. The subject was then seated in the dynamometer in an adjustable chair; the upper body was stabilised with straps secured across the shoulder, chest and hips. A resistance pad was also positioned on the thigh, proximal to the knee joint to localise the quadriceps and hamstrings. The axis of rotation of the dynamometer shaft was aligned with the axis of rotation of the knee joint, mid-way between the lateral condyle of the tibia and the lateral condyle of the femur. The cuff of the dynamometer's lever arm was attached to the ankle, proximal to the malleoli. These positions were recorded for each subject and standardised for subsequent trials. Range of motion (ROM) was pre-set to 0 to 90 °. The gravity compensation procedure required the subject to relax, while the leg was passively extended and flexed over the entire ROM.

The participant was instructed to grasp the handles adjacent to the chair during the tests and then perform two submaximal knee extension and flexion movements. Testing consisted of three maximal voluntary movements at angular velocities of 1.05, 2.09 and 5.23 rad.s^{-1} (in concentric mode) and 2.09 $_{ecc}$ rad.s^{-1} (in eccentric mode), first for the dominant and then for the non-dominant leg. This order of testing for the different angular velocities was standardised from the slowest to the fastest. Each trial was separated by 1 min of passive recovery. Verbal instructions were also standardised and visual feedback was given. Gravity-corrected peak torque was selected from the strength indices as a measure of muscular performance. The test protocol is highlighted in Table 4.2.2.

Table 4.2.2. The test protocol that was used in isokinetic dynamometry (n = 28).

Test	Muscle groups	Modes	Angular velocity (rad.s^{-1})
1	Hamstrings & Quadriceps	Concentric	1.05
2	Hamstrings & Quadriceps	Concentric	5.23
3	Quadriceps	Concentric/Eccentric	2.09
4	Hamstrings	Concentric/Eccentric	2.09

Data for 48 variables were recorded for each player. These included absolute quadriceps muscle strength for dominant and non-dominant legs at the four angular velocities (8 variables were included for the two legs and four tests), relative quadriceps muscle strength (peak torque/body mass) for dominant and non-dominant legs at different angular velocities (8 variables), absolute hamstrings muscle strength for dominant and non-dominant legs at different angular velocities (8 variables), relative hamstrings muscle strength (peak torque/body mass) for dominant and non-dominant legs at different angular velocities (8 variables), muscle balance (hamstrings/quadriceps ratio) for dominant and non-dominant legs at different angular velocities (8 variables), fast-speed to slow-speed ratio for dominant and non-dominant legs for quadriceps and hamstrings (4 variables). Finally a bilateral comparison (left/right ratio) was made for quadriceps and hamstrings (4 variables). Dynamic control ratio (DCR) was expressed as eccentric hamstrings relative to concentric quadriceps strength at 2.09 $_{(ecc)}$ rad.s^{-1}.

4.2.1.3. *Flexibility*

The flexibility of the participant's hip joint (in flexion) was measured by means of a goniometer (MIE goniometer, Medical Research Limited, Leeds). The subject lay supine on the floor with the legs extended and the head on the floor. The quadriceps muscle of the right leg was palpated and the goniometer was placed half-way down the limb (from the hip to the knee). The goniometer was then altered so that the liquid inside was level at 0 degrees. The subject then slowly lifted the right leg, keeping the left leg on the floor. With the help of another person, the point when maximum hip flexion had been reached was determined. This point was decided by observing the tenseness in the muscle and by the player's subjective response. The reading on the goniometer was recorded and this procedure was completed three times. This protocol was repeated on the opposite limb to assess flexibility of both dominant and non-dominant legs.

4.2.1.4. *Vertical jump*

An electronic timing mat was used to measure standing vertical jump height (Cranlea & Company, Bournville, Birmingham, England). The participant stood on the mat and placed his hands on the hips, to control the influence of the arms on the jump. The meter was reset and the subject performed three maximal vertical jumps, from which the highest distance jumped was recorded for analysis. The jump was recorded when the subject completed a full cycle of jumping, including preparation to jump, leaving from the mat and landing back on it.

4.2.2. Statistical analysis

The strength variables were categorised into seven groups for statistical analysis. These categories included quadriceps muscle strength (peak torque), relative quadriceps muscle strength (peak torque/ body mass), hamstring muscle strength (peak torque), relative hamstring muscle strength (peak torque/ body mass), muscle balance (hamstring/quadriceps ratio), fast to slow speed ratio (F/S Ratio) and bilateral comparison (left/right ratio). Each of these data sets was analysed using separate multivariate analyses of variance (MANOVA) in which "group" (elite, sub-elite) was the "between participant" variable. Follow-up univariate analysis of variance (ANOVA) tests were used where appropriate.

Those measures not included in this initial procedure were analysed using separate analyses of variance for independent samples. These measures included vertical jump height and hamstring flexibility. The level of significance on all tests was set at $P < 0.05$.

4.3. RESULTS

4.3.1. Anthropometric profiles

The MANOVA showed that there was a significant difference between the two groups of players with regard to measurement of body size (mass and height) (Wilks' lambda = 0.716, $F_{2,25} = 4.95$, $P < 0.01$). The significant difference in body mass was confirmed by ANOVA ($F_{1,26} = 9.83$, $P < 0.005$). The difference in height between groups was non-significant.

4.3.2. Quadriceps muscle strength profile (peak torque)

The MANOVA showed there was a difference between the two groups of players when the eight quadriceps peak torque variables were considered as a whole (different angular velocities, dominant and non-dominant leg) (Wilks' lambda = 0.12, $F_{8,19} = 16.78$, $P < 0.001$).

For the dominant leg, univariate ANOVA showed significant differences in quadriceps peak torque between groups at 1.05 rad.s^{-1} ($F_{1,26} = 7.42$, $P < 0.001$), 2.09 rad.s^{-1} ($F_{1,26} = 11.38$, $P < 0.002$), 5.23 rad.s^{-1} ($F_{1,26} = 13.18$, $P < 0.001$) and 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26} = 28.66$, $P < 0.001$). At all angular velocities, the elite players were stronger than the sub-elite players (see Figure 4.3.1).

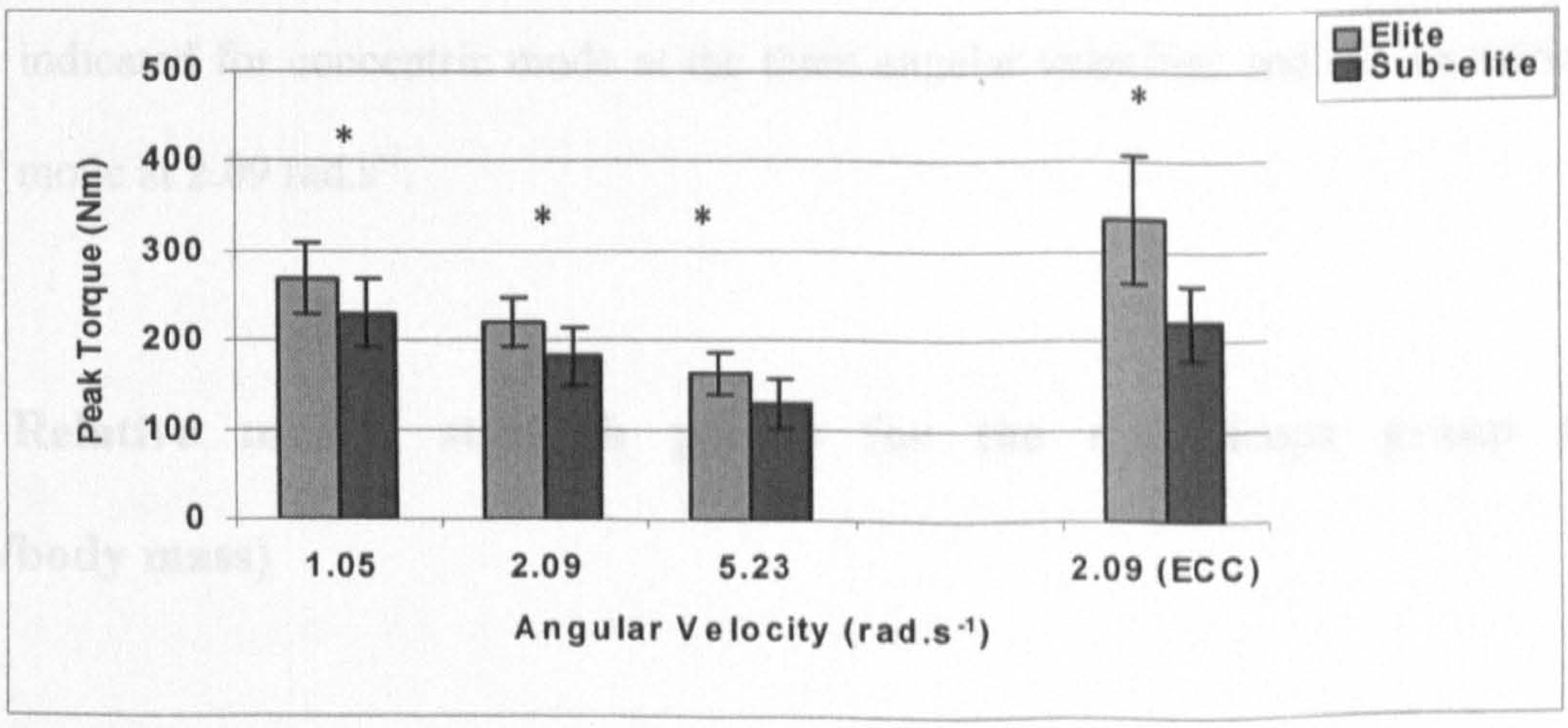


Figure 4.3.1. Comparison of quadriceps muscle strength (peak torque) between elite and sub-elite soccer players for the dominant leg. Results are indicated for concentric mode at the three angular velocities and for eccentric mode at 2.09 rad.s^{-1}.

For the non-dominant leg, univariate ANOVA showed significant differences in quadriceps muscle strength profile (peak torque) between groups at 1.05 rad.s^{-1} ($F_{1,26} = 12.90$, $P < 0.001$), 2.09 rad.s^{-1} ($F_{1,26} = 17.23$, $P < 0.001$), 5.23 rad.s^{-1} ($F_{1,26} = 8.84$, $P < 0.006$) and 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26} = 37.32$, $P < 0.001$). In all variables, the elite players were stronger than sub-elite players (Figure 4.3.2).

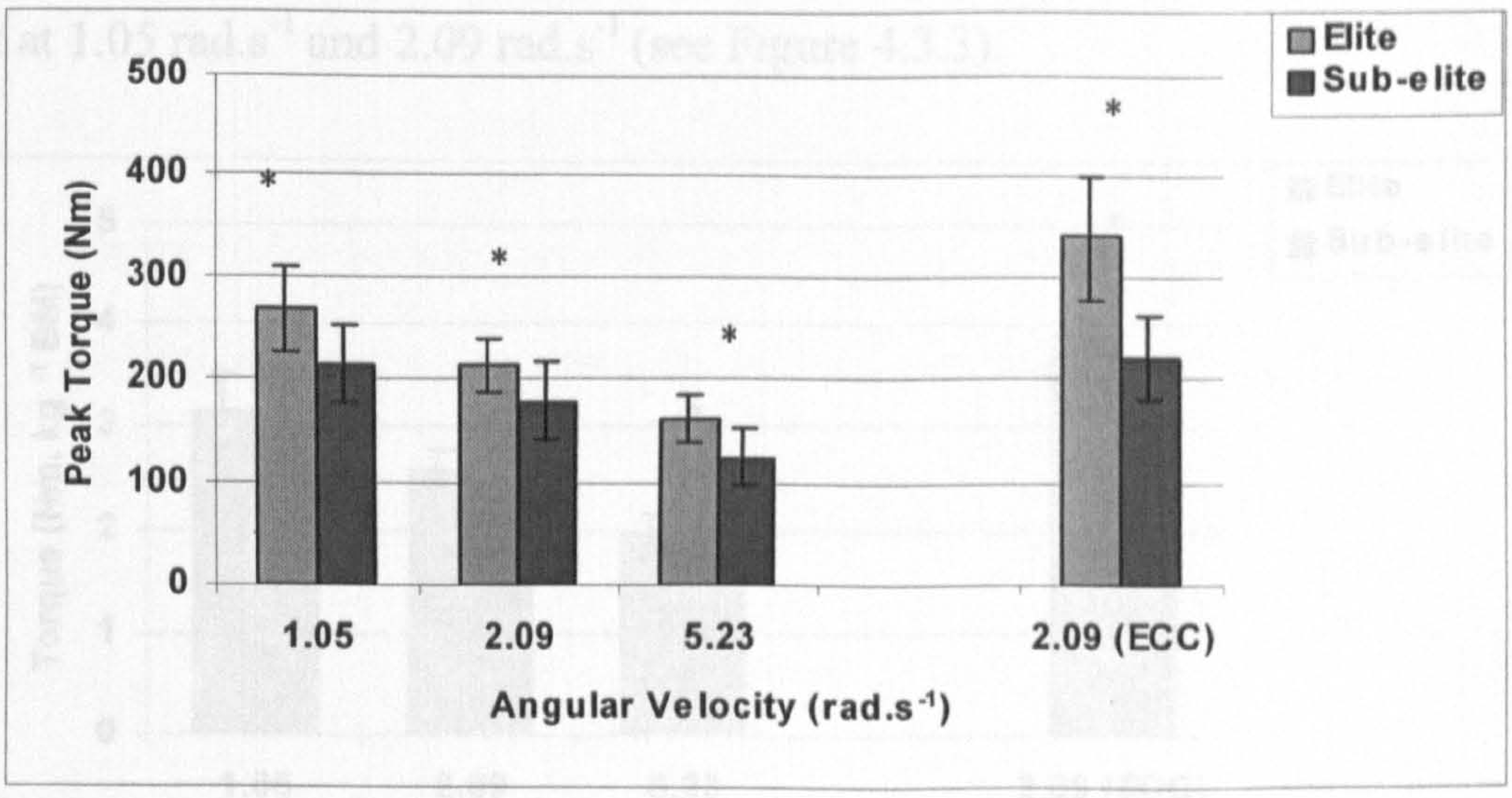


Figure 4.3.2. Comparison of quadriceps muscle strength (peak torque) between elite and sub-elite soccer players for the non-dominant leg. Results are indicated for concentric mode at the three angular velocities and for eccentric mode at 2.09 rad.s^{-1}.

4.3.3. Relative muscle strength profile for the quadriceps group (peak torque/body mass)

The MANOVA showed a significant group difference in the quadriceps relative muscle strength, when corrected for body mass (Wilks' Lambda = 0.18, $F_{8,19}$ =

17.83, $P < 0.001$). This finding corroborates the results of the comparison before data were normalised for body mass.

For the dominant leg, univariate ANOVA indicated significant differences in quadriceps relative muscle strength (peak torque normalised for body mass) between groups at 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26} = 24.27$, $P < 0.001$) and 5.23 rad.s^{-1} ($F_{1,26} = 4.57$, $P < 0.04$) with elite players being stronger than sub-elite players. No differences were apparent at 1.05 rad.s^{-1} and 2.09 rad.s^{-1} (see Figure 4.3.3).

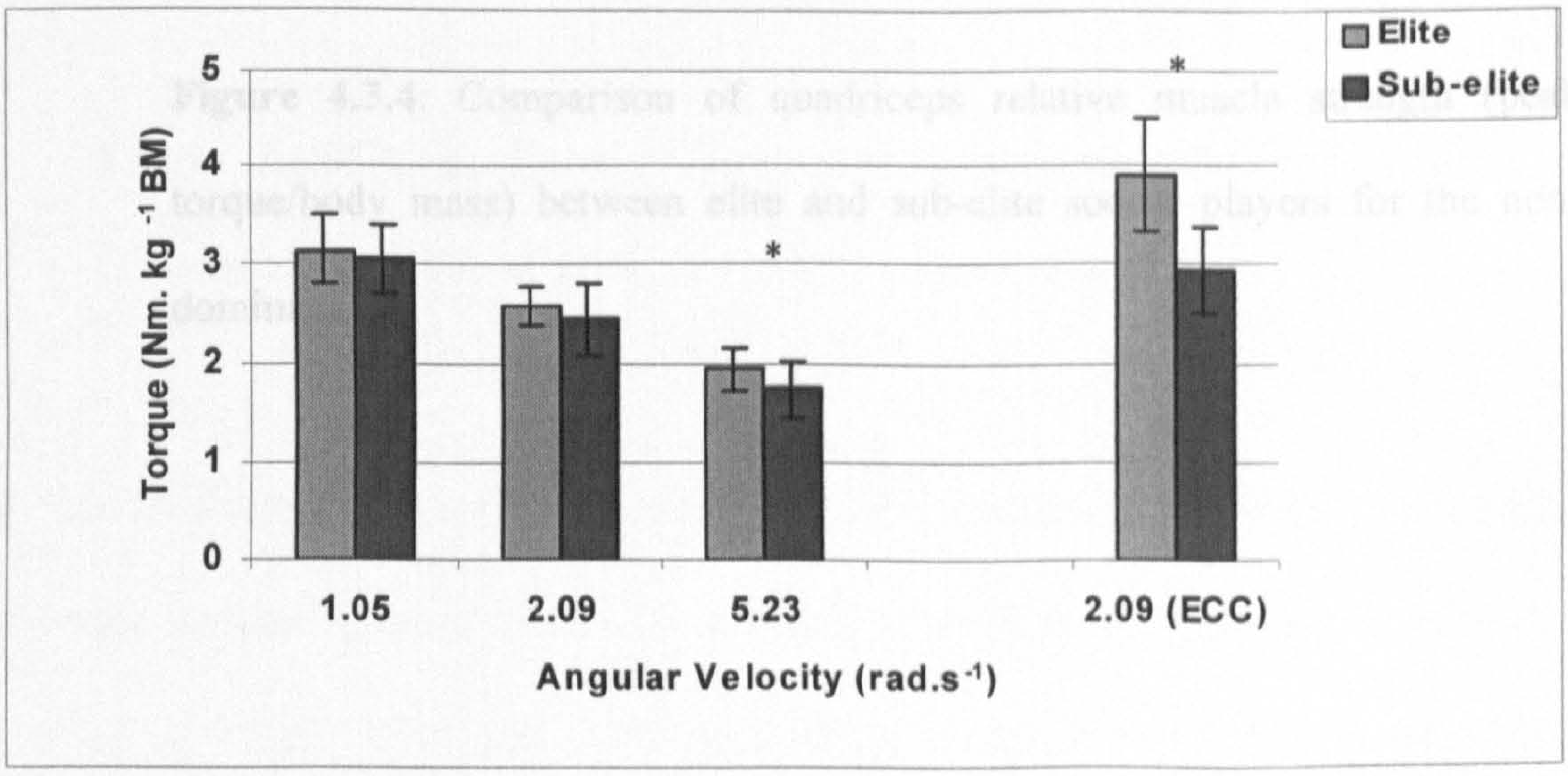


Figure 4.3.3. Comparison of quadriceps relative muscle strength (peak torque/body mass) between elite and sub-elite soccer players for the dominant leg.

For the non-dominant leg, univariate ANOVA revealed significant differences in quadriceps relative muscle strength (peak torque normalised for body mass) between groups at 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26} = 29.70$, $P < 0.001$) and 5.23 rad.s^{-1} ($F_{1,26} = 6.21$, $P < 0.02$). No differences were apparent at 1.05 rad .s^{-1} ($P > 0.05$) and 2.09 rad.s^{-1} ($P > 0.05$). According to these data, the elite players had greater muscle strength at high velocities and in eccentric actions than the sub-elite players (see Figure 4.3.4).

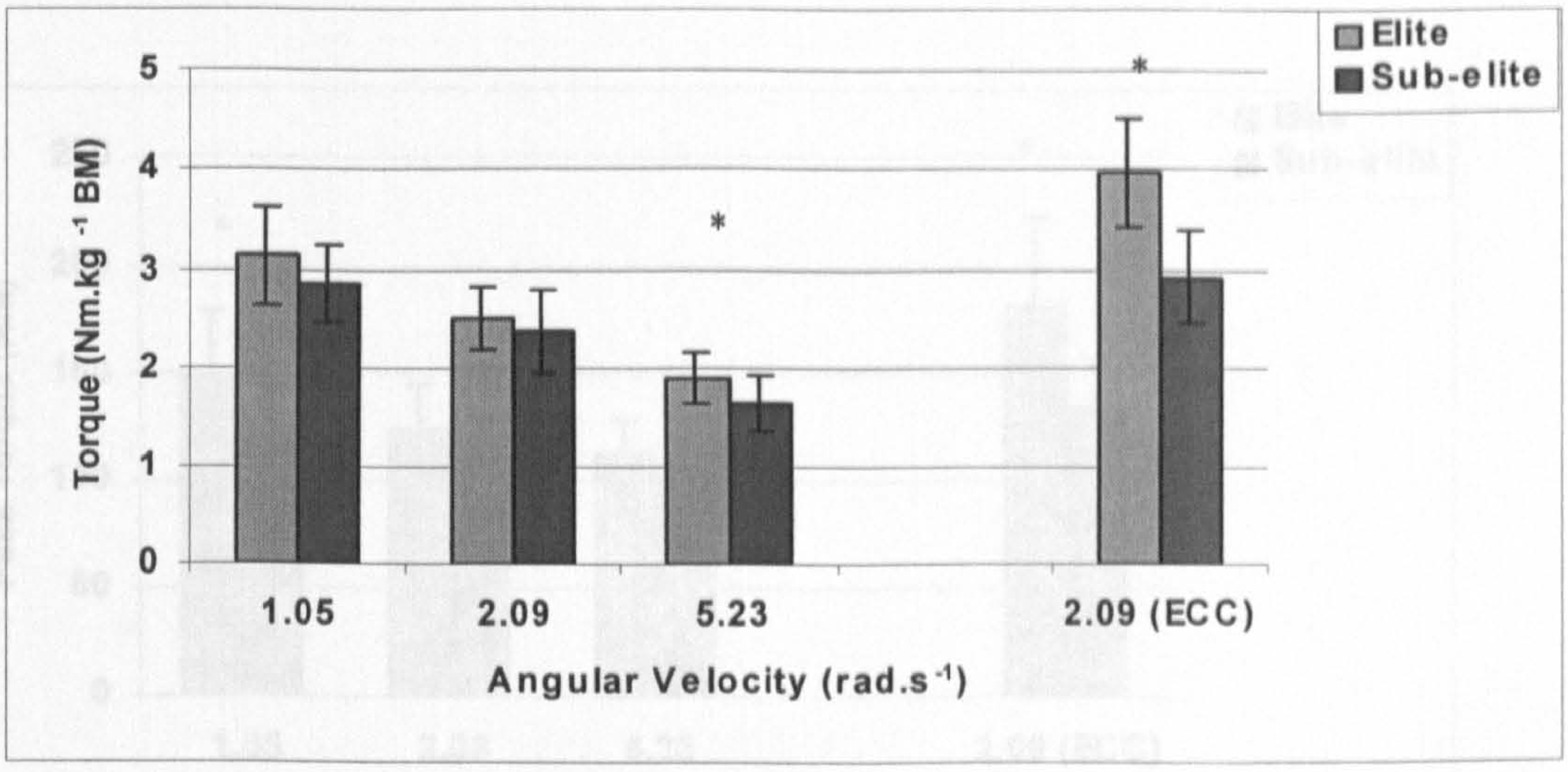


Figure 4.3.4. Comparison of quadriceps relative muscle strength (peak torque/body mass) between elite and sub-elite soccer players for the non-dominant leg.

4.3.4. Hamstrings muscle strength (peak torque)

No significant differences between groups were indicated using MANOVA in analysing hamstrings muscle strength (peak torque) (Wilks' Lambda = 0.57, $F_{8,19} = 1.77$, $P > 0.05$). Nevertheless, for the dominant leg, univariate ANOVA showed there was a significant difference in hamstrings muscle strength (peak torque) between groups at 1.05 rad.s^{-1} ($F_{1,26} = 4.93$, $P < 0.03$), and 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26} = 12.42$, $P < 0.002$) with elite players being stronger than sub-elite players. No differences were apparent at 2.09 rad.s^{-1} and 5.23 rad.s^{-1} ($P > 0.05$) (see Figure 4.3.5).

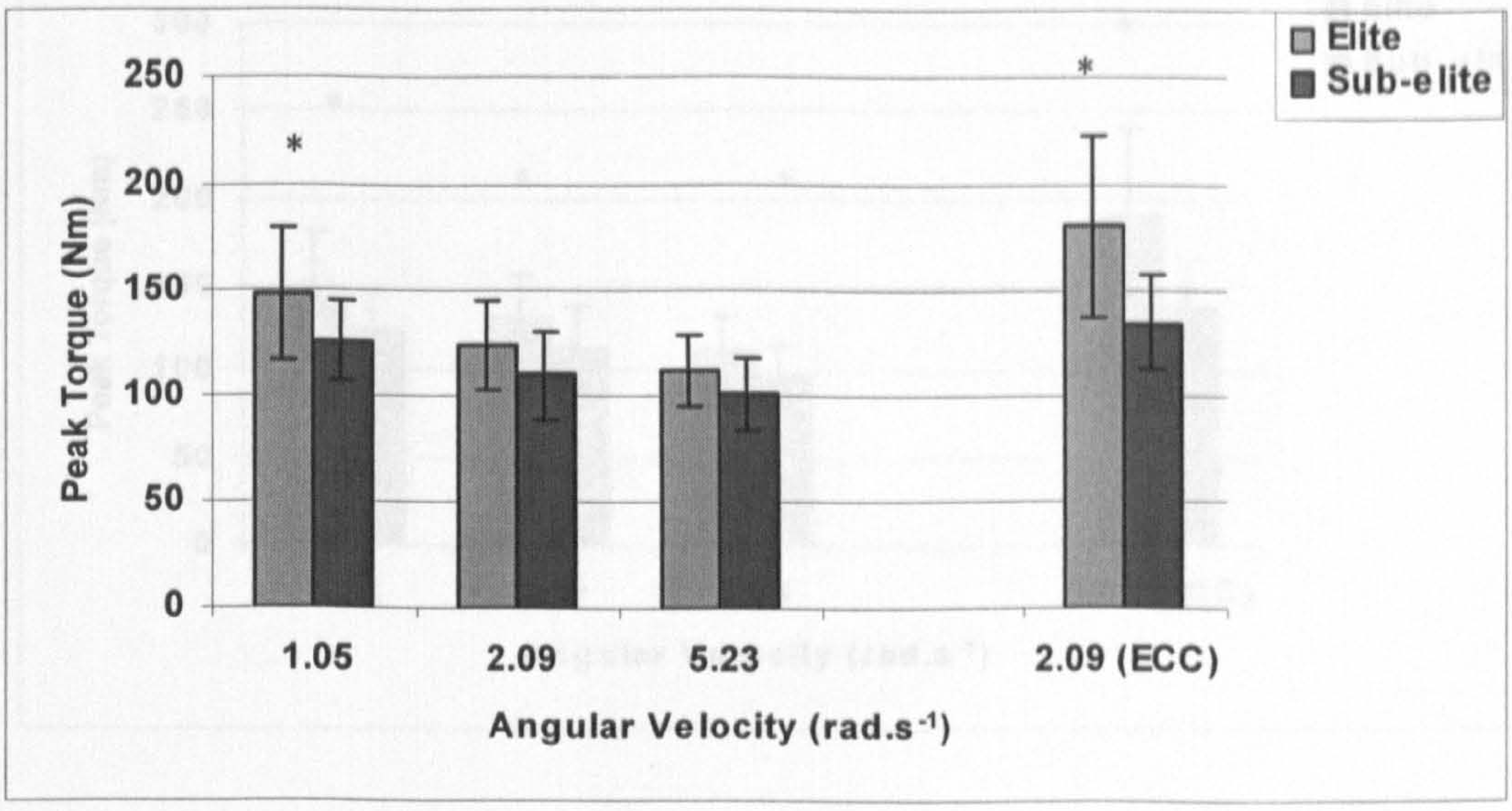


Figure 4.3.5. Comparison of hamstrings muscle strength (peak torque) between elite and sub-elite soccer players for the dominant leg.

For the non-dominant leg, univariate ANOVA indicated there was a significant difference between groups in muscle strength of the hamstrings (peak torque) at 1.05 rad .s^{-1} ($F_{1,26} = 5.22$, $P < 0.03$), 2.09 rad.s^{-1} ($F_{1,26} = 4.69$, $P < 0.04$), 5.23 rad.s^{-1} ($F_{1,26} = 4.68$, $P < 0.04$) and 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26} = 12.50$, $P < 0.002$). In all cases, the elite players were stronger than the sub-elite players (Figure 4.3.6).

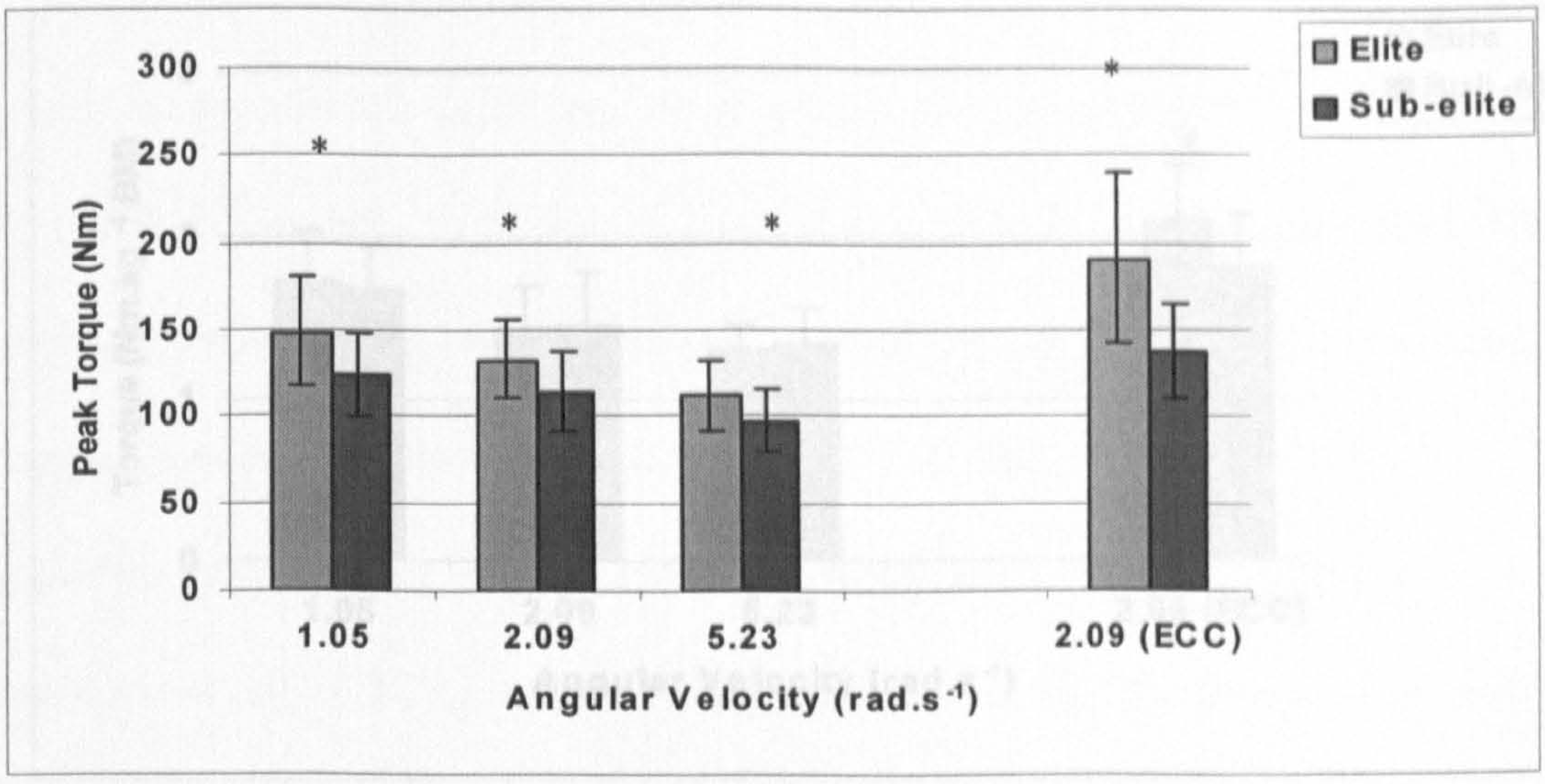


Figure 4.3.6. Comparison of hamstrings muscle strength (peak torque) between elite and sub-elite soccer players for the non-dominant leg.

4.3.5. Relative muscle strength profile for the hamstring group (peak torque/body mass)

No significant differences between the groups were indicated using MANOVA (Wilks' Lambda = 0.56, $F_{8,19} = 1.83$, $P > 0.05$) when data were normalised for body mass. This finding corroborates the results of the comparison before data were corrected for body mass. Nevertheless, for the dominant leg, univariate ANOVA revealed a significant main difference in hamstrings relative muscle strength (peak torque/BM) between groups at 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26} = 4.86$, $P < 0.05$). Again, the elite players showed the greater muscle strength (see Figure 4.3.7).

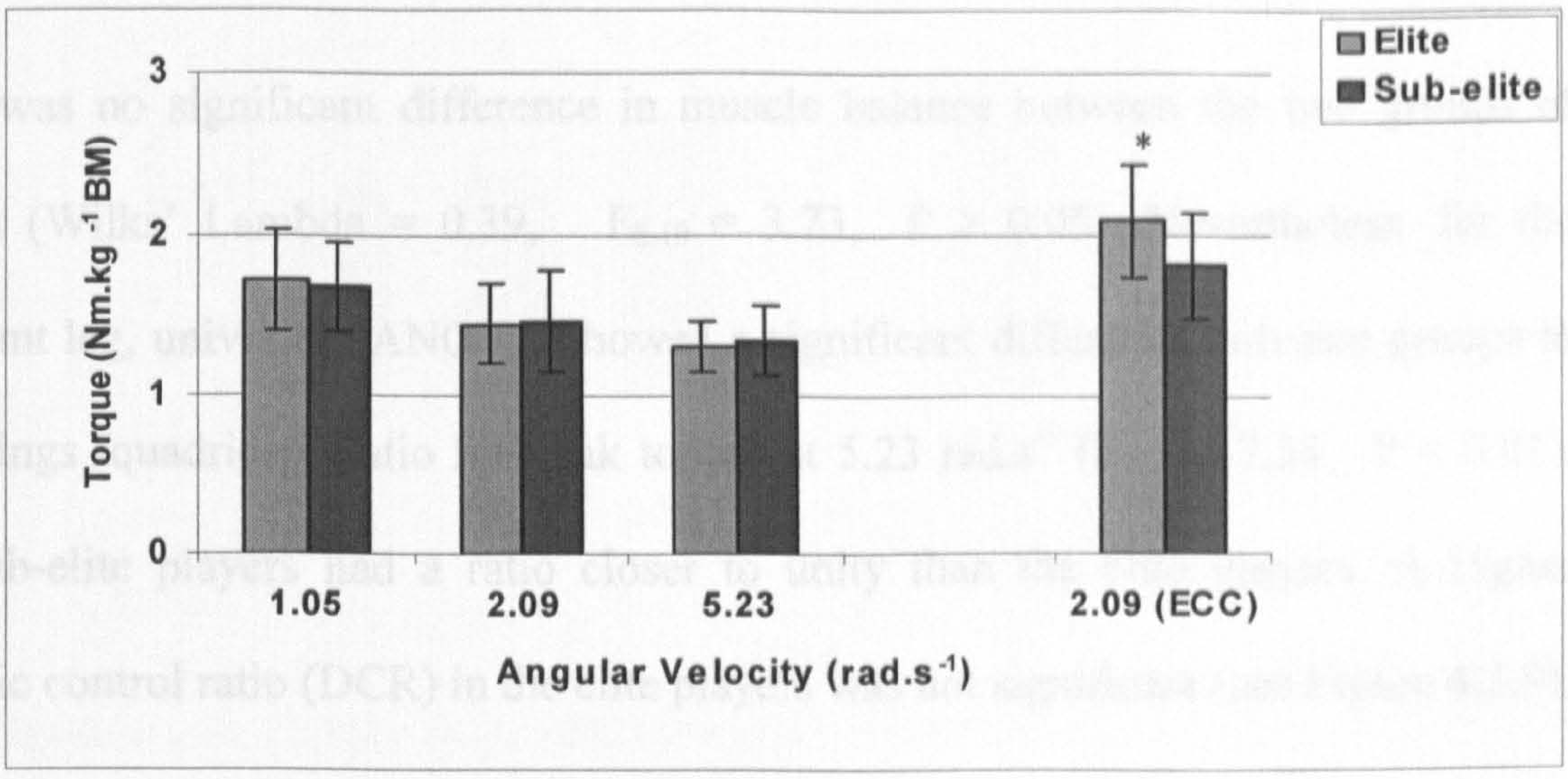


Figure 4.3.7. Comparison of hamstrings relative muscle strength (peak torque/body mass) between elite and sub-elite soccer players for the dominant leg.

For the non-dominant leg, univariate ANOVA revealed a significant main effect in relative muscle strength of the hamstrings (peak torque/BM) between groups at 2.09 $_{(ecc)}$ rad.s^{-1} ($F_{1,26}$ = 4.86, $P < 0.05$). The elite players showed the greater muscle strength (see Figure 4.3.8).

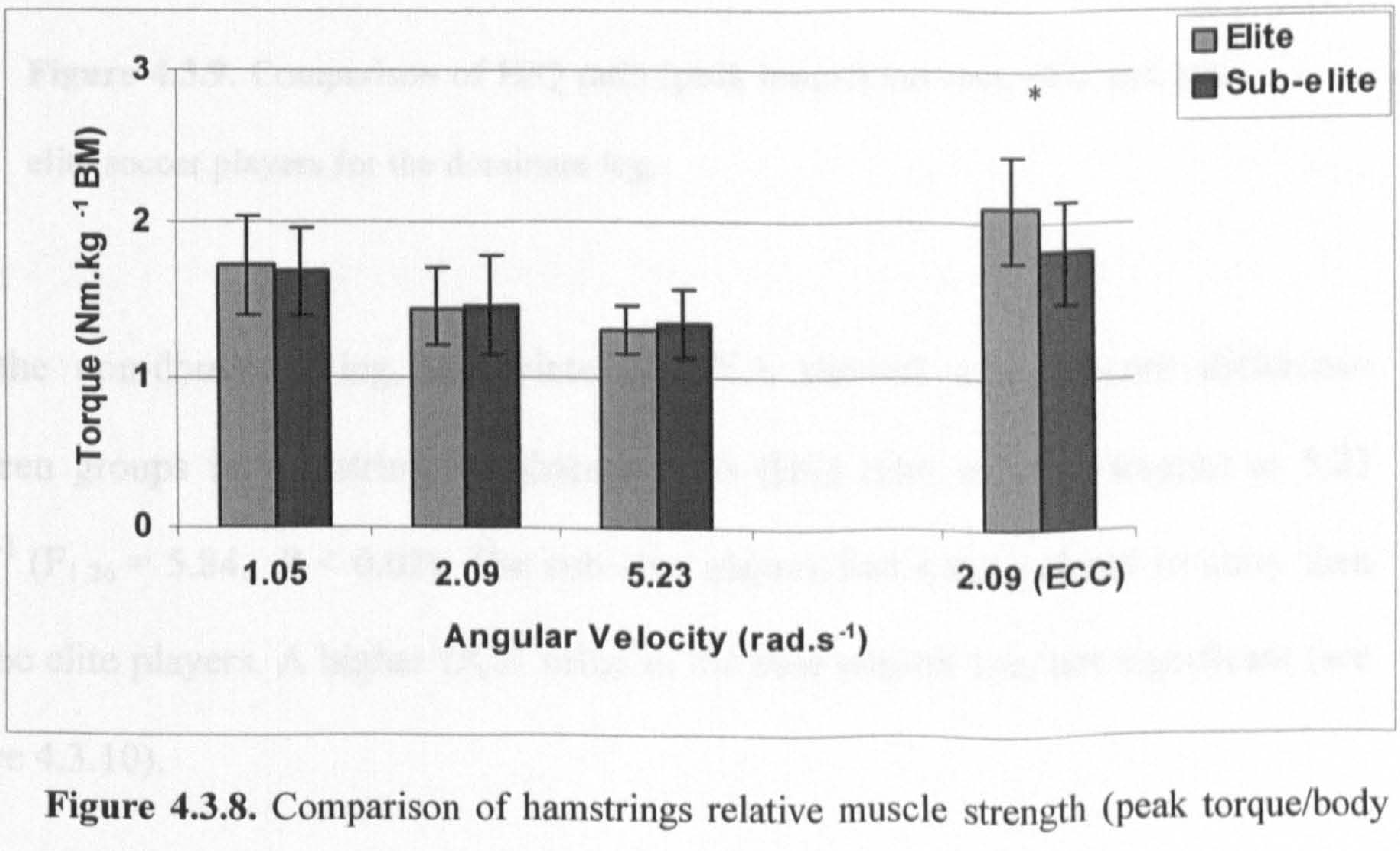


Figure 4.3.8. Comparison of hamstrings relative muscle strength (peak torque/body mass) between elite and sub-elite soccer players for the non-dominant leg.

4.3.6. Muscle balance (hamstring/quadriceps ratio)

There was no significant difference in muscle balance between the two groups of players (Wilks' Lambda = 0.39, $F_{8,19} = 3.73$, $P > 0.05$). Nevertheless, for the dominant leg, univariate ANOVA showed a significant difference between groups in hamstrings /quadriceps ratio for peak torque at 5.23 rad.s^{-1} ($F_{1,26} = 7.34$, $P < 0.01$). The sub-elite players had a ratio closer to unity than the elite players. A higher dynamic control ratio (DCR) in the elite players was not significant (see Figure 4.3.9).

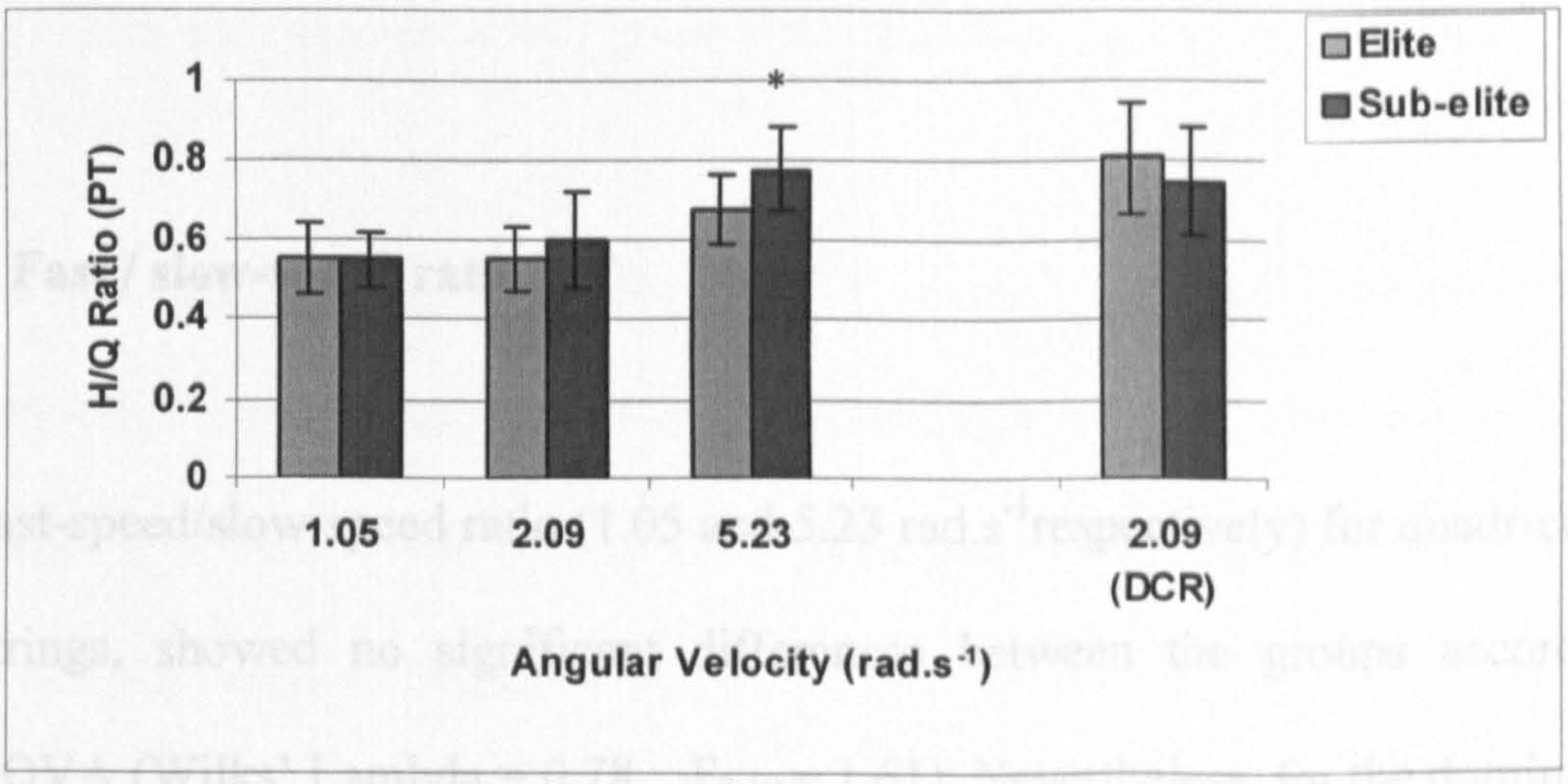


Figure 4.3.9. Comparison of H/Q ratio (peak torque) between elite and sub-elite soccer players for the dominant leg.

For the non-dominant leg, univariate ANOVA showed a significant difference between groups in hamstring /quadriceps ratio (H/Q ratio of peak torque) at 5.23 rad.s^{-1} ($F_{1,26} = 5.84$, $P < 0.02$). The sub-elite players had a ratio closer to unity than did the elite players. A higher DCR value in the elite players was not significant (see Figure 4.3.10).

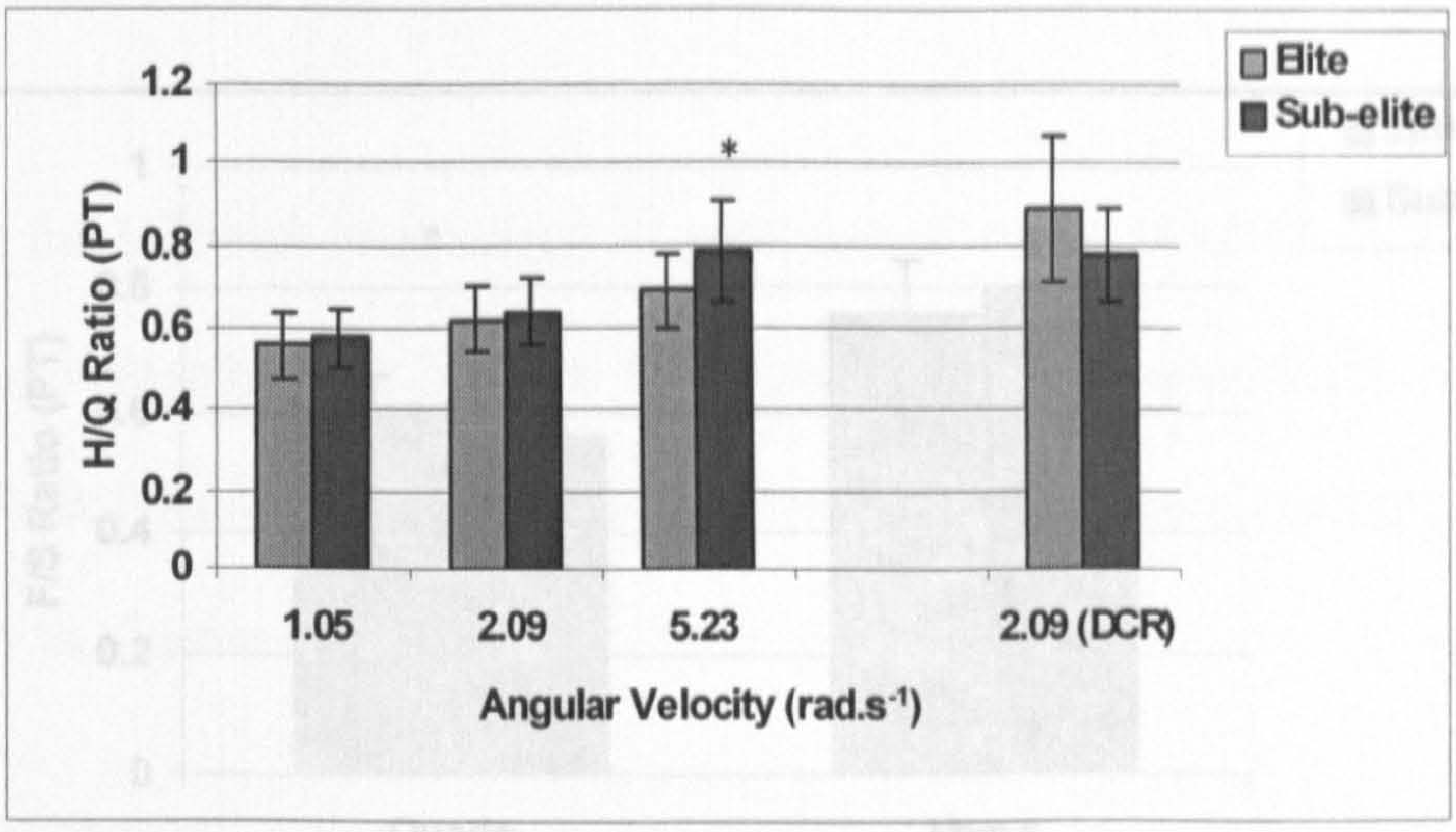


Figure 4.3.10. Comparison of H/Q ratio (peak torque) between elite and sub-elite soccer players for the non-dominant leg.

4.3.7. Fast / slow-speed ratio

The fast-speed/slow-speed ratio (1.05 and 5.23 rad.s^{-1}respectively) for quadriceps and hamstrings, showed no significant differences between the groups according to MANOVA (Wilks' Lambda = 0.78, $F_{8,19} = 1.61$). Nevertheless, for the dominant leg, univariate ANOVA showed that elite players had a higher fast-speed/slow-speed ratio in the quadriceps than the sub-elite players ($\overline{X}$ = 0.61 ± 0.05 vs. 0.56 ± 0.09 Nm, $F_{1,26} = 6.25$, $P < 0.02$). No significant difference was found between the groups in the ratio for the hamstrings ($\overline{X}$ = 0.76 ± 0.06 vs. 0.8 ± 0.13 Nm) (Figure 4.3.11).

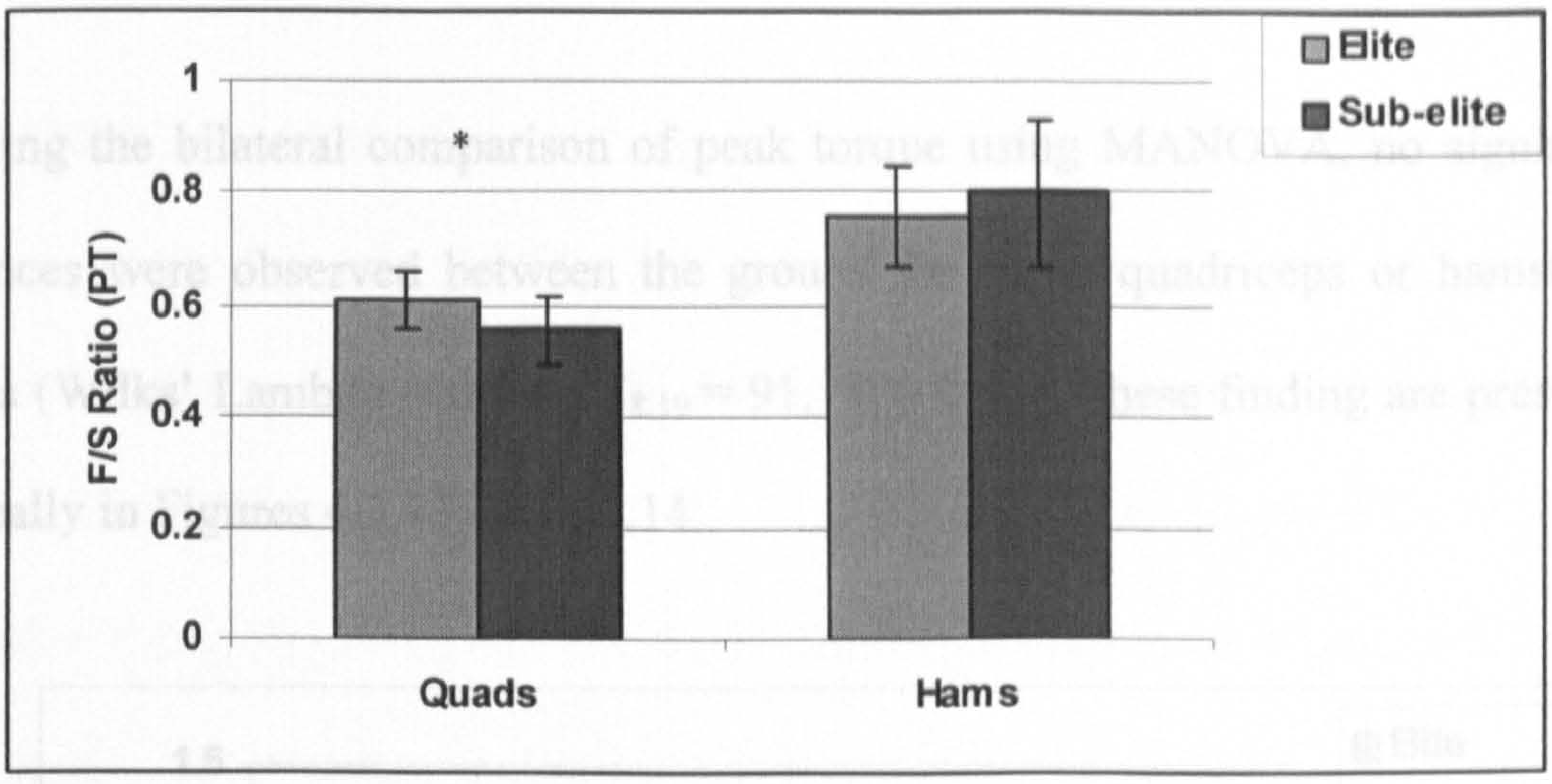


Figure 4.3.11. Comparison of fast/slow speed ratio (peak torque) between elite and sub-elite soccer players in the quadriceps for the dominant leg.

For the non-dominant leg, univariate ANOVA showed that there were no significant differences between groups in fast-speed/slow-speed ratio for peak torque in either quadriceps (x̅ = 0.61 ± 0.05 vs. 0.58 ± 0.06 Nm) or hamstrings (x̅ = 0.77 ± 0.11 vs. 0.79 ± 0.1 Nm) muscles (Figure 4.3.12).

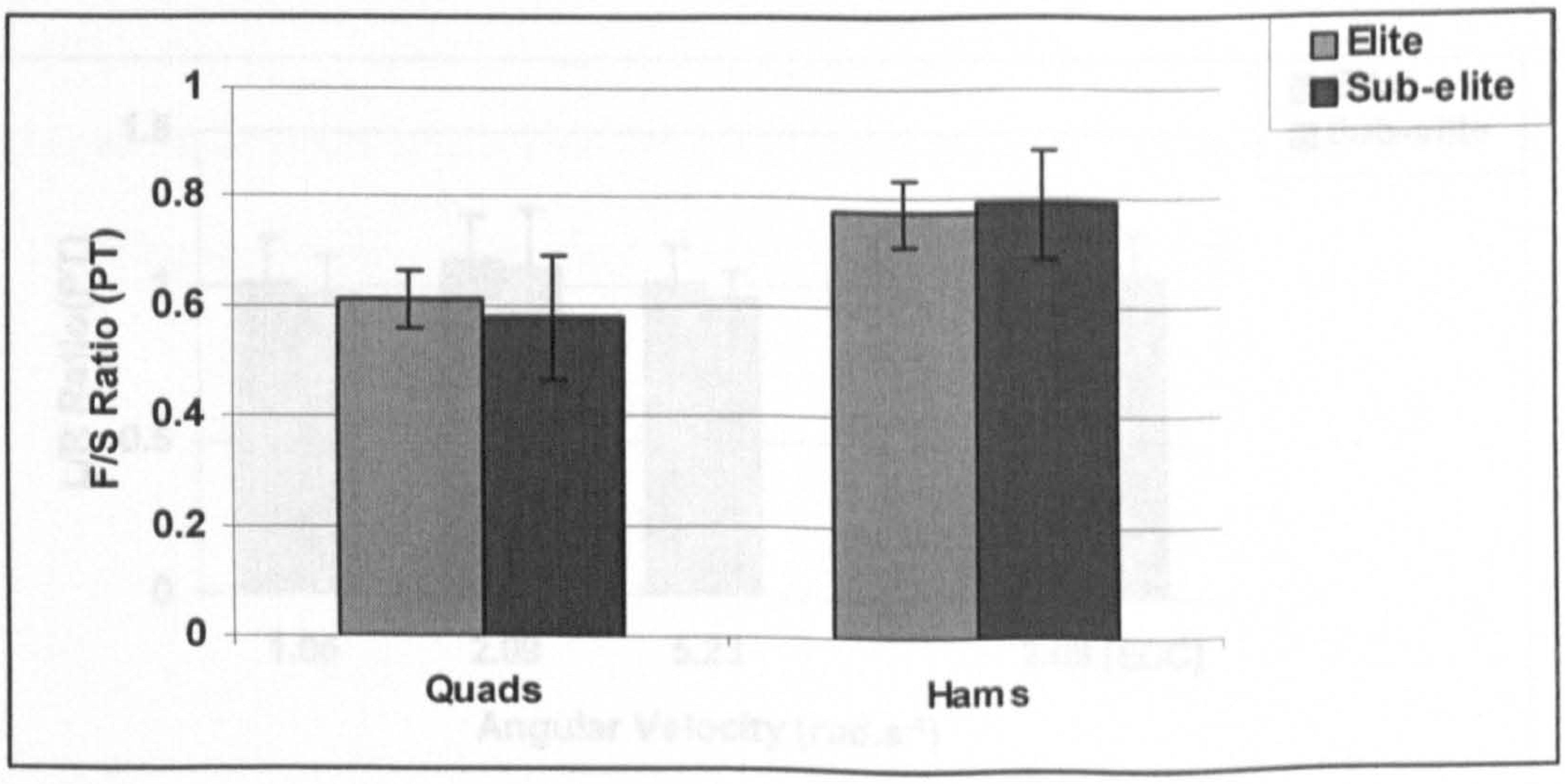


Figure 4.3.12. Comparison of fast/slow speed ratio (peak torque) between elite and sub-elite soccer players in the quadriceps for the dominant leg.

4.3.8. Bilateral comparison (left/right ratio)

Regarding the bilateral comparison of peak torque using MANOVA, no significant differences were observed between the groups for either quadriceps or hamstrings muscles (Wilks' Lambda = 0.72, $F_{8,19} = 91$, $P > 0.05$). These finding are presented graphically in Figures 4.3.13 and 4.3.14.

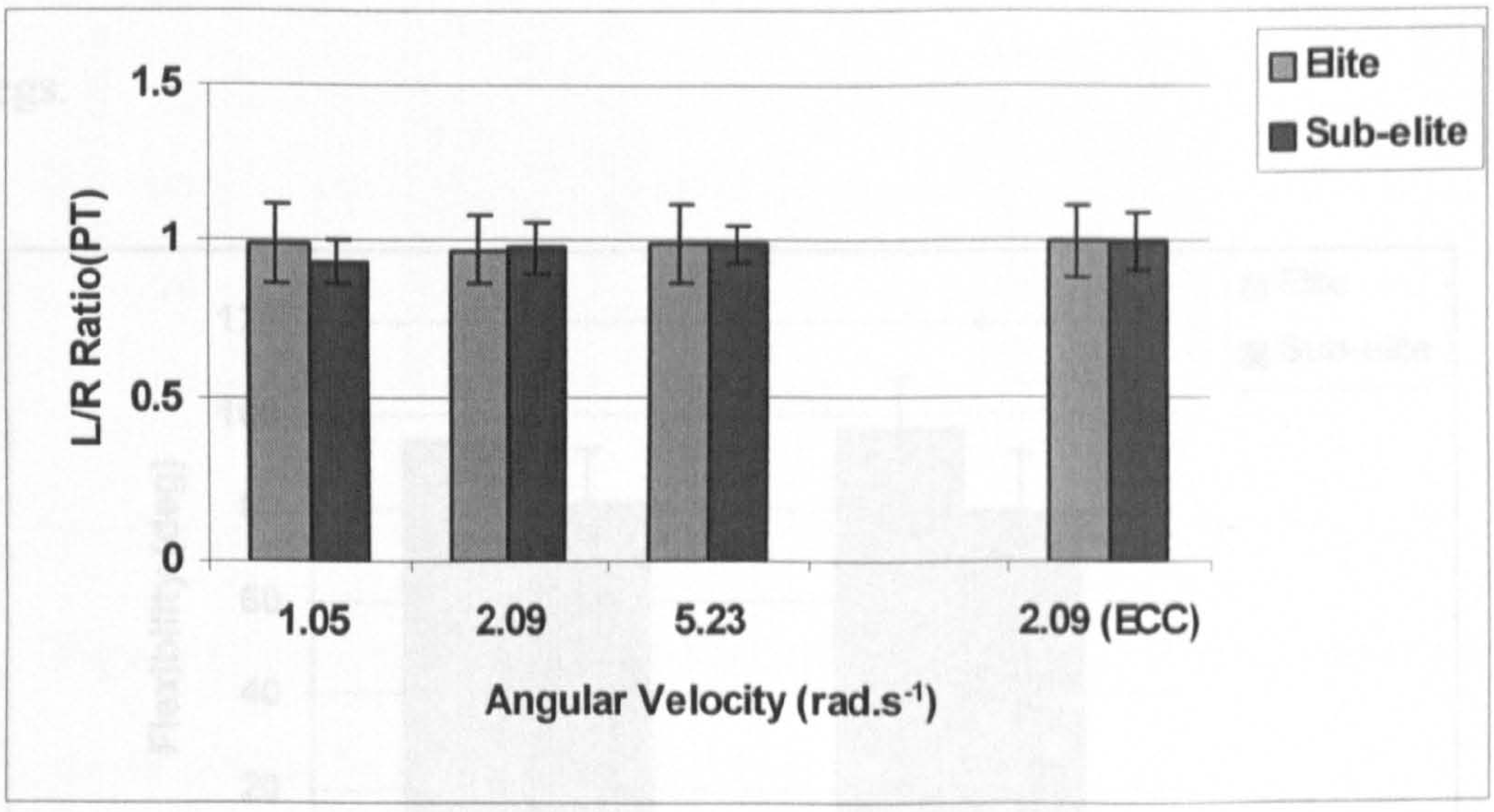


Figure 4.3.13. Comparison of left/right ratio (peak torque) between elite and sub-elite soccer players in the quadriceps.

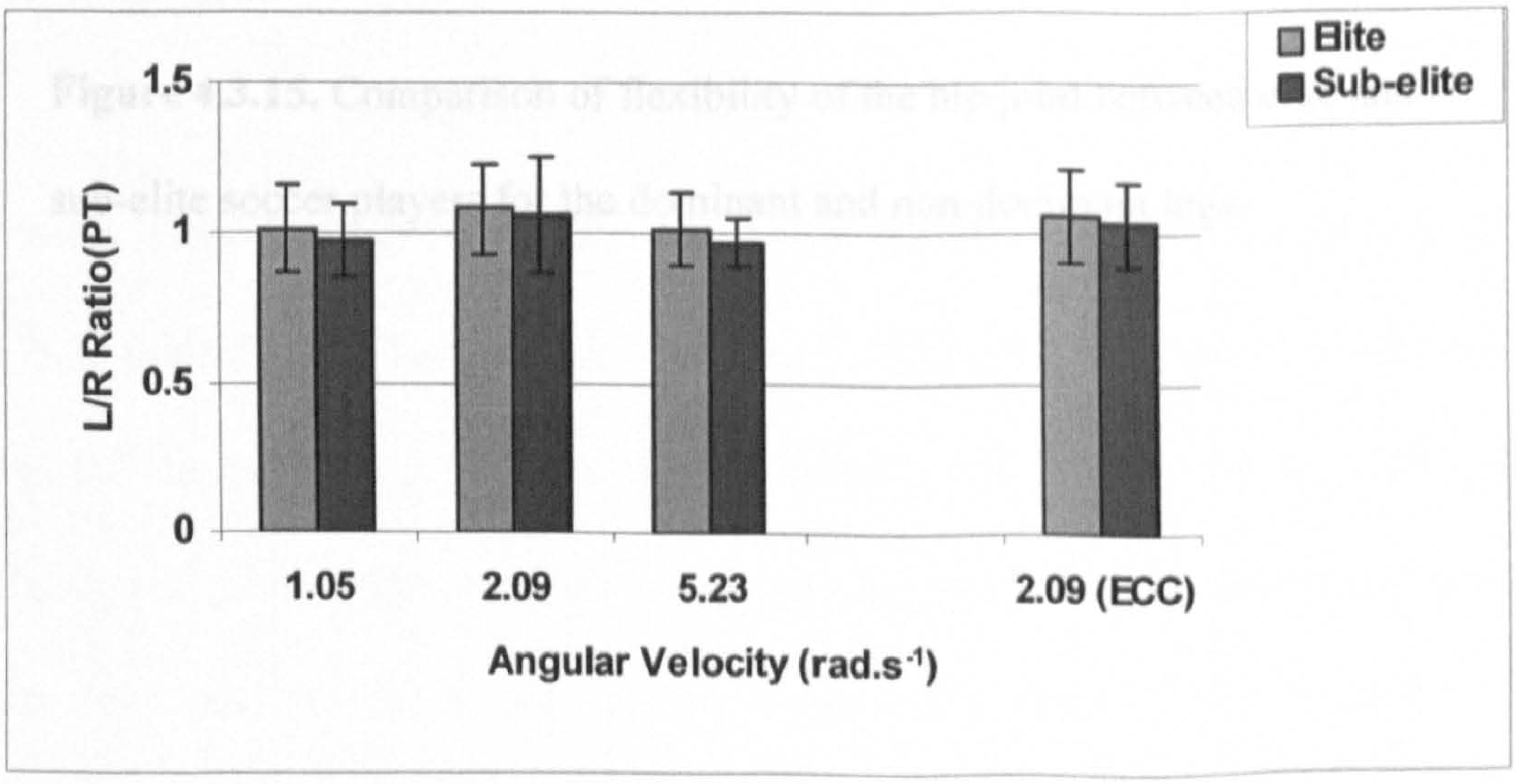


Figure 4.3.14. Comparison of left/right ratio (peak torque) between elite and sub-elite soccer players in the hamstrings.

4.3.9. Flexibility of the hip joint

The MANOVA results showed a significant difference between groups in the flexibility of the hip joint (Wilks' Lambda = 0.57, $F_{8,19} = 9.48$, $P < 0.001$). Univariate analyses indicated a significant difference for both the dominant leg ($\overline{x}$ = 95 ± 11 vs. 81 ± 7 deg, $F_{1,26} = 17.38$, $P < 0.001$) and the non-dominant leg ($\overline{x}$ = 97 ± 12 vs. 80 ± 8 deg, $F_{1,26} = 18.62$, $P < 0.001$). The elite players were the more flexible in both legs.

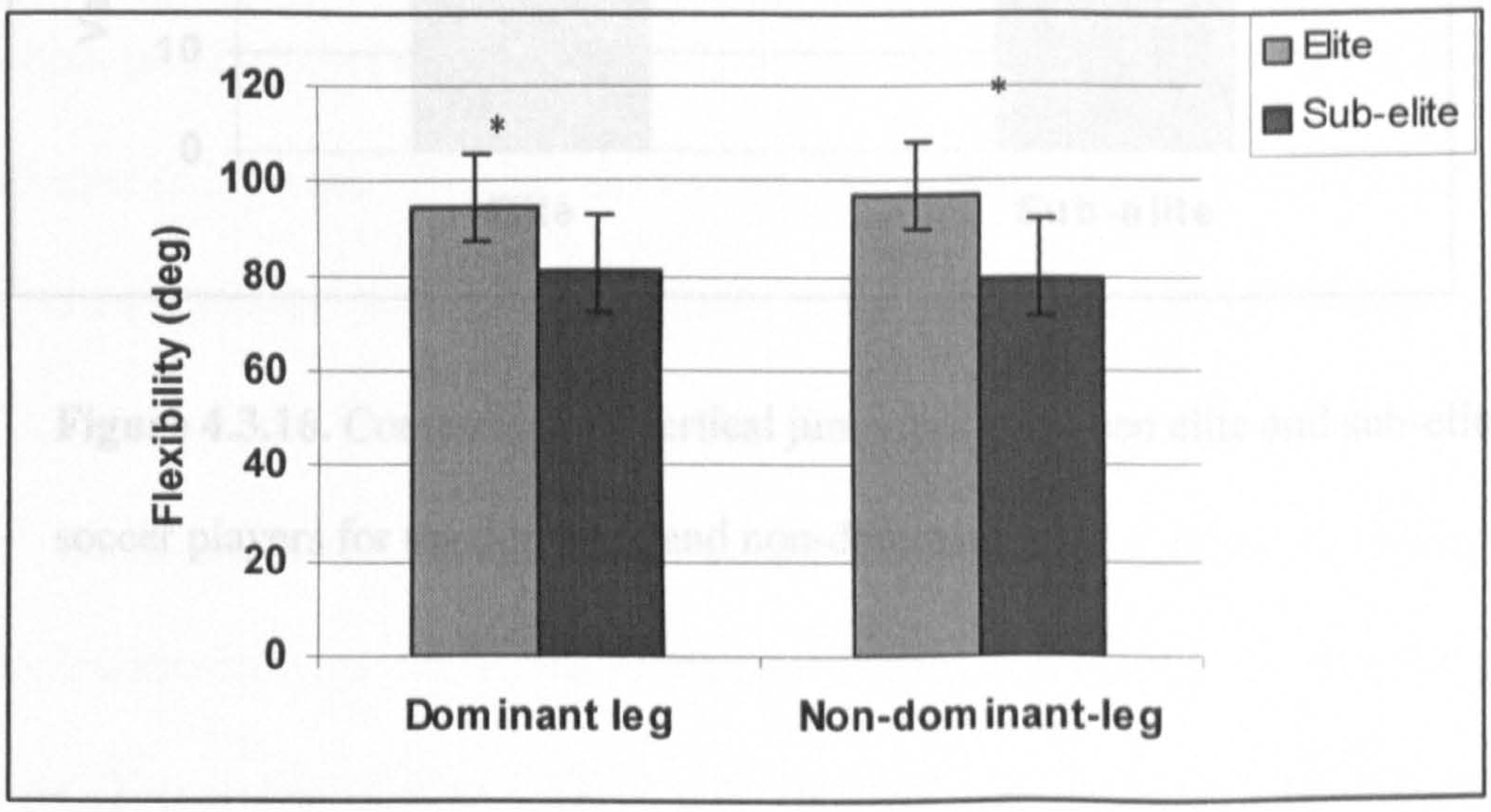


Figure 4.3.15. Comparison of flexibility of the hip joint between elite and sub-elite soccer players for the dominant and non-dominant legs.

4.3.10. Vertical jump

Regarding the vertical jump, no significant difference between the elite and the sub-elite players ($\overline{x}$ = 39 ± 5 cm vs. 36 ± 4 cm) was indicated using ANOVA.

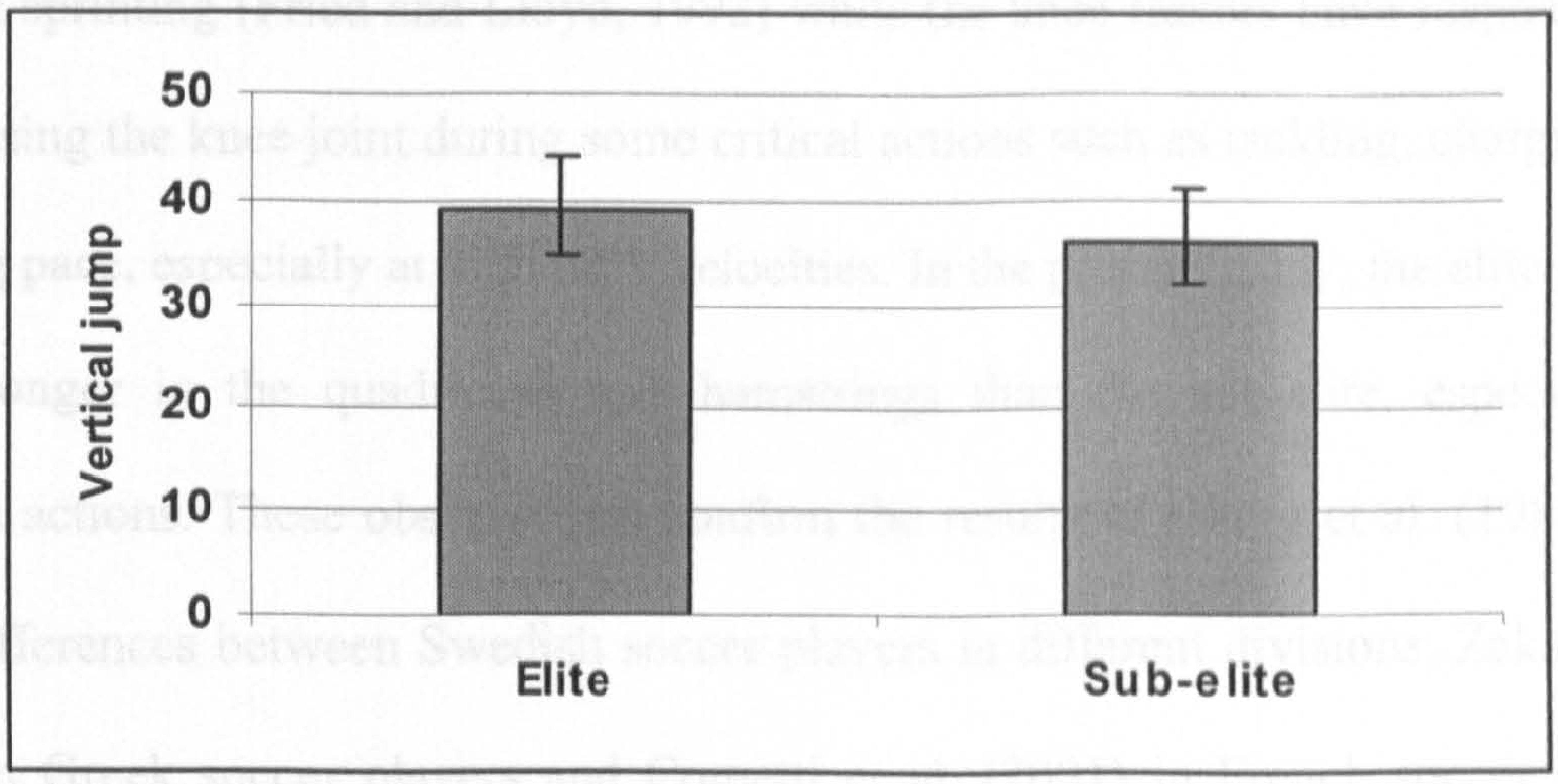


Figure 4.3.16. Comparison of vertical jump (cm) between elite and sub-elite soccer players for the dominant and non-dominant legs.

4.4. DISCUSSION

In this study important differences were noted between elite and sub-elite soccer players. The elite players had the higher values in (i) the peak torque levels of knee extensors, (ii) the peak torque levels of knee flexors, (iii) quadriceps strength relative to body size, (iv) hamstrings strength relative to body size in both dominant and non-dominant legs and in both contraction modes (concentric and eccentric), (v) hamstrings to quadriceps strength ratio in eccentric mode (both legs), (vi) fast-speed to slow-speed ratio in the quadriceps of the dominant leg and (vii) flexibility of the hip joint (both sides). The sub-elite players had a ratio closer to unity at high speed for both legs. No significant differences were found between these two groups of players for bilateral quadriceps and hamstrings strength ratio or vertical jump.

With respect to knee extensors and knee flexors, it is thought that the knee extensors play a main role in some soccer specific activities such as kicking the ball, jumping to head and sprinting (Fried and Lloyd, 1992) while the knee flexors have responsibility in stabilising the knee joint during some critical actions such as tackling, charging and changing pace, especially at high limb velocities. In the present study, the elite players were stronger in the quadriceps and hamstrings than the sub-elite, especially in eccentric actions. These observations confirm the results of Oberg et al. (1986) who found differences between Swedish soccer players in different divisions. Zakas et al. (1995) in Greek soccer players and Cometti et al. (2001) in French soccer players reported similar trends. It would seem that many years of soccer training increase quadriceps and hamstrings strength, as reflected in the superior strength values in the current professionals. This difference between elite and less skilled athletes is noted in other sports. Thorstensson et al. (1977) and Haymes and Dickinson (1980) reported similar differences in alpine skiers, jumpers, sprinters and skiing disciplines. It seems that the influence of specific soccer training is reflected in the strength differences between different levels of play.

The correction of peak torque values in flexors and extensors for body size did not change the findings substantially. This conclusion applied even though the professionals were on average 10 kg heavier than the other group of players.

An increase in the H/Q ratio with increasing velocity was observed in each limb, a finding which is consistent with previous research (Gilliam, 1979; Scudder., 1980; Davies et al., 1981; Wyatt and Edward, 1981; Stafford and Grana, 1984; Oberg et al., 1986). Although the sub-elite players had the higher H/Q strength ratio (but only at the higher angular velocity), the H/Q ratios of both groups were within the normal range (58%-80%) reported by Fowler and Reilly (1993). The H/Q ratio found in this study was 58 % for both groups which is close to the ratio observed in US national and Asian soccer players (Mangine et al., 1990; Chin et al., 1994). Ratios for DCR of 81 % (elite players) and 75 % (sub-elite players) were observed. It is thought that this functional H/Q ratio is more suitable to recognise the ability of the knee flexors in stabilising the knee joint than the conventional ratio. Due to the high eccentric hamstring torque, the elite players had a marginally greater H/Q ratio than the sub-elite. In agreement with Cometti et al. (2001), due to the importance of the hamstring muscles in some specific soccer activities and the need for stabilisation of the knee joint during critical events, it is recommended that trainers should pay more attention to eccentric actions and strength training in their training sessions, in order to minimise the likelihood of injury occurrence. In soccer, the knee flexors are used concentrically to flex the knee and extend the hip in preparation for a kick and are used eccentrically to control knee extension and hip flexion towards the end of the kicking action (Clarys et al., 1988). If the knee extensor strength greatly exceeds that of the hamstrings, the ability to resist knee extension is reduced which may result in a forced stretch of the hamstrings and consequent muscle damage (Fowler and Reilly, 1993).

Oberg et al. (1986) reported the relatively greater fast-speed/slow-speed ratio in national players compared to others. This present study showed a higher fast-speed/slow-speed ratio in the quadriceps of the dominant leg in elite players than in sub-elite players which confirms the results of previous research. The greater fast-speed/slow-speed ratio indicates that a fast-speed capability is an important attribute in top-class soccer. Since some actions are performed at a high velocity (e.g. hard shots on goal), coaches should pay attention to fast actions in training.

With respect to bilateral quadriceps and hamstrings ratio, there was no difference between the groups. As limb symmetry was within the normal range (0.9-1.1), it seems that soccer strength training need not compromise the strength ratio between left and right limbs. Knapik et al. (1991) suggested that subjects with an imbalance exceeding 15 % were 2.6 times more likely to suffer injury in the weaker leg. There was no such deficit observed among the players in this current study. This result is in agreement with studies by Oberg et al. (1986) and Goslin and Charteris (1979) who failed to observe differences in strength between the limbs.

With respect to flexibility of the hip joint, since the elite players were more flexible than the sub-elite participants in both dominant and non-dominant legs, it seems that intensity of soccer training in top-class soccer improves the range of motion in the hip joint. If training programmes can be organised appropriately, the player can develop both muscle and joint flexibility. One of the major concerns of coaches in relation to strength training is that they believe it reduces flexibility whilst increasing muscle size but this is shown not to be the case. This point can be important if the hamstring muscles are to be protected from injury. Furthermore, the use of flexibility training to prevent muscle strain should not be neglected in the design of training a rehabilitation programmes for players.

Although the elite players demonstrated 3 % better performance than the sub-elite in vertical-jumping ability, the difference was not significant. This observation confirms the results of Cometti et al. (2001). Thomas and Reilly (1979) reported that vertical-jump ability of English soccer players was constant throughout the competitive season. The lack of difference in vertical jump performance between players suggests that soccer training has more of an effect on peak torque than on "explosive" actions. Therefore, trainers and players should pay more attention to specific plyometric training programmes during their training sessions to improve jumping ability and other dynamic activities.

In conclusion, this study has revealed that elite soccer players differ from sub-elite soccer players in terms of most muscle functional variables; the elite players demonstrated greater absolute strength and also greater strength relative to body mass and greater flexibility. They had the better values in the DCR ratio and fast-speed/slow-speed ratio which shows they are less likely to be at risk of injury than less skilled players. It is thought that several years of soccer training and match-play at a high level improve the strength of knee extensors and knee flexors, irrespective of body size, and also flexibility in elite players.

CHAPTER FIVE

MUSCLE FATIGUE DURING EXERCISE SIMULATING THE WORK-RATE OF COMPETITIVE SOCCER

5.0 MUSCLE FATIGUE DURING EXECISE SIMULATING THE WORK-RATE OF COMPETITIVE SOCCER

5.1. INTRODUCTION

Muscular fatigue is often evident in the course of a football game, especially towards the end of play. Players are able to continue to exercise at lower intensities but have a reduced ability to perform maximally (Drust, 1997). Fatigue is indicated by a reduction of maximal force or power that is associated with sustained exercise and is reflected in a decline in performance (Reilly, 1994; Taylor et al., 2000). In top-class soccer, a fatigue effect is noticeable in the second half as a drop in the work-rate (Reilly and Thomas, 1976). Van Gool et al. (1988) reported that Belgian University players covered, on the average, a distance of 444 m more in the first half than in the second half of the game. In an investigation of professional players, Bangsbo et al. (1991) reported a 5% greater distance covered in the first half. The decline in work-rate has been attributed to a reduced glycogen content in the thigh muscles of players (Saltin, 1973). Other factors such as dehydration and physiological changes within the muscle cell (Karlsson and Saltin, 1971; Saltin, 1973; Jacobs et al., 1982; Bangsbo, 1994b) may also be implicated.

The reduction in muscle force due to fatigue is likely to be linked with a decrease in the number of fibres that can be recruited to generate force as fibres already recruited begin to fail (Bangsbo, 1994a). The fatigue produced by any activity can be assessed by comparing the force of maximal voluntary contraction pre-exercise and post-exercise. The onset of fatigue is more difficult to determine (Taylor et al., 2000), particularly in intermittent exercise, such as a soccer game.

Gleeson et al. (1995) investigated the effect of a fatigue task (30 reciprocal maximal voluntary actions of the knee flexors and extensors) on isokinetic leg strength in female collegiate soccer players. They reported that this fatigue protocol reduced the ability of the knee flexors and extensors to generate force by 20% to 60% during concentric muscle actions at 3.14 rad.s^{-1} angular velocity. Furthermore, Kawakami et al. (1993) assessed concentric and eccentric muscle strength of youth subjects before, during and after a fatigue protocol (50 consecutive maximal trials) using a specially constructed dynamometer and movements at angular velocities of 0.21, 0.52 and 1.05 3.14 rad.s^{-1}. They reported a decline in concentric and eccentric muscle strength of 27% to 40%. These protocols produce fatigue relatively quickly and are unsuitable as models for studying the phenomenon of fatigue as it occurs in soccer.

Muscle strength is important in many playing actions in soccer (e.g. tackling, jumping, kicking, turning and changing pace), which have to be sustained until the game ends. A reduction in muscle strength might increase the susceptibility of a player to injury, particularly as incidents intensify towards the end of the match (as shown in chapter 3). Muscle fatigue has been suggested as a factor which can lead to injury (Lieber and Friden, 1988; Davis and Bailey, 1997) and is evidenced by the greater injury incidence in the second half, particularly during the last quarter of the match (Hawkins et al., 2001).

Although there are valuable data in the literature related to physiological and metabolic responses (such as oxygen consumption, heart rate, rectal temperature, sweat production and minute ventilation) to laboratory-based intermittent exercise protocols relevant to the work-rate of soccer (Bangsbo, 1994a; Nevill et al., 1995; Nicholas et al., 1995; Drust et al., 2000), little is known about isokinetic strength changes during a fatigue-inducing intermittent exercise task. Since muscle fatigue during exercise simulating the work-rate of competitive soccer has not previously been investigated, the purpose of this study was to establish the effects of a soccer-related simulation task, used to induce fatigue, on the functional characteristics of lower-limb muscles in sub-elite soccer players.

5.2. MATERIALS AND METHODS

5.2.1. Participants

Thirteen male sub-elite soccer players took part in this investigation [age (means ± sd) 23.3 ± 3.9 years, height 1.78 ± 0.05 m, body mass 74.8 ± 3.6 kg]. Sub-elite players were classed as those who were playing regularly for local and University teams. Participants were recruited if they were not injured or rehabilitating from injury at the time of testing and were aged between 18-25 years. Informed consent was obtained in accordance with the University's ethical procedure before data collection. Ethical approval for the study was obtained from the institution's Human Ethics Committee.

All participants were tested during the 2000-2001 English competitive soccer season. All the tests were scheduled for the same time of day (10:00 hours) to remove the effects of any circadian variation on the variables measured (Reilly and Brooks, 1986). Measurements for each participant were in two categories, player characteristics and muscle strength profiling, which are described in turn.

5.2.1.1. Player characteristics

Body mass (kg) was determined using a calibrated precision weighing scales (Hotline, Hamburg, Germany) at the start, at half-way and post-exercise. Height was measured by means of a standard stadiometer (Seca, Hamburg, Germany) at the start of testing. The flexibility of the participant's hip joint (in flexion) was measured by means of a goniometer (MIE goniometer, Medical Research Limited, Leeds) at the start of testing. The participant lay supine on the floor with the legs extended and the head on the floor. The quadriceps muscle on the right leg was palpated and the goniometer was placed approximately half-way down the limb (from the hip joint to the knee joint). The goniometer was then altered so that the liquid inside was level at 0 degrees. The participant then slowly lifted the right leg, keeping the left leg on the floor. With the help of an assistant, the point when maximum hip flexion had been reached was determined. This point was decided by observing the tension in the muscle and the subjective response of the participant. The reading on the goniometer was recorded and this procedure was completed three times. This protocol was repeated on the opposite limb to assess hip joint flexibility of the dominant and non-dominant legs. Vertical jump height was measured by means of an electronic timing mat (Cranlea & Company, Bournville, Birmingham, England) at the start of testing. The participant stood on the mat and placed his hands on the hips, to control the influence of the arms on the jump. The meter was reset and the subject performed three maximal vertical jumps, from which the highest distance jumped was recorded for analysis. The jump was recorded when the subject completed a full cycle of jumping, including preparation to jump, leaving from the mat and landing again on it.

5.2.1.2. Muscle strength profiling

Isokinetic strength of knee flexors and extensors (both dominant and non-dominant legs) was measured on an isokinetic dynamometer (Lido Active, Loredan, Davis, CA). Each participant visited the laboratory and was tested with the same protocol on two separate occasions. The first visit entailed a familiarisation with the treadmill and dynamometer and the experimental procedure. In the second session, the participant performed a soccer-related simulation exercise on a treadmill for 90 min and muscle strength was assessed (i) pre-exercise (ii) at half-way and (iii) post-exercise.

A standardised warm-up was initially performed on a Monark cycle ergometer for 5 min with no resistance at 60 rev.min^{-1} prior to the experimental protocol. This exercise was followed by 10 min of static stretching of the relevant muscle groups, which were concentrated in the lower extremities. The participant was then seated on the dynamometer in an adjustable chair and the upper body was stabilised with straps secured across the shoulder, chest and hips. A resistance pad was also positioned on the thigh, proximal to the knee joint to localise the quadriceps and hamstrings. The axis of rotation of the dynamometer shaft was aligned with the axis of rotation of the knee joint, midway between the lateral condyle of the tibia and the lateral condyle of the femur. The cuff of the dynamometer's lever arm was attached to the ankle, proximal to the malleoli. These positions were recorded for each participant and standardised for subsequent trials. Range of motion (ROM) was pre-set to 0 to 90 °.

The participant was instructed to grasp the handles adjacent to the chair during the tests and then perform two sub-maximal knee extension and flexion movements. Testing consisted of three maximal voluntary movements at angular velocities of 1.05 rad.s^{-1}, 2.09 rad.s^{-1}, 5.23 rad.s^{-1} (in concentric mode) and 2.09 $_{ecc}$ rad.s^{-1} (in eccentric mode), first for the dominant and then for the non-dominant leg. This order of testing for the different angular velocities was standardised from the slowest to the highest. Each trial was separated by 1 min of passive recovery. Verbal instructions were also standardised and visual feedback was given. Gravity-corrected peak torque was selected from the strength indices as a measure of muscular performance. The test protocol is highlighted in Table 5.2.1.

Table 5.2.1. The test protocol that was used in this study for assessment of isokinetic strength.

Test	Muscle groups	Modes	Angular velocity (rad.s^{-1})
1	Hamstrings & Quadriceps	Concentric	1.05
2	Hamstrings & Quadriceps	Concentric	5.23
3	Quadriceps	Concentric/Eccentric	2.09
4	Hamstrings	Concentric/Eccentric	2.09

Data for 126 variables were recorded for each player. These included absolute quadriceps muscle strength for dominant and non-dominant legs at the four angular velocities [20 variables were included:- two legs × four tests × two measures before and after the game (16) + dominant leg × four tests × one measure at half-way (4)], relative quadriceps muscle strength profile (peak torque/body mass) (20 variables), absolute muscle strength of hamstrings (20 variables), relative muscle strength of hamstrings (peak torque/body mass) (20 variables), muscle balance (hamstring/quadriceps ratio) (20 variables), fast to slow speed ratio [10 variables were included:- two legs × two measures (before and after game) × two groups muscles (8) + two legs × one measure at half-way (2)] and finally bilateral comparison (left/right ratio) for quadriceps and hamstrings (16 variables were included for the two legs × four tests × two muscle groups).

5.2.1.3. Fatigue protocol

A soccer-specific intermittent exercise protocol was developed to provide fatiguing exercise estimated to be equivalent to playing a game of soccer. The soccer-specific intermittent protocol was performed on a programmable motorised treadmill (Pulsar, HP Cosmos, Nussforf-Traunstein, Germany) (Figure 5.2.1). It consisted of the different exercise intensities that are observed during soccer match-play (e.g. walking, jogging, running, sprinting), following the procedure employed by Drust et al. (2000a,b) and in accordance with the observations by Van Gool et al. (1988) during soccer match-play.

The pattern of activities in the protocol was similar to those observed by Reilly and Thomas (1976) and the percentage of the total time spent in each activity approximated data observed with respect to time-motion analysis (Reilly and Thomas, 1976; Van Gool et al., 1988; Yamanaka et al., 1988; Bangsbo et al., 1991; Bangsbo 1994a).

The speeds of each activity in this protocol were 6 km.h^{-1} (walking), 12 km.h^{-1} (jogging), 15 km.h^{-1} (cruising) and 21 km.h^{-1} (sprinting). Backward, sideways movements and actions with the ball were not included in the protocol because of the technical impracticalities when using a motorised treadmill.

Each half of the soccer-specific intermittent protocol was structured as two parts, each 22 min 30 s in duration separated by a 70-s static rest leading to a total of 46 min 10 s. The extra 70 s was considered as representative of added stoppage time. The replication of this protocol for the two halves of activity permitted the assessment of muscle strength to be made for comparisons between the first and the second periods of the protocol, thereby demonstrating changes in muscle strength as the exercise progressed. Performance of this protocol on the treadmill was determined by Drust (1997) as reliable and repeatable with a reported coefficient of variation of 4.8% and coefficient of variation of the limits of agreement 9.4%.

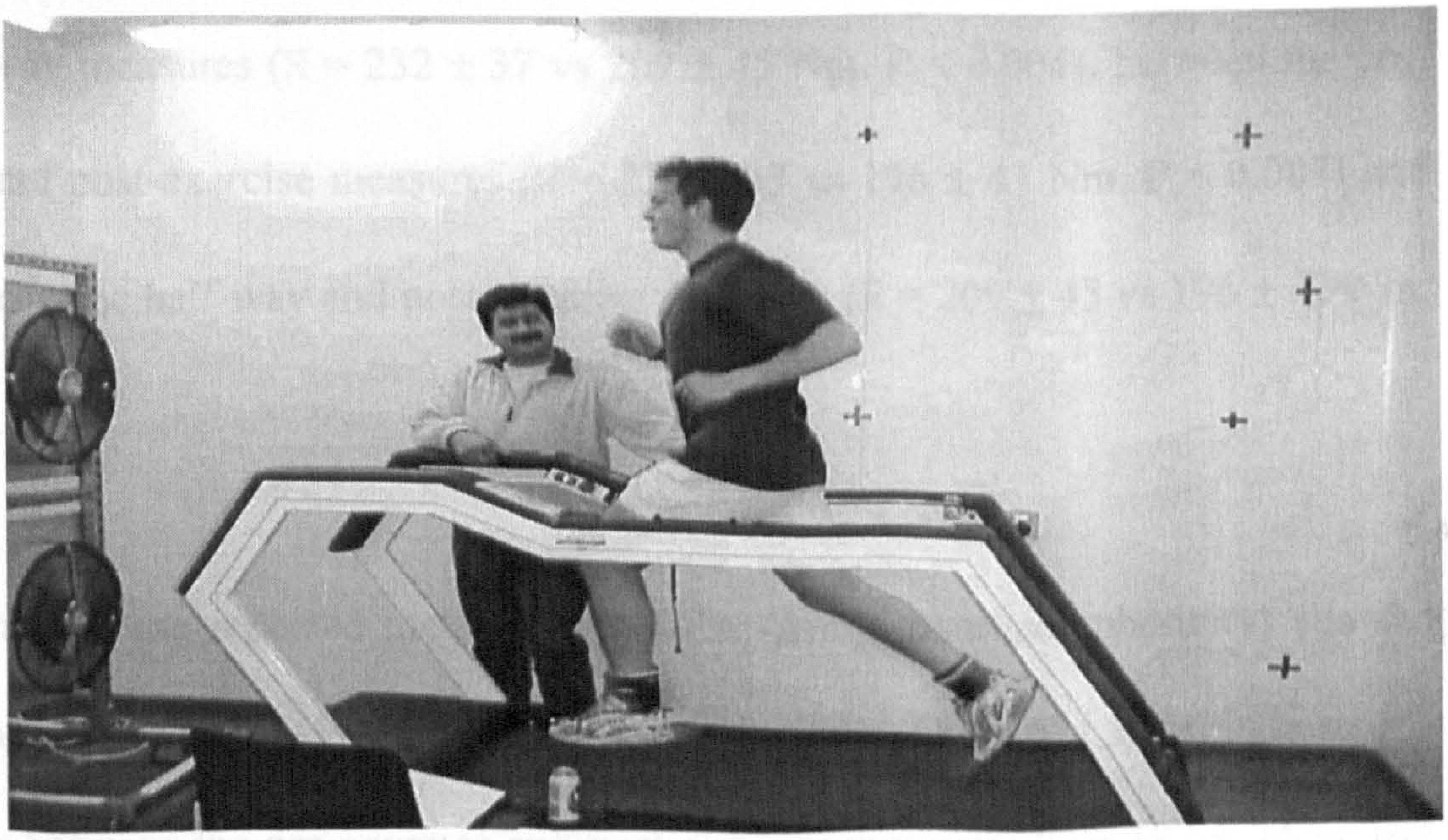


Figure 5.2.1. The programmable motorised treadmill.

5.2.2. Statistical analysis

Analyses of variance (ANOVA) for repeated measures with the Least Significant Difference (LSD) post hoc test were used where muscle strength was measured at three time points (pre-exercise, half-way and post-exercise measures). A paired t-test was used where measures were obtained at two time points (pre-exercise and post-exercise measures). The level of significance on all tests was set at $P < 0.05$.

5.3. RESULTS

5.3.1. Quadriceps muscle strength in the dominant leg (i) pre-exercise (ii) half-way and (iii) post-exercise

Mean peak torque values are presented graphically in Figure 5.3.1. A repeated measures ANOVA (using Greenhouse-Geisser epsilon due to lack of sphericity) showed significant differences ($F_{(1.21,\ 14.56)} = 17.19$, $P < 0.001$) in quadriceps muscle strength at 1.05 rad.s^{-1}. The LSD tests indicated a difference between the pre-exercise and half-way measures ($\bar{x} = 232 \pm 37$ vs 209 ± 45 Nm, $P < 0.001$), between the pre-exercise and post-exercise measures ($\bar{x} = 232 \pm 37$ vs 196 ± 43 Nm, $P < 0.007$) and also between the half-way and post-exercise measures ($\bar{x} = 209 \pm 45$ vs 196 ± 43 Nm, $P < 0.001$).

At 2.09 rad.s^{-1}, the repeated measures ANOVA (using assumed sphericity) showed significant differences ($F_{(2,\ 24)} = 12.03$, $P < 0.001$). The LSD tests indicated a difference between the pre-exercise and post-exercise measures ($\bar{x} = 182 \pm 34$ vs 167

± 35 Nm, $P < 0.001$), and between the half-way and post-exercise measures ($\bar{x} = 177 \pm 35$ vs 167 ± 35 Nm, $P < 0.01$).

At 5.23 rad.s^{-1}, the repeated measures ANOVA (using Greenhouse-Geisser epsilon due to lack of sphericity) showed a significant differences ($F_{(1.21,\ 14.51)} = 10.56$, $P < 0.004$). The LSD tests indicated a difference between the pre-exercise and half-way measures ($\bar{x} = 129.23 \pm 27$ vs 125.23 ± 26 Nm, $P < 0.01$), between the pre-exercise and post-exercise measures ($\bar{x} = 129.23 \pm 27$ vs 117.61 ± 24 N·m, $P < 0.005$) and also between the half-way and post-exercise measures ($\bar{x} = 125.23 \pm 26$ vs 117.61 ± 24 Nm, $P < 0.01$).

For the eccentric action at 2.09 (ecc) rad.s^{-1} repeated measures ANOVA (using assumed sphericity) showed significant differences ($F_{(2,\ 24)} = 12.15$, $P < 0.001$). The LSD tests indicated a difference between pre-exercise and post-exercise measures ($\bar{x} = 219.23 \pm 41$ vs 203.70 ± 43 Nm, $P < 0.001$), and between the half-way and post-exercise measures ($\bar{x} = 213.61 \pm 43$ vs 203.70 ± 43 Nm, $P < 0.008$).

These results demonstrated that peak torque values for the quadriceps at all angular velocities were greater pre-exercise than at half-way. Additionally, they were also greater at half-way than post-exercise.

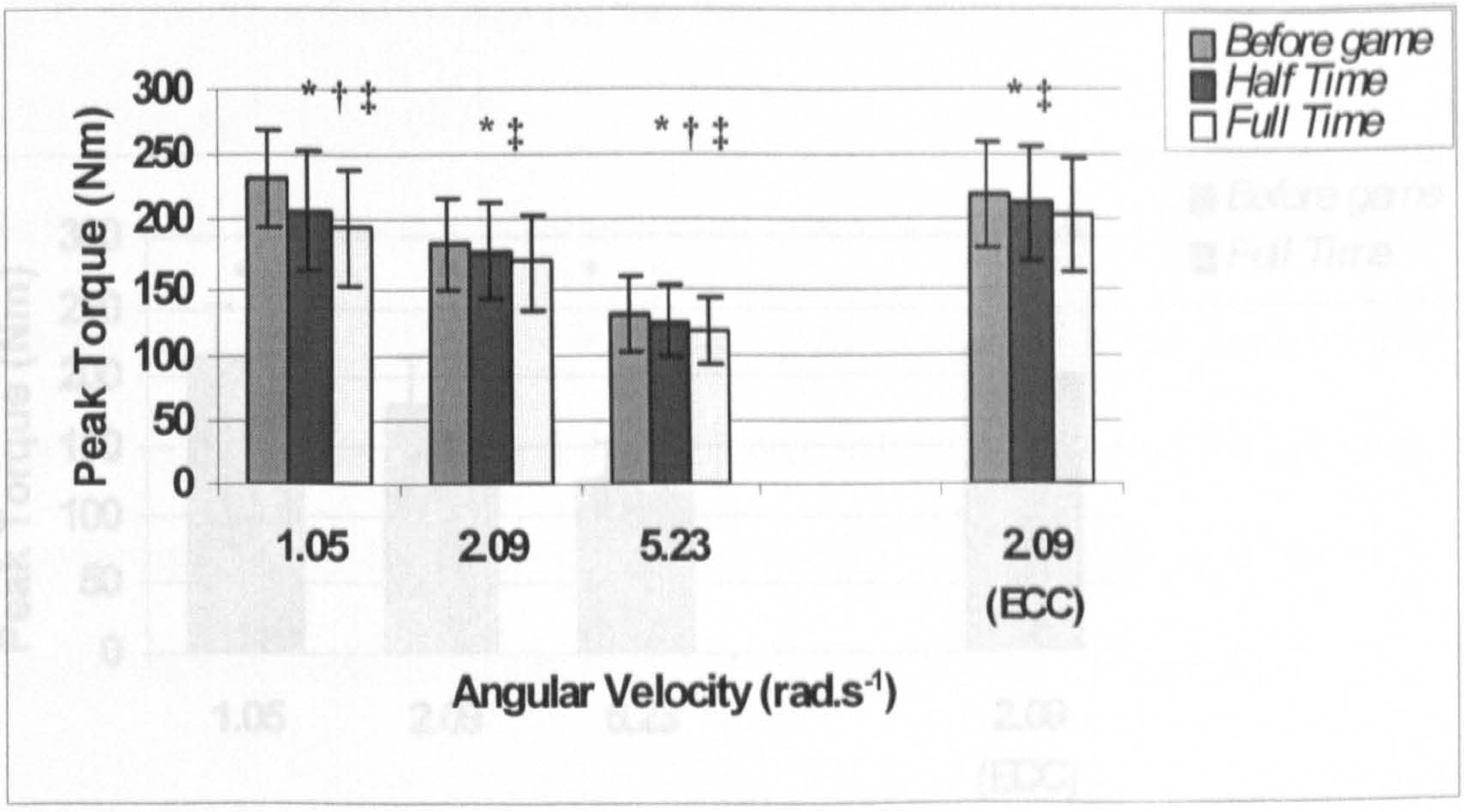


Figure 5.3.1. Comparison of quadriceps peak torque for the dominant leg, before, half-way (Half time) and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the eccentric mode at 2.09 rad.s^{-1}.

* denote significant difference between before and after game
† denote significant difference between before and half-time
‡ denote significant difference between half-time and after game

5.3.2. Quadriceps muscle strength in the non-dominant leg (i) pre-exercise and (ii) post-exercise

Mean peak torque values are presented graphically in Figure 5.3.2. Paired t-tests indicated a significant difference in quadriceps muscle strength between the pre-exercise and post-exercise measures for the non-dominant leg at 1.05 rad.s^{-1} ($\bar{x} = 216 \pm 36$ vs 188 ± 42 Nm, $t = 4.90$, $P < 0.001$), 2.09 rad.s^{-1} ($\bar{x} = 181 \pm 36$ vs 162 ± 28 Nm, $t = 3.81$, $P < 0.002$), 5.23 rad.s^{-1} ($\bar{x} = 125.31 \pm 27$ vs 115.77 ± 23 Nm, $t = 2.74$, $P < 0.01$) and 2.09 (ecc) rad.s^{-1} ($\bar{x} = 222.61 \pm 40$ vs 202 ± 35 Nm, $t = 4.80$, $P < 0.001$). The peak torque values were greater pre-exercise than post-exercise.

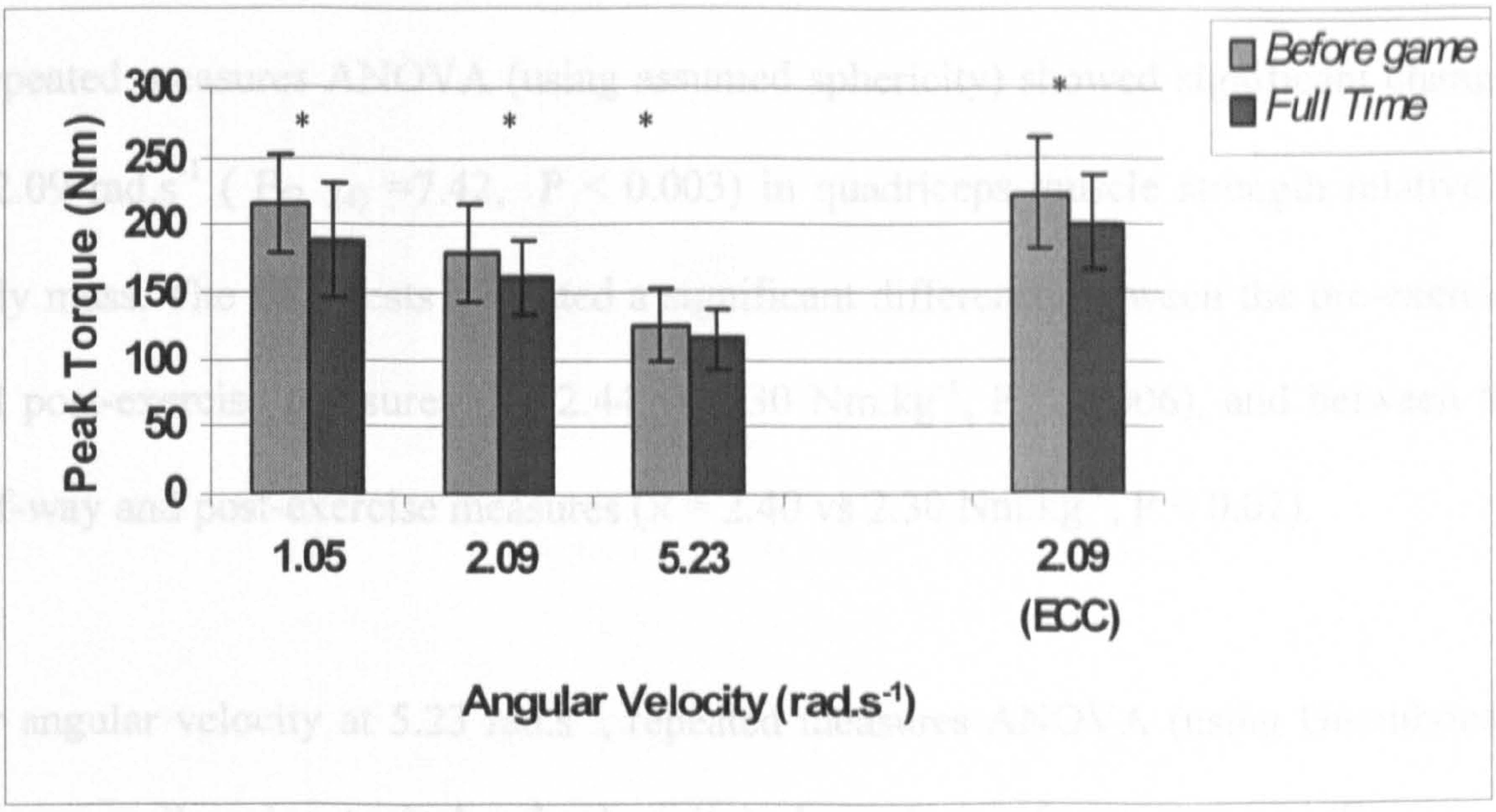


Figure 5.3.2. Comparison of quadriceps peak torque for the non-dominant leg, before and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the eccentric mode at 2.09 rad.s^{-1}.

5.3.3. Relative quadriceps muscle strength (peak torque/body mass) in the dominant leg (i) pre-exercise (ii) half-way and (iii) post-exercise

Results for this section are presented graphically in Figure 5.3.3. A repeated measures ANOVA (using Greenhouse-Geisser epsilon due to lack of sphericity) showed significant changes ($F_{(1.27,\ 15.31)}$ =14.39, $P < 0.001$) occurred in quadriceps muscle strength relative to body mass at 1.05 rad.s^{-1}. The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\overline{x}$ = 3.09 vs 2.83 Nm.kg^{-1}, $P < 0.01$), between the pre-exercise and post-exercise measures ($\overline{x}$ = 3.09 vs 2.68

$Nm.kg^{-1}$, $P < 0.001$) and also between the half-way and post-exercise measures ($\bar{x}$ = 2.83 vs 2.68 $Nm.kg^{-1}$, $P < 0.002$).

Repeated measures ANOVA (using assumed sphericity) showed significant changes at 2.09 $rad.s^{-1}$ ($F_{(2, 24)} = 7.42$, $P < 0.003$) in quadriceps muscle strength relative to body mass. The LSD tests indicated a significant difference between the pre-exercise and post-exercise measures ($\bar{x}$= 2.44 vs 2.30 $Nm.kg^{-1}$, $P < 0.006$), and between the half-way and post-exercise measures ($\bar{x}$ = 2.40 vs 2.30 $Nm.kg^{-1}$, $P < 0.02$).

For angular velocity at 5.23 $rad.s^{-1}$, repeated measures ANOVA (using Greenhouse-Geisser epsilon due to lack of sphericity) showed significant changes ($F_{(1.30, 15.64)} = 8.05$, $P < 0.008$) in quadriceps muscle strength relative to body mass. The LSD tests indicated a significant difference between the pre-exercise and post-exercise measures ($\bar{x}$ = 1.73 vs 1.60 $Nm.kg^{-1}$, $P < 0.01$) and also between the half-way and post-exercise measures ($\bar{x}$ = 1.69 vs 1.60 $Nm.kg^{-1}$, $P < 0.02$).

At 2.09 (ecc) $rad.s^{-1}$, repeated measures ANOVA (using assumed sphericity) showed significant changes ($F_{(2, 24)} = 7.56$, $P < 0.003$) in quadriceps muscle strength relative to body mass. The LSD tests indicated a significant difference between the pre-exercise and post-exercise measures ($\bar{x}$ = 2.93 vs 2.78 $Nm.kg^{-1}$, $P < 0.005$), and between the half-way and post-exercise measures ($\bar{x}$= 2.89 vs 2.78 $Nm.kg^{-1}$, $P < 0.02$).

These results demonstrated that relative quadriceps muscle strength values at all angular velocities were greater pre-exercise than at half-way. Also values were greater at half-way than post-exercise and confirmed the data previously reported regarding absolute quadriceps strength.

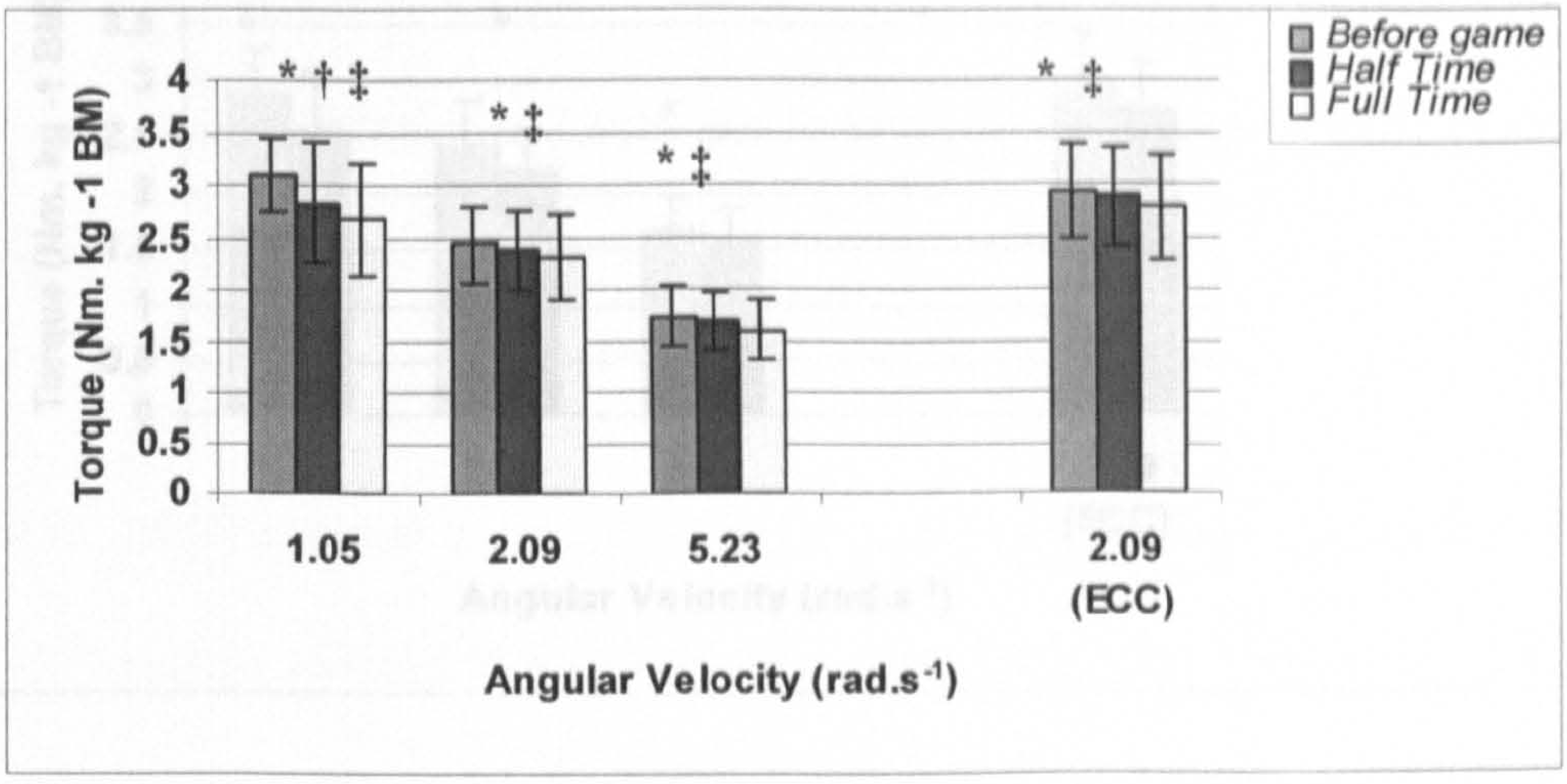


Figure 5.3.3. Comparison of relative quadriceps peak torque for the dominant leg, before, half-way (Half time) and after a treadmill simulation of work-rate in a soccer game. Results are indicated for concentric mode at three angular velocities and for eccentric mode at 2.09 rad.s^{-1}.

5.3.4. Relative quadriceps muscle strength (peak torque/body mass) in the non-dominant leg (i) pre-exercise and (ii) post-exercise

Results for this section are presented graphically in Figure 5.3.4. Paired t-tests indicated a significant change in quadriceps muscle strength relative to body mass for the pre-exercise and post-exercise measures in the non-dominant leg at 1.05 rad.s^{-1} ($\overline{x}$ = 2.90 vs 2.60 Nm, $t = 4.37$, $P < 0.001$), 2.09 rad.s^{-1} ($\overline{x}$ = 2.42 vs 2.21 Nm, $t = 3.23$, $P < 0.007$), 5.23 rad.s^{-1} ($\overline{x}$ = 1.67 vs 1.60 Nm, $t = 2.16$, $P < 0.05$) and 2.09 (ecc) rad.s^{-1} ($\overline{x}$ = 2.99 vs 2.76 Nm, $t = 3.76$, $P < 0.003$). The relative peak torque values were greater pre-exercise than post-exercise and confirmed the finding for absolute quadriceps strength.

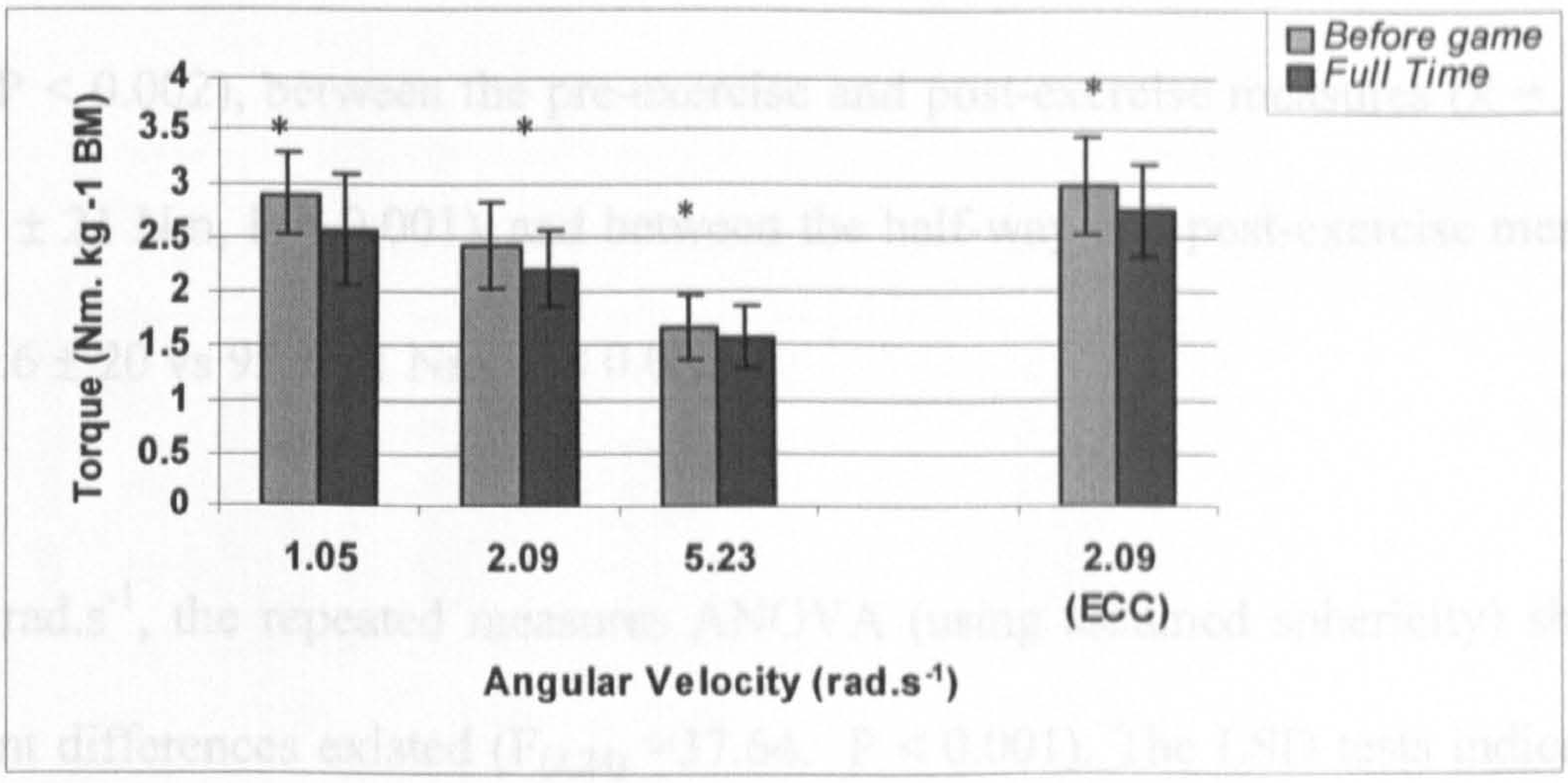


Figure 5.3.4. Comparison of relative quadriceps peak torque for the non-dominant leg, before and after a treadmill simulation of work-rate in a soccer game. Results are indicated for concentric mode at three angular velocities and for eccentric mode at 2.09 rad.s^{-1}.

5.3.5. Hamstrings muscle strength in the dominant leg (i) pre-exercise (ii) half-way and (iii) post-exercise

Mean peak torque values are presented graphically in Figure 5.3.5. A repeated measures ANOVA (using assumed sphericity) showed significant changes ($F_{(2,24)} = 23.77$, $P < 0.001$) in hamstrings muscle strength at 1.05 rad.s^{-1}. The LSD tests indicated a difference between the pre-exercise and half-way measures ($\bar{x} = 126.5 \pm 20$ vs 114 ± 31 Nm, $P < 0.005$), between the pre-exercise and post-exercise measures ($\bar{x} = 126.5 \pm 25$ vs 104.5, $P < 0.001$) and also between the half-way and post-exercise measures ($\bar{x} = 114 \pm 31$ vs 104.5 ± 25 Nm, $P < 0.001$).

At 2.09 rad.s^{-1}, the repeated measures ANOVA (using assumed sphericity) showed a significant main effect ($F_{(2, 24)} = 24.66$, $P < 0.001$). The LSD tests indicated a difference between the pre-exercise and half-way measures ($\overline{x}$ = 112 ± 19 vs 101.6 ± 20 Nm, $P < 0.002$), between the pre-exercise and post-exercise measures ($\overline{x}$ = 112 ± 19 vs 95 ± 21 Nm, $P < 0.001$), and between the half-way and post-exercise measures ($\overline{x}$ = 101.6 ± 20 vs 95 ± 21 Nm, $P < 0.002$).

At 5.23 rad.s^{-1}, the repeated measures ANOVA (using assumed sphericity) showed significant differences existed ($F_{(2,24)}$ =37.64, $P < 0.001$). The LSD tests indicated a difference between the pre-exercise and half-way measures ($\overline{x}$ = 101.5 ± 16 vs 92 ± 15 Nm, $P < 0.001$), between the pre-exercise and post-exercise measures ($\overline{x}$ = 101.5 ± 16 vs 86.7 ± 13 Nm, $P < 0.001$) and also between the half-way and post-exercise measures ($\overline{x}$ = 92 ± 15 vs 86.7 ± 13 Nm, $P < 0.01$).

For the eccentric action at 2.09 (ecc) rad.s^{-1}, the repeated measures ANOVA (using assumed sphericity) showed significant differences with time ($F_{(2, 24)}$ =33.58, $P < 0.001$). The LSD tests indicated a difference between the pre-exercise and half-way measures ($\overline{x}$ = 137 ± 23 vs 125 ± 25 Nm, $P < 0.001$), between the pre-exercise and post-exercise measures ($\overline{x}$ = 137 ± 23 vs 113.8 ± 27 Nm, $P < 0.001$), and between the half-way and post-exercise measures ($\overline{x}$ = 125 ± 25 vs 113.8 ± 27 Nm, $P < 0.001$).

These results demonstrated that peak torque values for the hamstrings at all angular velocities were greater pre-exercise than at half-way. They were also greater at half-way than post-exercise. There was therefore a progressive deterioration with the duration of exercise.

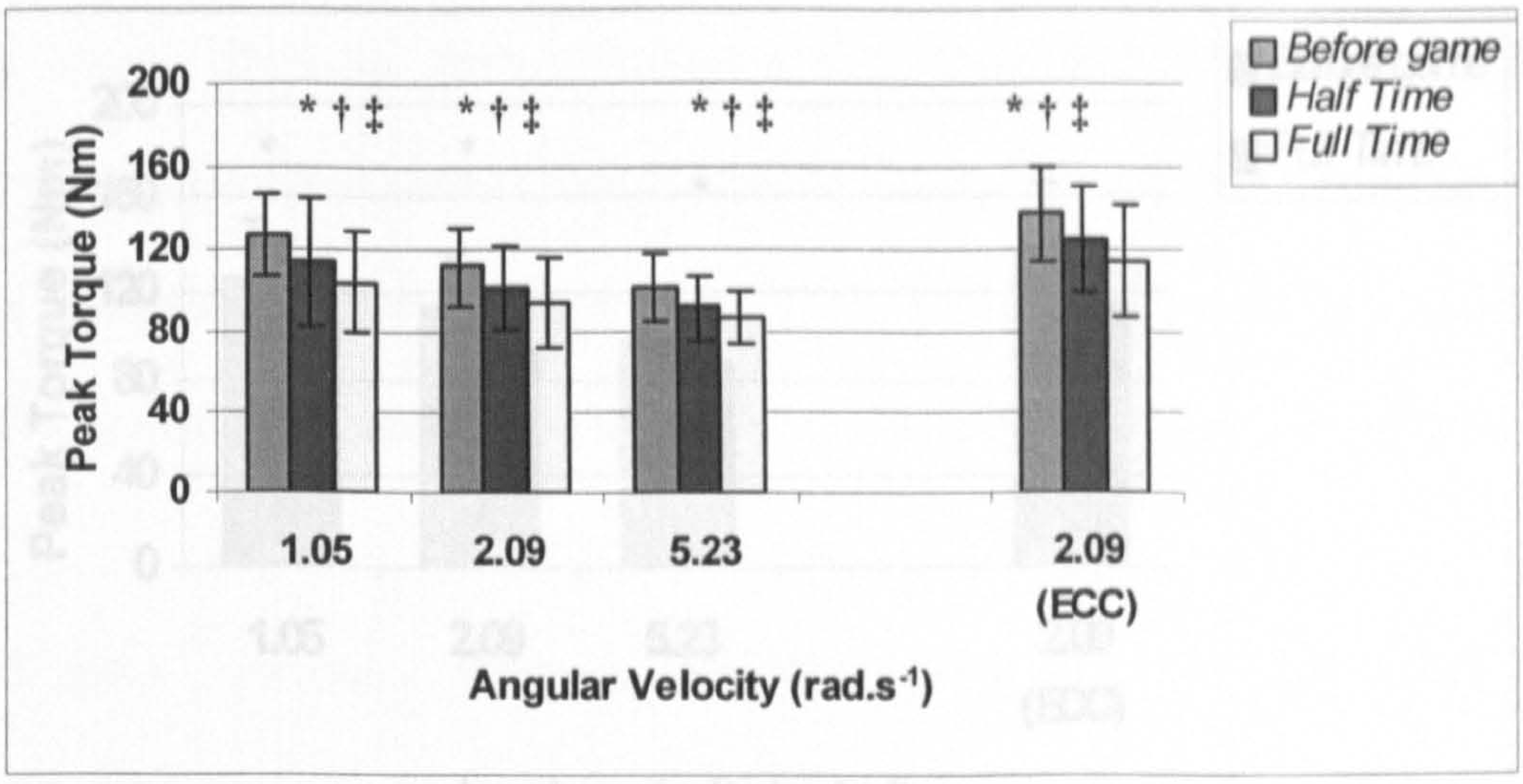


Figure 5.3.5. Comparison of hamstrings peak torque for the dominant leg, before, half-way (Half time) and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the eccentric mode at 2.09 rad.s^{-1}.

5.3.6. Hamstrings muscle strength in the non-dominant leg (i) pre-exercise and (ii) post-exercise

The results are presented graphically in Figure 5.3.6. Paired t-tests indicated a significant difference in hamstrings muscle strength for the pre-exercise and post-exercise measures for the non-dominant leg at 1.05 rad.s^{-1} ($\bar{x}$ = 126 ± 24 vs 106 ± 27 Nm, $t = 7.46$, $P < 0.001$), 2.09 rad.s^{-1} ($\bar{x}$ = 114 ± 23 vs 95 ± 17 Nm, $t = 3.15$, $P < 0.008$), 5.23 rad.s^{-1} ($\bar{x}$ = 99 ± 18 vs 87 ± 14 Nm, $t = 2.89$, $P < 0.01$) and 2.09 (ecc) rad.s^{-1} ($\bar{x}$ = 138 ± 28 vs 113 ± 20 Nm, $t = 3.56$, $P < 0.004$). Peak torque values for the hamstrings were greater pre-exercise than post-exercise.

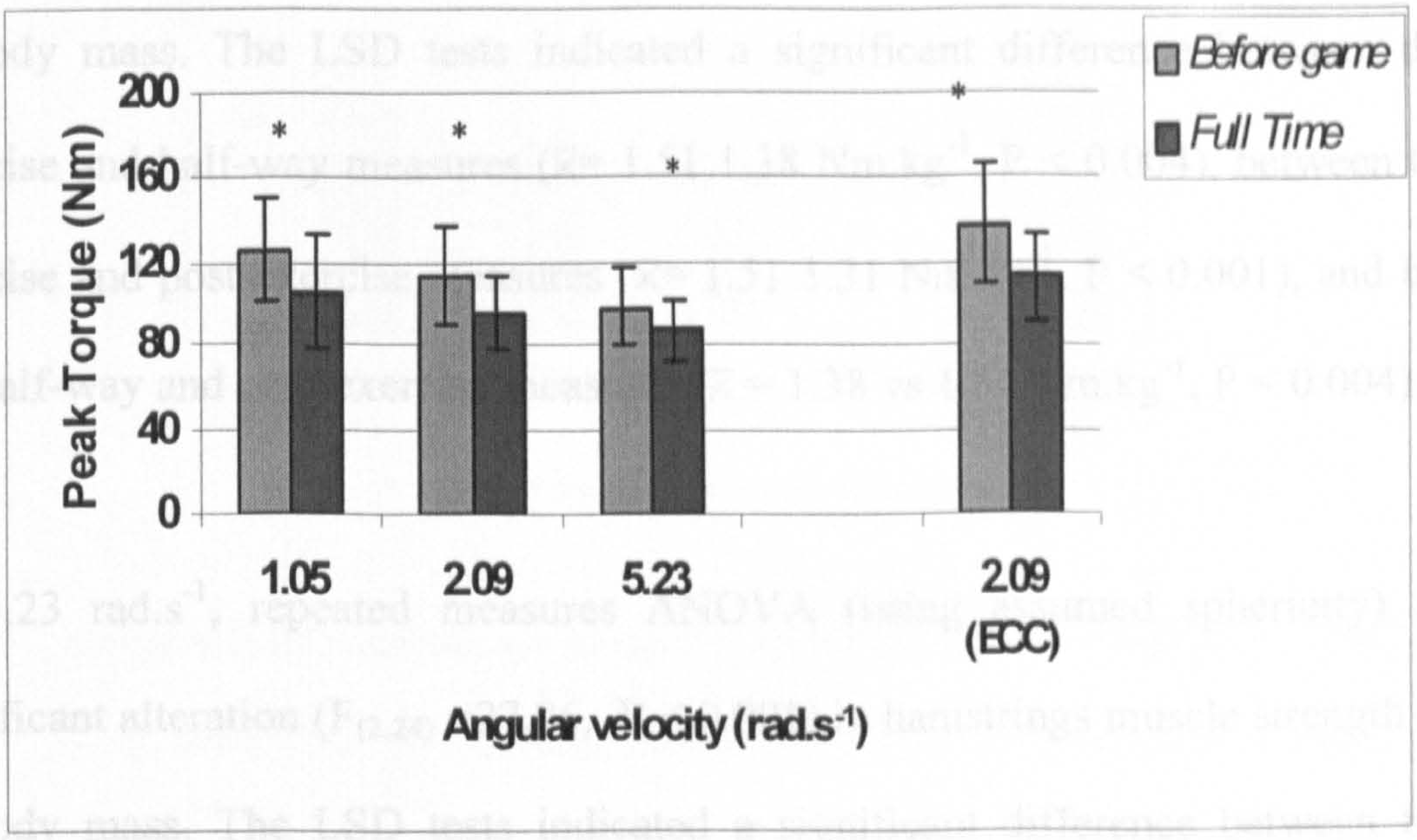


Figure 5.3.6. Comparison of hamstrings peak torque for the non-dominant leg, before, and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the eccentric mode at 2.09 rad.s^{-1}.

5.3.7. Relative hamstrings muscle strength (peak torque/body mass) in the dominant leg (i) pre-exercise (ii) half-way and (iii) post-exercise

Results for this section are presented graphically in Figure 5.3.7. A repeated measures ANOVA (using assumed sphericity) showed significant changes ($F_{(2,24)}$ =16.52, $P < 0.001$) in hamstrings muscle strength relative to body mass at 1.05 rad.s^{-1}. The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\bar{x}$ = 1.71 vs 1.55 Nm.kg^{-1}, $P < 0.02$), between the pre-exercise and post-exercise measures ($\bar{x}$ = 1.71 vs 1.43 Nm.kg^{-1}, $P < 0.001$) and also between the half-way and post-exercise measures ($\bar{x}$ = 1.55 vs 1.43 Nm.kg^{-1}, $P < 0.006$).

At 2.09 rad.s^{-1}, repeated measures ANOVA (using assumed sphericity) showed significant changes ($F_{(2, 24)} = 20.35$, $P < 0.001$) in hamstrings muscle strength relative to body mass. The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\bar{x}$= 1.51 1.38 Nm.kg^{-1}, $P < 0.004$), between the pre-exercise and post-exercise measures ($\bar{x}$= 1.51 1.31 Nm.kg^{-1}, $P < 0.001$), and between the half-way and post-exercise measures ($\bar{x}$ = 1.38 vs 1.31 Nm.kg^{-1}, $P < 0.004$).

At 5.23 rad.s^{-1}, repeated measures ANOVA (using assumed sphericity) showed significant alteration ($F_{(2,24)} = 27.06$, $P < 0.001$) in hamstrings muscle strength relative to body mass. The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\bar{x}$ = 1.36 vs 1.25 Nm.kg^{-1}, $P < 0.001$), between the pre-exercise and post-exercise measures ($\bar{x}$ = 1.36 vs 1.18 Nm.kg^{-1}, $P < 0.001$) and also between the half-way and post-exercise measures ($\bar{x}$ = 1.25 vs 1.18 Nm.kg^{-1}, $P < 0.01$).

At 2.09 (ecc) rad.s^{-1}, repeated measures ANOVA (using assumed sphericity) showed significant changes ($F_{(2, 24)} = 25.38$, $P < 0.001$) in hamstrings muscle strength relative to body mass. The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\bar{x}$ = 1.84 vs 1.71 Nm.kg^{-1}, $P < 0.002$), between the pre-exercise and post-exercise measures ($\bar{x}$ = 1.84 vs 1.55 Nm.kg^{-1}, $P < 0.001$), and between the half-way and post-exercise measures ($\bar{x}$= 1.71 vs 1.55 Nm.kg^{-1}, $P < 0.001$). These results demonstrated that relative hamstrings torque values at all angular velocities were greater pre-exercise than at half-way. Also values were greater at half-way than post-exercise and confirmed the data previously reported for absolute hamstrings strength.

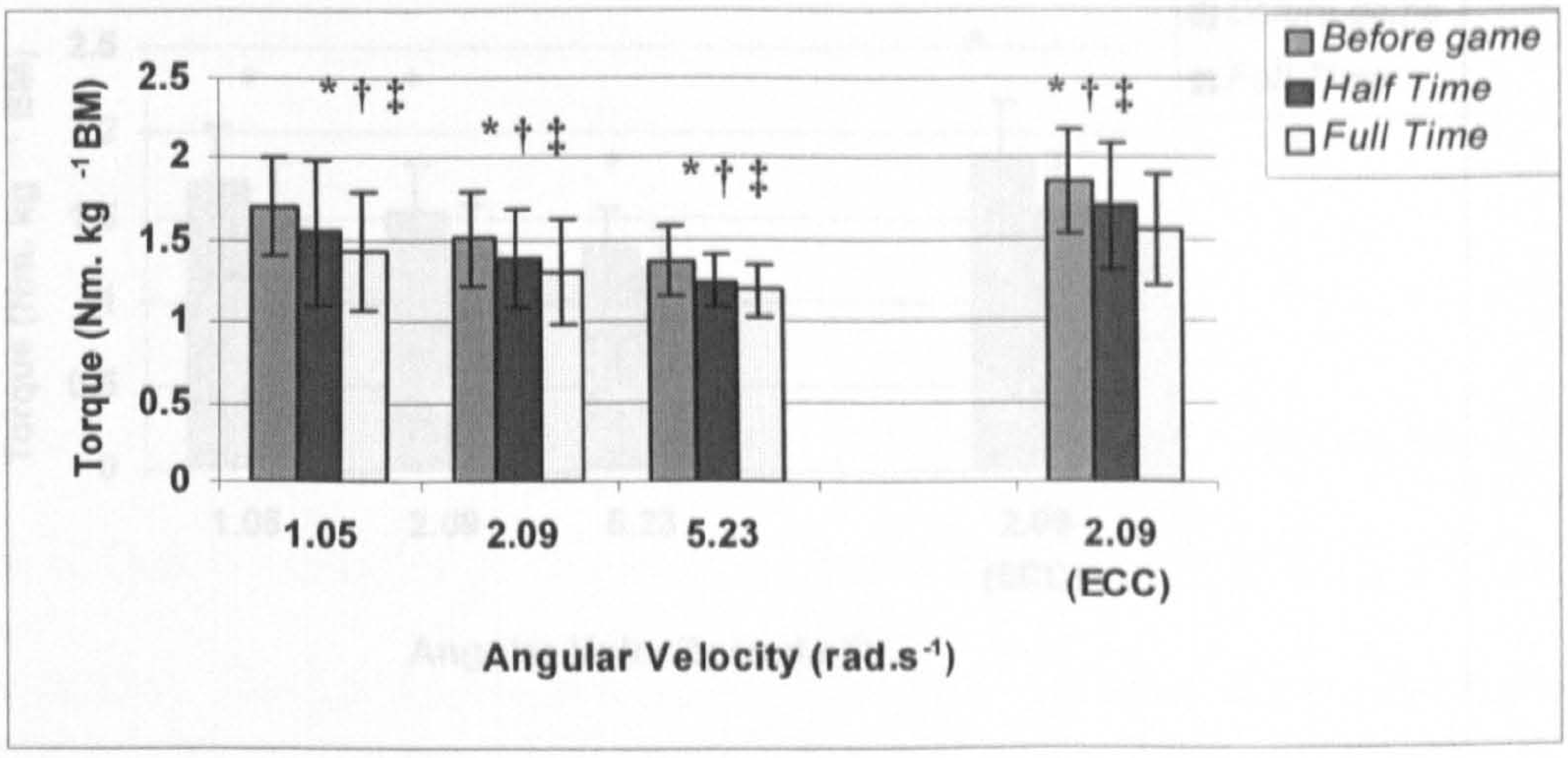


Figure 5.3.7. Comparison of relative hamstrings peak torque for the dominant leg, before, half-way (Half time) and after a treadmill simulation of work-rate in a soccer game. Results are indicated for concentric mode at three angular velocities and for eccentric mode at 2.09 rad.s^{-1}.

5.3.8. Relative hamstrings muscle strength (peak torque/body mass) in the non-dominant leg (i) pre-exercise and (ii) post-exercise

Results for this section are presented graphically in Figure 5.3.8. Paired t-tests indicated a significant difference in relative hamstrings muscle strength to body mass for the pre-exercise and post-exercise measures for the non-dominant leg at 1.05 rad.s^{-1} ($\bar{x}$ = 1.71 vs 1.44 Nm, t = 6.60, $P < 0.001$), 2.09 rad.s^{-1} ($\bar{x}$ = 1.54 vs 1.32 Nm, t = 2.98, $P < 0.01$), 5.23 rad.s^{-1} ($\bar{x}$ = 1.33 vs 1.20 Nm, t = 2.52, $P < 0.05$) and 2.09 (ecc) rad.s^{-1} ($\bar{x}$ = 1.85 vs 1.56 Nm, t = 3.39, $P < 0.005$). The relative hamstrings peak torque values were greater pre-exercise than post-exercise and confirmed the finding for absolute hamstrings strength.

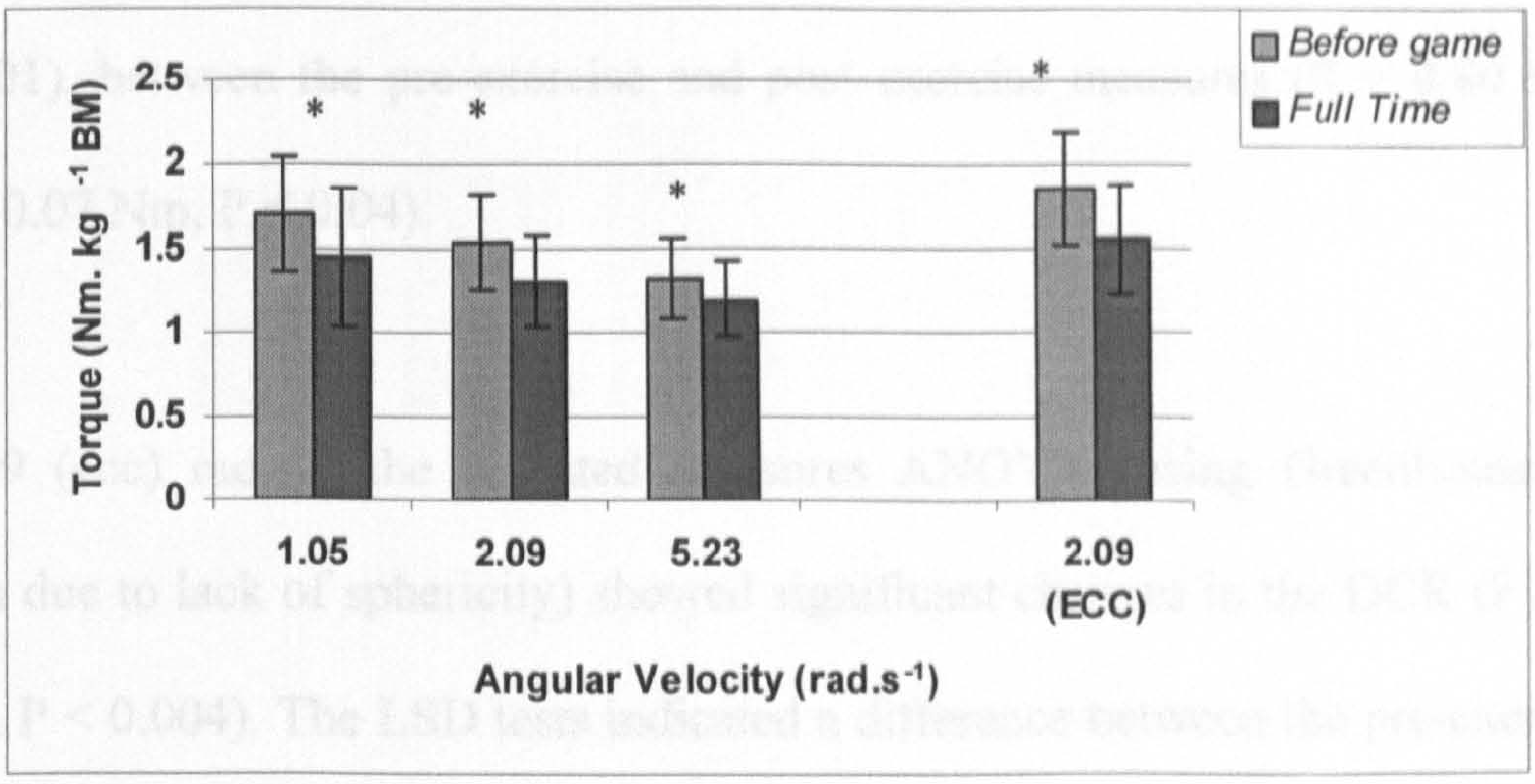


Figure 5.3.8. Comparison of relative hamstrings peak torque for the non-dominant leg, before and after a treadmill simulation of work-rate in a soccer game. Results are indicated for concentric mode at three angular velocities and for eccentric mode at 2.09 rad.s^{-1}.

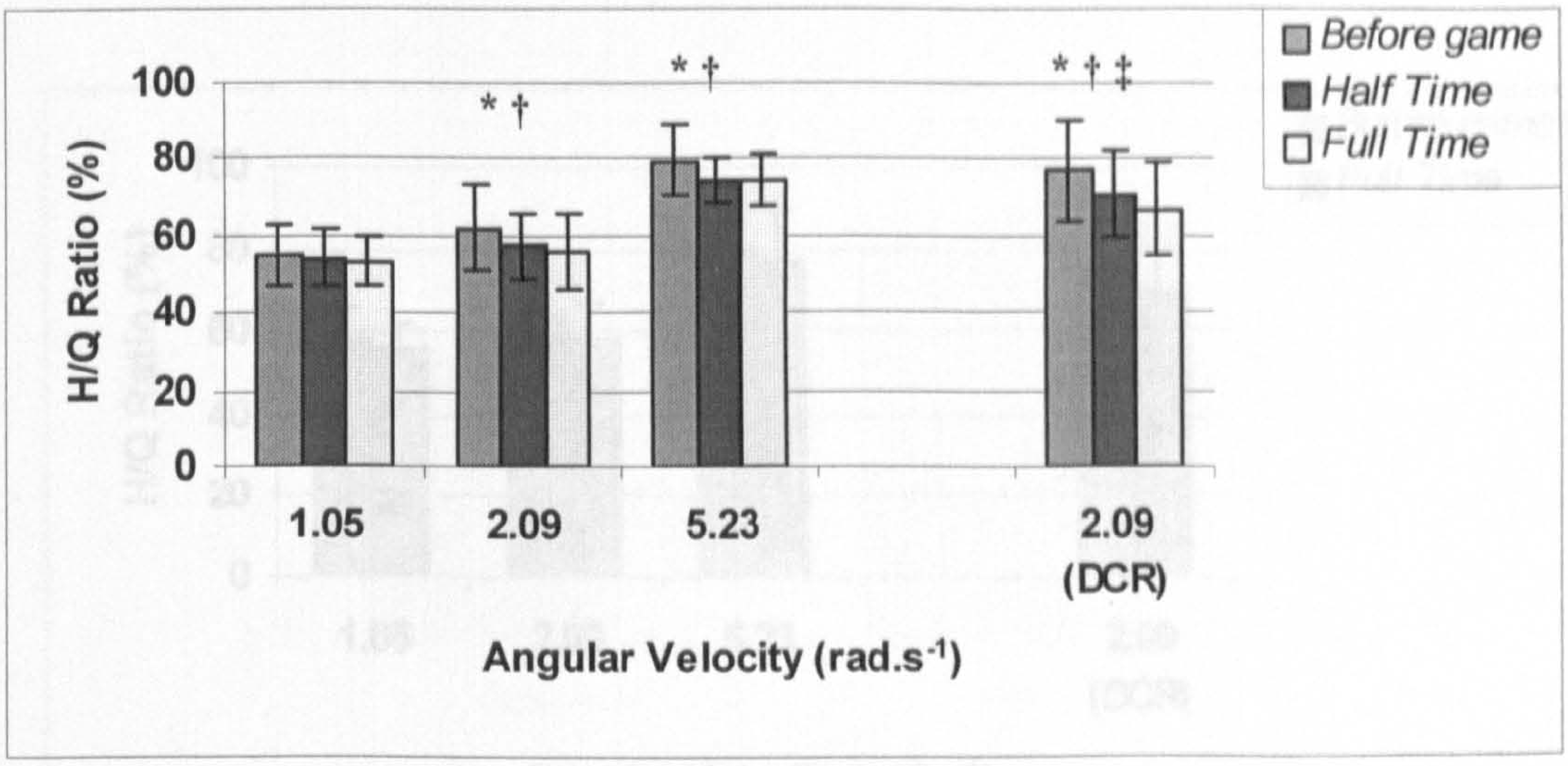
5.3.9. Hamstrings/Quadriceps ratio in the dominant leg (i) pre-exercise (ii) half-way and (iii) post-exercise

The results are presented graphically in Figure 5.3.9. A repeated measures ANOVA (using Greenhouse-Geisser epsilon due to lack of sphericity) showed significant changes ($F_{(1.32,\ 15.85)} = 7.24$, $P < 0.01$) in muscle balance at 2.09 rad.s^{-1}. The LSD tests indicated a difference between the pre-exercise and half-way measures ($\overline{x} = 0.62 \pm 0.11$ vs 0.57 ± 0.08 Nm, $P < 0.02$), and between the pre-exercise and post-exercise measures ($\overline{x} = 0.62 \pm 0.11$ vs 0.56 ± 0.09 Nm, $P < 0.01$).

At 5.23 rad.s^{-1}, the repeated measures ANOVA (using assumed sphericity) showed significant main effects ($F_{(2,24)} = 5.26$, $P < 0.01$). The LSD tests indicated a difference between the pre-exercise and half-way measures ($\bar{x}$ = 0.80 ± 0.09 vs 0.74 ± 0.06 Nm, $P < 0.01$), between the pre-exercise and post-exercise measures ($\bar{x}$ = 0.80 ± 0.09vs 0.75 ± 0.07 Nm, $P < 0.04$).

At 2.09 (ecc) rad.s^{-1}, the repeated measures ANOVA (using Greenhouse-Geisser epsilon due to lack of sphericity) showed significant changes in the DCR ($F_{(1,29,\ 15.56)}$ = 9.78, $P < 0.004$). The LSD tests indicated a difference between the pre-exercise and half-way measures ($\bar{x}$ = 0.77 ± 0.13 vs 0.71 ± 0.11 Nm, $P < 0.02$), between the pre-exercise and post-exercise measures ($\bar{x}$ = 0.77 ± 0.13 vs 0.67 ± 0.12 Nm, $P < 0.005$), and between the half-way and post-exercise measures ($\bar{x}$ = 0.71 ± 0.11 vs 0.67 ± 0.12 Nm, $P < 0.01$).

These results demonstrated that hamstrings/quadriceps ratios for the majority of the angular velocities were greater pre-exercise than at half-way, and greater at half-way than post-exercise. This finding applied to both the conventional hamstring/quadriceps ratio and the DCR.



DCR= Dynamic control ratio

Figure 5.3.9. Comparison of hamstrings/quadriceps peak torque ratio for the dominant leg, before, half-way (Half time) and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the DCR at 2.09 rad.s^{-1}.

5.3.10. Hamstrings/quadriceps ratio in the non-dominant leg (i) pre-exercise and (ii) post-exercise

The results are presented graphically in Figure 5.3.10. Paired t-tests indicated a significantly greater ratio for the pre-exercise compared to the post-exercise measures for the non-dominant leg at 1.05 rad.s^{-1} ($\overline{x} = 0.58 \pm 0.07$ vs 0.56 ± 0.06 Nm, $t = 3.74$, $P < 0.003$). Although the hamstring/quadriceps ratios were higher for the pre-exercise measures than for the post-exercise measures at the other angular velocities, the differences were not statistically significant.

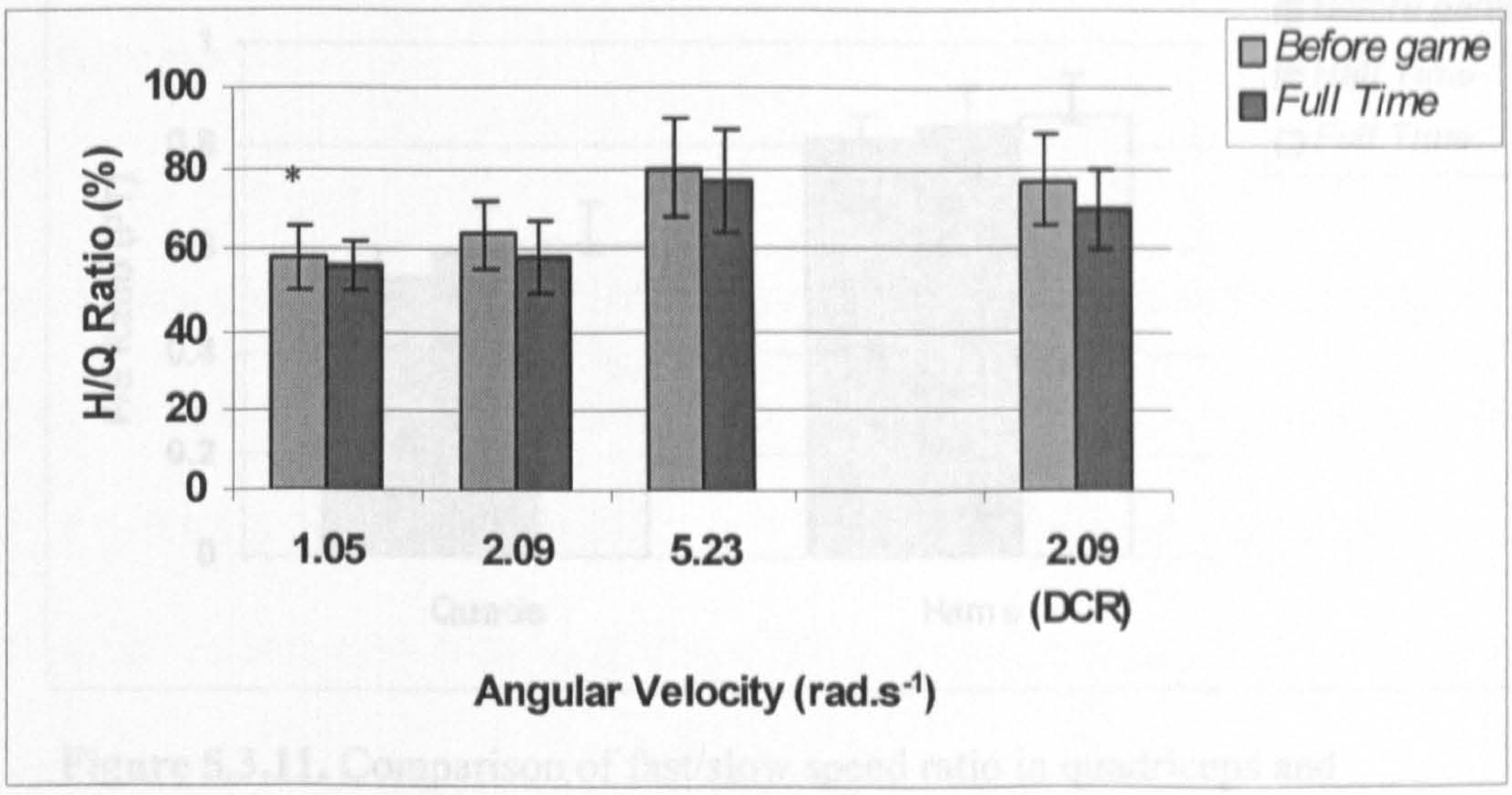


Figure 5.3.10. Comparison of hamstrings/quadriceps peak torque ratio for the non-dominant leg, before and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the DCR at 2.09 rad.s^{-1}.

5.3.11. Fast/slow speed ratio in the dominant leg (i) pre-exercise (ii) half-way and (iii) post-exercise

No significant differences were observed using repeated measures ANOVA in fast/slow speed ratio in quadriceps and hamstrings peak torque for the dominant leg between the pre-exercise and post-exercise measures ($\overline{x}$ = 0.55 ± 0.05 vs 0.61 ± 0.08 Nm, 0.81 ± 0.14 vs 0.86 ± 0.16 Nm). The same finding applied to the comparison between the pre-exercise and half-way measures ($\overline{x}$ = 0.55 ± 0.05 vs 0.60 ± 0.08 Nm, 0.81 ± 0.14 vs 0.84 ± 0.17 Nm) or between half-way and post-exercise measures ($\overline{x}$ = 0.60 ± 0.08 vs 0.61 ± 0.08 Nm, 0.84 ± 0.17 vs 0.86 ± 0.16 Nm) (Figure 5.3.11).

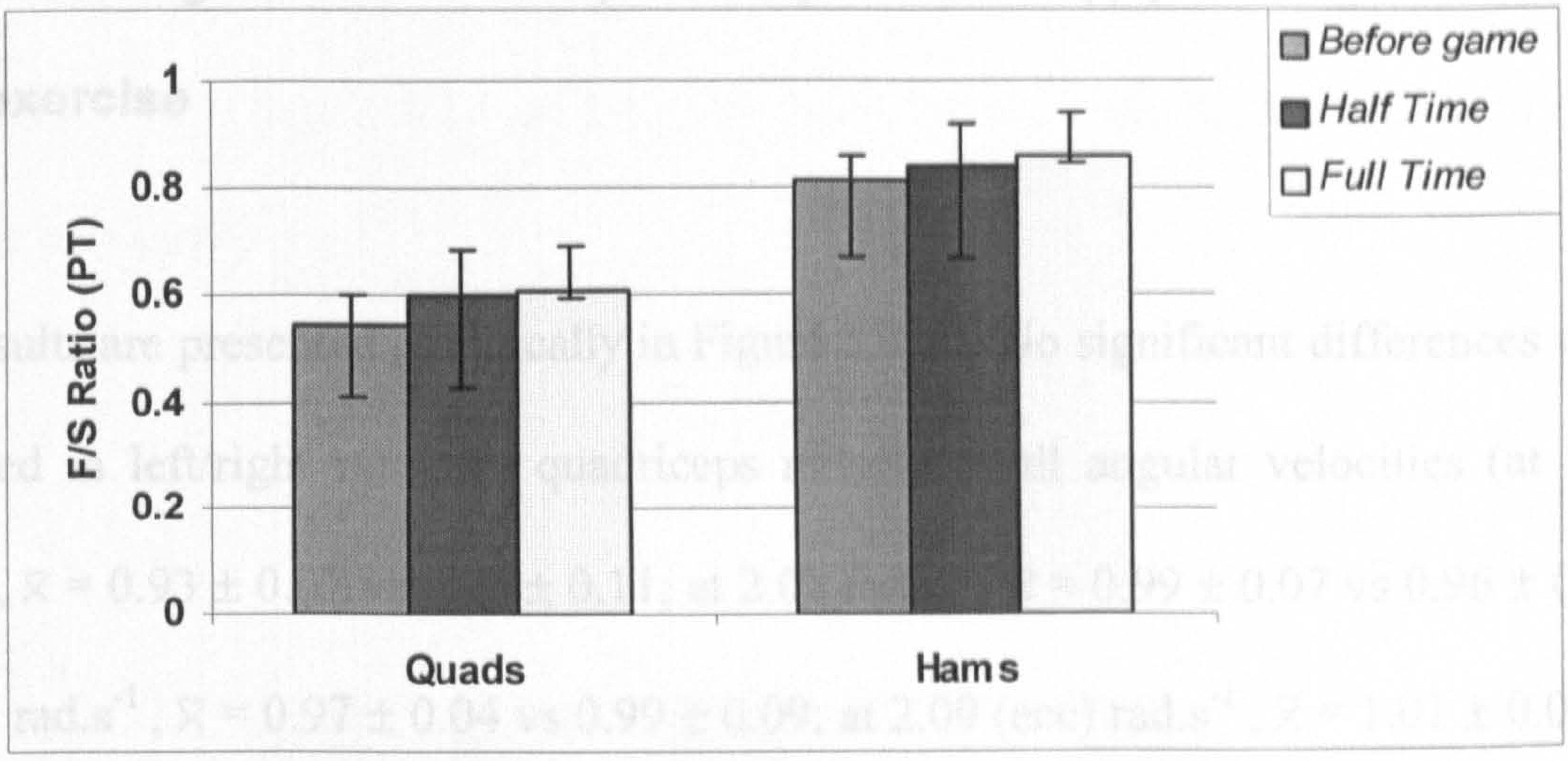


Figure 5.3.11. Comparison of fast/slow speed ratio in quadriceps and hamstrings for the dominant leg, before, half-way (Half time) and after a treadmill simulation of game work-rate.

5.3.12. Fast/slow speed ratio in the non-dominant leg (i) pre-exercise and (ii) post-exercise

No significant difference was observed in fast/slow speed ratio in quadriceps ($\overline{x}$ = 0.58 ± 0.06 vs 0.63 ± 0.12 Nm) and hamstrings ($\overline{x}$ = 0.79 ± 0.11 vs 0.86 ± 0.17 Nm) peak torque for the non-dominant leg between the pre-exercise and post-exercise measures.

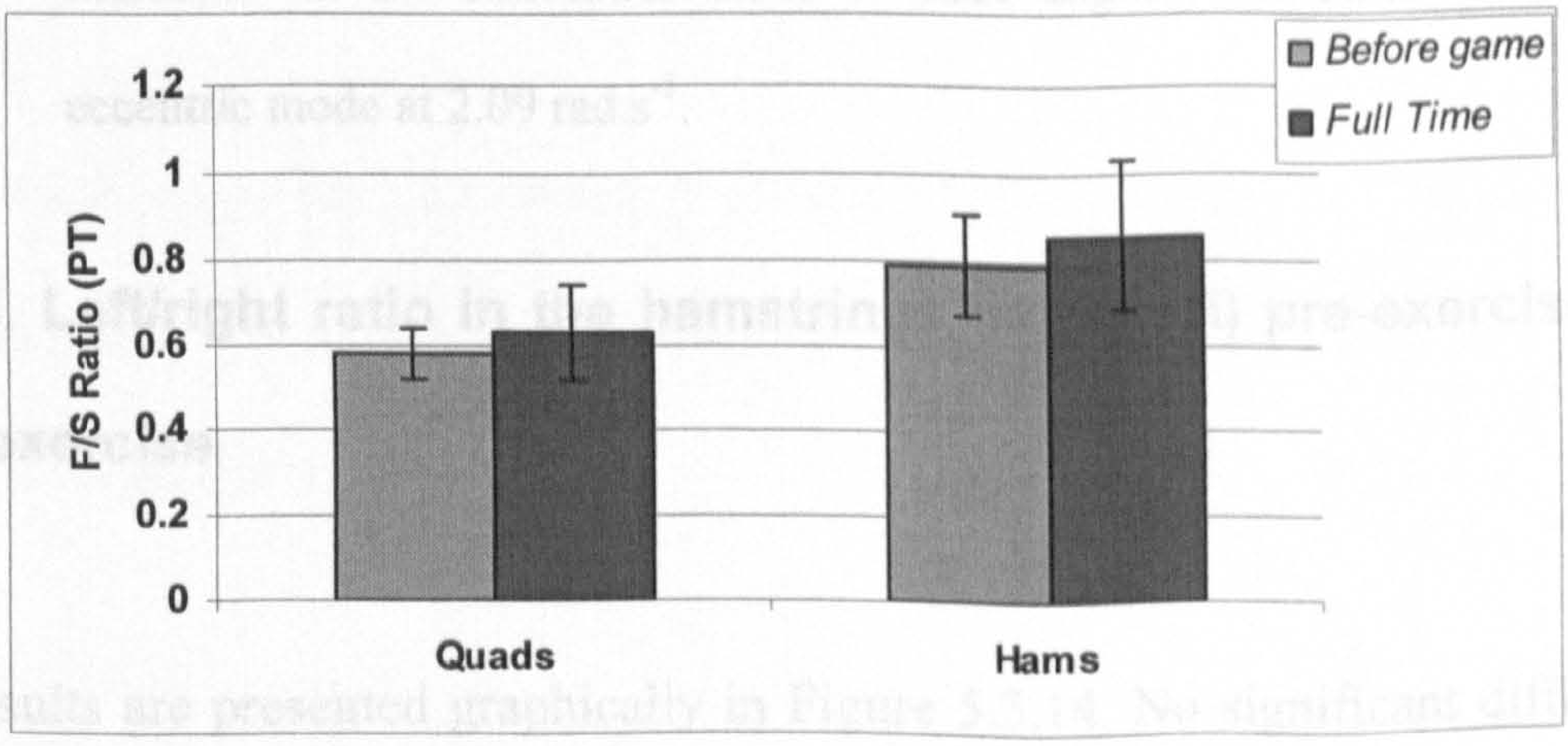


Figure 5.3.12. Comparison of fast/slow speed ratio in quadriceps and hamstrings for the non-dominant leg, before and after a treadmill simulation of game work-rate.

5.3.13. Left/right ratio in the quadriceps muscle (i) pre-exercise and (ii) post-exercise

The results are presented graphically in Figure 5.3.13. No significant differences were observed in left/right ratio for quadriceps muscle at all angular velocities (at 1.05 rad.s^{-1}, $\overline{x}$ = 0.93 ± 0.07 vs 0.96 ± 0.11; at 2.09 rad.s^{-1}, $\overline{x}$ = 0.99 ± 0.07 vs 0.96 ± 0.07; at 5.23 rad.s^{-1}, $\overline{x}$ = 0.97 ± 0.04 vs 0.99 ± 0.09; at 2.09 (ecc) rad.s^{-1}, $\overline{x}$ = 1.01 ± 0.07 vs 1 ± 0.07, Nm) between the pre-exercise and post-exercise measures.

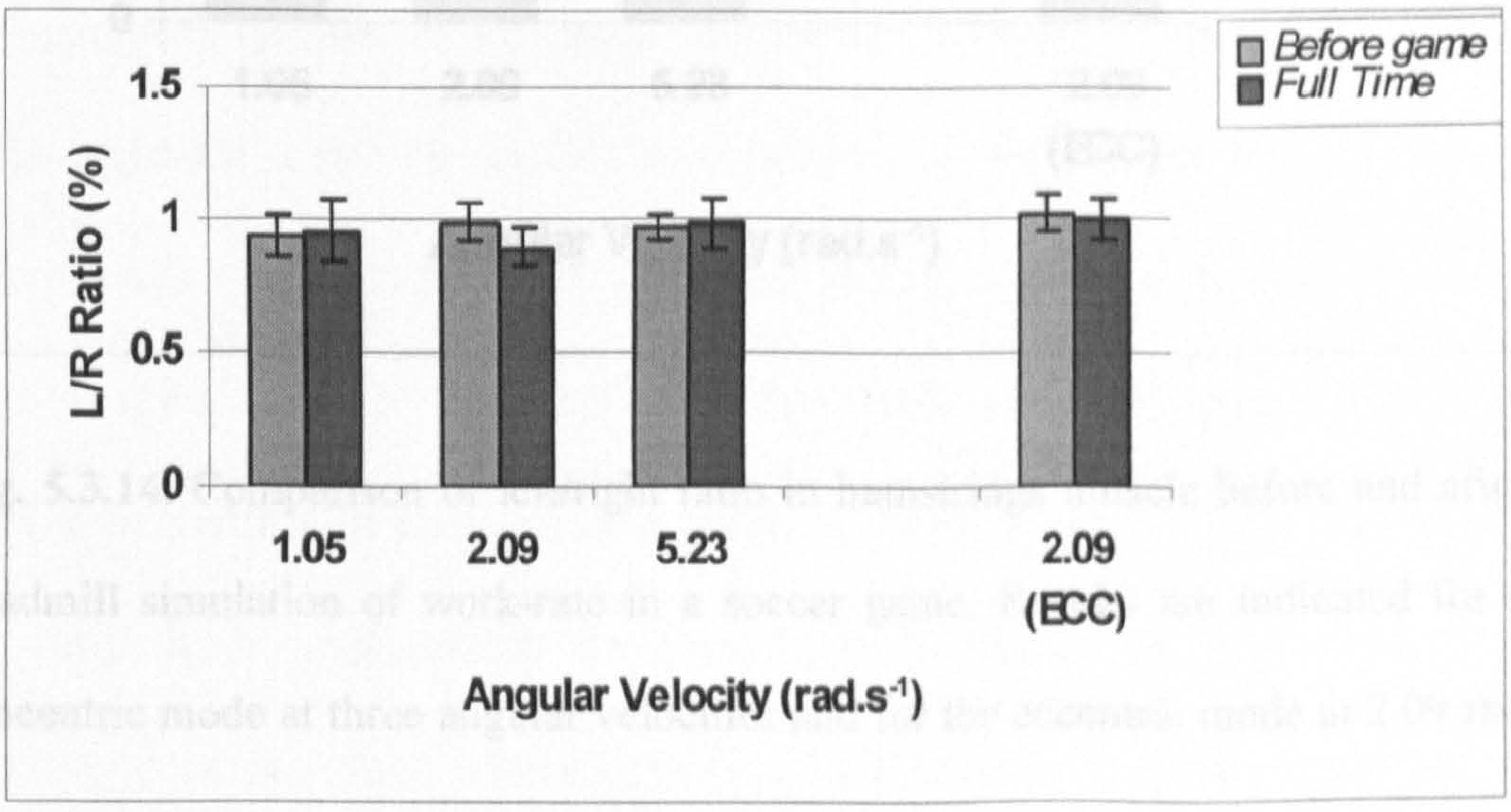


Figure 5.3.13. Comparison of left/right ratio in quadriceps muscle before and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the eccentric mode at 2.09 rad.s^{-1}.

5.3.14. Left/right ratio in the hamstrings muscle (i) pre-exercise and (ii) post-exercise

The results are presented graphically in Figure 5.3.14. No significant difference was observed at any angular velocity (at 1.05 rad.s^{-1}, $\overline{x}$ = 0.99 ± 0.12 vs 1 ± 0.19; at 2.09

rad.s^{-1}, $\overline{x} = 1.03 \pm 0.15$ vs 1 ± 0.15; at 5.23 rad.s^{-1}, $\overline{x} = 1 \pm 0.09$ vs 1 ± 0.14; at 2.09 (ecc) rad.s^{-1}, $\overline{x} = 1.01 \pm 0.14$ vs 1 ± 0.13, Nm), between the pre-exercise and post-exercise measures.

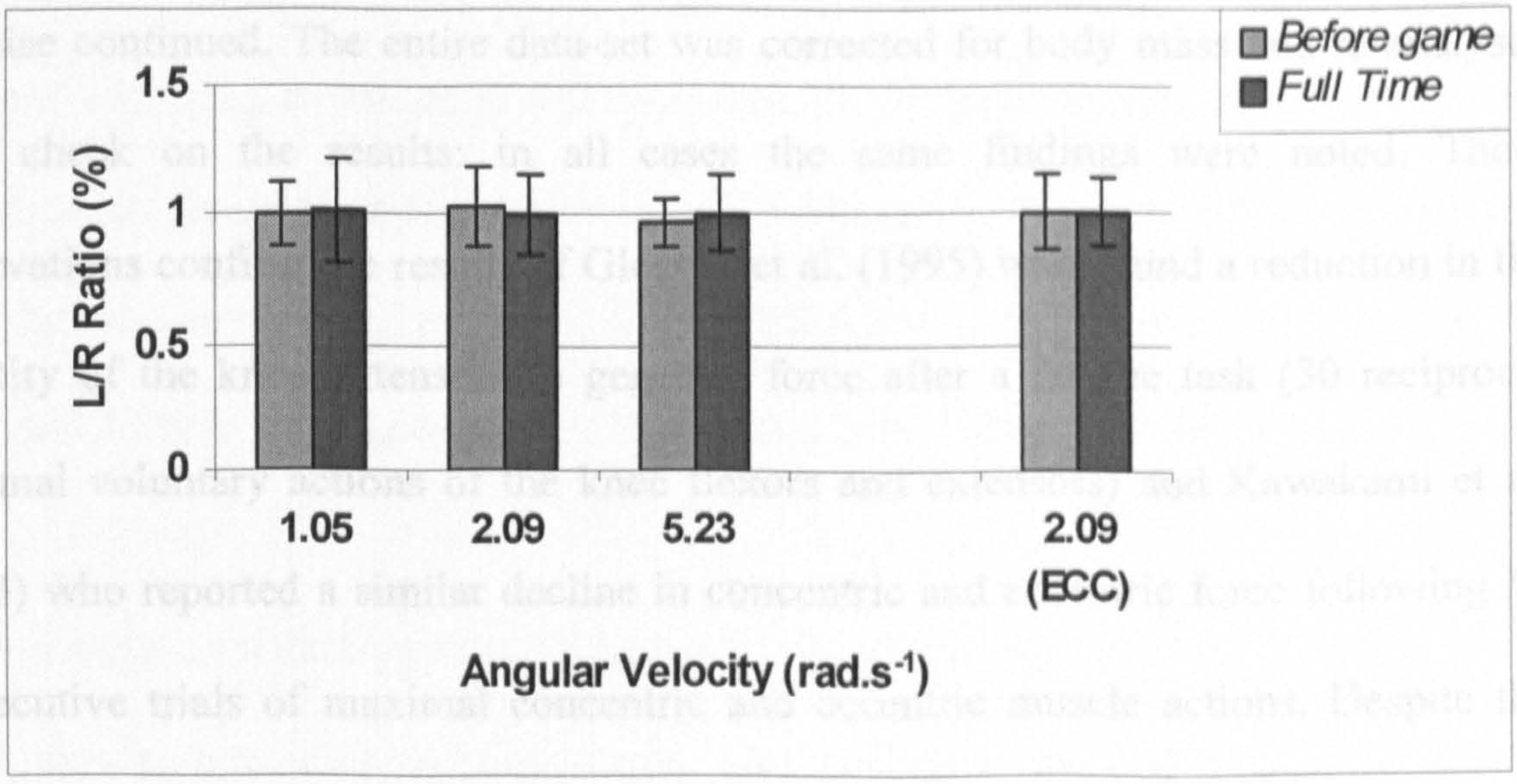


Fig. 5.3.14. Comparison of left/right ratio in hamstrings muscle before and after a treadmill simulation of work-rate in a soccer game. Results are indicated for the concentric mode at three angular velocities and for the eccentric mode at 2.09 rad.s^{-}

5.3.15. Vertical jump height and flexibility of the hip joint

The vertical height jumped (means ± sd) was 35.9 ± 4.6 cm. The flexibility values of dominant and non-dominant legs were (means ± sd) 81.2 ± 7.4 and 80.2 ± 6.3 degrees, respectively.

5.4. DISCUSSION

The exercise protocol designed to induce fatigue as experienced in a soccer game reduced the capability of the knee extensor and flexor muscles to develop force. The reduction in strength was evidenced by a decline in peak torque as the duration of exercise continued. The entire data-set was corrected for body mass and re-analysed as a check on the results: in all cases the same findings were noted. These observations confirm the results of Gleeson et al. (1995) who found a reduction in the capacity of the knee extensors to generate force after a fatigue task (30 reciprocal maximal voluntary actions of the knee flexors and extensors) and Kawakami et al. (1993) who reported a similar decline in concentric and eccentric force following 50 consecutive trials of maximal concentric and eccentric muscle actions. Despite the fact that there are large differences between these tasks and the fatigue protocol of this study, a similar decline in strength as a result of fatigue was evident. The decline in strength would have implications for the ability of players to perform their skills towards the end of the game where they will be able to run, sprint, jump and tackle less vigorously than they would at the start of the game. It may also lead to a higher number of errors which will affect players' susceptibility to injury as the game progresses.

The decline in muscle strength with fatigue in the knee extensors is influenced by the angular velocity of limb movements. The absolute strength of the dominant leg was reduced by 15.5%, 8%, 8.5%, at angular velocities of 1.05, 2.09 and 5.23 rad.s^{-1} respectively. The greater decline in strength at low angular velocities could affect the performance of explosive actions such as jumping, sprinting from rest or changing direction, which require high quadriceps strength at the initiation of movement where the joint extension velocity is low. This trend was not evident in the knee flexors (with a decline of 17%, 15% and 15%, respectively) but their decline in strength was greater than that in the knee extensors at all speeds. This would change the muscle balance where the quadriceps will become more dominant, particularly at high contraction speeds. Gleeson et al. (1995) reported that the H/Q ratio remained constant following exposure to a fatigue task. In contrast, significant changes in the H/Q strength ratio were found following the simulated soccer task of the present study with the ratio decreasing by 3.6%, 9.7%, and 6.2% in the dominant leg and 3.4%, 7.9% and 3.7% in the non-dominant leg at 1.05, 2.09, 5.23 rad.s^{-1} respectively.

In the eccentric mode around a 10% greater reduction in strength was observed in the hamstrings compared to the quadriceps. This difference may be due to the greater efforts of the hamstrings in the control of running activities and for stabilising the knee joint during foot contact. If so, then this decline might lead to less control and lower stability of the knee towards the end of the game and thus lead to a greater risk of injury. The DCR, thought to be an indicator of lower limb capability where the bilateral muscles work against each other in an explosive movement, has an ideal value range of 0.80 – 1.0 (Aagaard et al., 1995). In this study the DCR was 0.77 and decreased progressively as the duration of exercise continued. Furthermore the magnitude of decline exceeded that observed in the conventional H/Q ratio. The deficit in hamstrings strength with fatigue is of concern in that it may correspond with a compromised capability for joint stabilisation and so potentially, an increased risk of injury. Local muscle fatigue has been identified as a factor in injury causation (Lieber and Friden, 1988; Davis and Bailey, 1997) and Hawkins et al. (2001) claimed that this can explain the greater injury incidence observed in the second half of competitive matches, especially during the final quarter. Consequently trainers should focus on the eccentric function of the hamstrings as well as the concentric action of the quadriceps in training sessions, to ensure a good bilateral muscle balance over a wide range of playing skills.

The decline in strength for the non-dominant leg was similar to that of the dominant leg, and so the left/right ratios did not change as fatigue was induced. This would be expected, due to the task (walking, jogging, running and sprinting) which placed equal demand on both legs. This may not be so in a game, and it is possible that under game conditions dominant/non-dominant asymmetry may develop. The fast-speed/slow-speed ratio for the quadriceps and hamstrings increased in both the dominant and non-dominant leg due to the smaller decline in muscle force at the higher speed, but this trend was not statistically significant. This confirms the influence of fatigue on the force-velocity characteristics of muscle as noted earlier, with the greater effect being more noticeable at the lower angular velocities.

The decline in absolute strength values with fatigue may be due to other factors such as dehydration, glycogen depletion or neural activation of the muscles. Dehydration was observed in the present study with an estimated sweat rate of 1.2 $l.h^{-1}$ in the participants, based on the change in body mass and the mean fluid intake. This suggested that the performance of players will decrease in the second half, especially in the last 15 min of the game. Soccer is an intermittent high-intensity team sport where high sweat losses of approximately 3 litres can be expected. Ekblom (1986) and Rico-Sanz et al. (1996) have reported that during a soccer match, a player may run between 8 to 13 km in 90 min at an intensity requiring 75 to 80% of $\dot{V}O_{2\,max}$. The sweat glands can produce between 12 to 30 g of sweat per minute depending on environmental conditions and intensity of exercise, and can lead to a decrease in exercise performance (McGregor et al., 1999). Typical sweating rates for athletes range from 1 to 3 $l.h^{-1}$ depending on environmental temperature (Rehrer and Burke, 1996) and rates of 1.5 $l.h^{-1}$ have been reported for soccer players (Kirkendall, 1993). The sweat impacts directly on performance, making the effects of fatigue more likely to be noticeable at an earlier stage of the game. Glycogen depletion during prolonged intermittent exercise may lead to fatigue (Bangsbo, 1994a). Essen (1978) reported that the muscle fibres that are most frequently recruited in performance and have the lowest capacity to restore glycogen may become depleted of glycogen first and this probably reduces the number of fibres that can be recruited to compensate for a loss in muscle force. Therefore the muscle may not able to generate enough force during the high-intensity exercise periods. In a later study, Bangsbo (1994a) reported that fatigue during prolonged intermittent exercise may also be caused by changes in the function of the sarcoplasmic reticulum. Neural activation may also lead to a reduction in force and it is difficult to evaluation, but it is possible to monitor such electrical activity of muscles by electromyography.

In general, this present study showed that fatigue occurred progressively in soccer players' muscles and therefore maximum force decreased progressively from the beginning to the end of the game. A reduction in muscle glycogen and also a decline in body water content or other factors such as impaired activation of muscle fibres may be involved in the fatigue process but the precise mechanisms of fatigue can not be isolated in the present study. Nevertheless, further research into the role of carbohydrate intake, rehydration and neural activation in attenuating fatigue is warranted.

In conclusion, the present findings indicate that a simulated soccer-specific exercise protocol reduced the capacity of the knee extensors and flexors to generate force. The reduction in strength was evidenced in absolute peak torque and relative peak torque. The fatigue task affected the H/Q strength ratio, which decreased, while the left/right and fast/slow speed ratios were unaffected. A number of factors may be responsible for the observed reduction in muscle strength such as dehydration, glycogen depletion or neural activation of the muscle. These findings have implications for competitive performance and increased risk of injury as the game progresses.

CHAPTER SIX

ELECTROMYOGRAPHIC ANALYSIS OF SELECTED MUSCLES DURING A SIMULATED SOCCER GAME

6.0. ELECTROMYOGRAPHIC ANALYSIS OF SELECTED MUSCLES DURING A SIMULATED SOCCER GAME

6.1. INTRODUCTION

Fatigue is indicated by a decrease of muscle strength and power, which occurs in the course of exercise. In the majority of activities, most of the decline in force occurs due to changes within the muscle, but force also decreases as a result of changes within the central nervous system. So, the total fatigue due to any activity can be measured by comparing the force or power, before and at the end of that activity. In an isometric maximal voluntary contraction the loss of force occurs after a few seconds, but in intermittent exercise, the onset of fatigue is more difficult to recognise. Electromyography (EMG) has been increasingly used to investigate the characteristics of fatigue and may therefore provide a means of detecting the onset of this phenomenon.

Surface EMG analysis of muscle function has received increasing attention during recent years. EMG has been useful in comparing muscular activity among different movements and it is valuable in evaluating co-ordination. In the last two decades, analysis of the surface EMG has become an important tool in the study of local muscle fatigue. During maximal voluntary contraction several changes are observed. The root mean square (RMS) of the EMG signal generally shows a gradual decrement during sustained maximum voluntary contraction, but conflicting results have been reported (Bigland-Ritchie et al., 1983; Moritani et al., 1985). Oda and Kida (2001) investigated the neuromuscular fatigue during maximal concurrent hand grip, elbow extension and flexion in eight physically fit subjects and reported a significant decrease in RMS value in biceps brachii but no changes in the triceps. The median frequency of the EMG signal shows a shift to a lower frequency during sustained maximal voluntary contraction (Kranz et al., 1983). Masuda et al. (1999) investigated the changes in surface EMG parameters during static and dynamic fatiguing contractions. They examined the median frequency of surface EMG in the vastus lateralis of 19 healthy male adults, who performed knee extension both statically and dynamically until they were exhausted. It was reported that the median frequency decreased 22.4 % from its initial value during the static contraction. A similar tendency was observed during the dynamic contraction, in which the median frequency decreased 15.2 % from its initial value.

Most studies of neuromuscular activity and fatigue have evaluated isometric contractions. Isometric contractions may not be representative of muscle activity and fatigue development during human locomotion (Green, 1995). Indeed, available data suggest that the development of fatigue may be specific to contraction type, activity and duration (Tesch et al., 1990; Enoka and Stuart, 1992). Despite this, no study appears to have previously compared neuromuscular fatigue profiles during prolonged exercise such as a soccer game.

To establish the effect of fatigue on muscle activity and co-ordination in soccer, the EMG activity in such movements as sprinting, running, jogging and walking can be used. In the previous chapter, it was shown that muscle strength declines during the course of activity simulating the exercise intensity of a soccer game. Since muscle activity throughout competitive soccer has not been investigated, the present study aimed to analyse muscle activity of the major lower extremity muscles during a simulated soccer game with reference to selected fundamental locomotor movements.

6.2. MATERIAL AND METHODS

6.2.1. Participants

Ten amateur soccer players volunteered to participate in this study. Participants were recruited if they were not injured or rehabilitating from injury at the time of testing and were aged between 19-30 years. Recruitment occurred by word of mouth and by advertisements in various campus and soccer club publications. Informed consent was obtained from all subjects in accordance with the University's ethical procedures before data collection. Ethical approval for the study was obtained from the institution's Human Ethics Committee.

All participants were tested during the 2000-2001 English competitive soccer season. All the tests were scheduled for the same time of day (11:00 hours) to remove the effects of any circadian variation on the variables measured (Reilly and Brooks, 1986). Measurements for each participant were in two categories: anthropometric (height and mass) and EMG activity of major lower limb muscles. The procedures in each category are described in turn. Table 6.2.1 summarises subject characteristics of age, height and mass. Each participant attended the laboratory twice. On the first occasion the fatigue protocol was performed. On the second occasion a control protocol was performed.

Table 6.2.1. Mean (± SD) age, height and mass of amateur soccer players (N = 10).

Variable	Mean	SD
Age (years)	21.40	3.13
Height (m)	1.77	0.06
Mass (kg)	75.5	3.5

6.2.1.1. Anthropometric profiling

Participants' body mass (kg) and height (m) were determined according to the procedure used in Chapter 4.

6.2.1.2. Electromyography

Procedure

All tests were performed on a programmable motorised treadmill (Pulsar, HP Cosmos, Nusrf-Traunstein, Germany) as described in Chapter 5. The EMG activity was recorded and stored using a "biopac" system (MP 100 system, Biopac System INC, Santa Barbara, CA). The EMG data were analysed using the custom-written software. The subjects were prepared for EMG electrode placement by shaving the skin of each electrode site and cleaning it carefully with alcohol wipe and sandpaper to maintain a low inter-electrode resistance of < 2000 Ω. The sampling frequency was set at 2000 Hz. To ensure that movements artifacts were kept to a minimum the electrodes were taped to the skin with elastic surgitape and the cables held in place by means of skin-fitting tights worn by the subjects.

The largest area of each of the muscles was identified during a maximal voluntary isometric effort from the seated and prone position. Two electrodes were placed on the rectus femoris muscle mid-way between the anterior superior iliac spine and the superior border of the patella. For the biceps femoris muscle, two electrodes were located over the long head of biceps femoris, half-way between the ischial tuberosity and lateral femoral epicondyle. For the tibialis anterior muscle, two electrodes were placed over the area of greatest muscle bulk just lateral to the crest of the tibia on the proximal half of the leg. For the gastrocnemius muscle, two electrodes were located on the lateral head over the area of greatest muscle bulk on the lateral calf. Biopac Ag-Ag/CI surface electrodes (Biopac systems INC, Santa Barbara, CA diameter 4 cm) were used for the EMG measurements (Figure 6.2.1). The distance between the centres of the recording electrodes was 4 cm. The four ground (reference) electrodes were positioned approximately on the medial and lateral epicondyle of the femur. The position of the electrodes was not altered during the test protocol. The same investigator performed all tests.

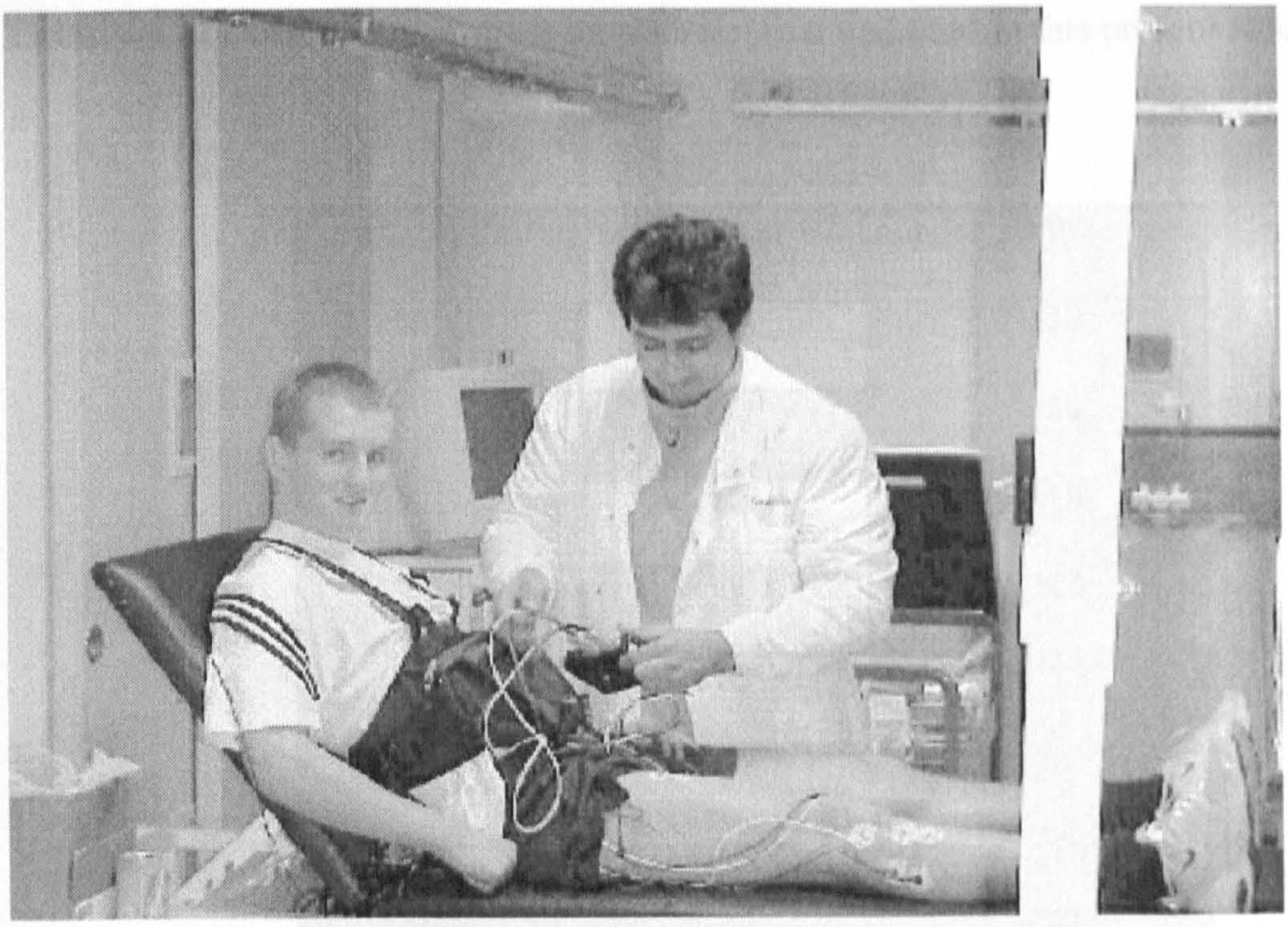


Figure 6.2.1. Preparing subject for perform the protocol .

Test procedure

The EMG activity was recorded three times throughout the test following the measurement protocol in Table 6.2.2. The design consisted of observations made pre-start, half-way and post-exercise which simulated a game of soccer.

Table 6.2.2. The EMG measurement protocol that was used in this present study.

Duration	Speed (km.h^{-1})	Time
00:00	6	01:10
01:10	5	00:20
01:30	12	00:15
01:45	5	00:20
02:05	15	00:15
02:20	5	00:20
02:40	21	00:15
02:55	5	00:05
03:00	STOP	

Each participant performed a warm-up, which included some stretching exercises specific to soccer and running at a slow speed on the treadmill. Then the participant performed the measurement protocol on the treadmill, which included walking (6 km.h^{-1}), jogging (12 km.h^{-1}), running (15 km.h^{-1}) and sprinting (21 km.h^{-1}). The EMG was recorded during performance of that protocol. After the measurement protocol, the subject performed a 45-min soccer-specific intermittent exercise protocol, which consisted of the different exercise intensities that are observed during soccer match-play (Drust et al., 2000a,b) as used in Chapter 5. The EMG activity was recorded for a second time after finishing the first half of the simulation. Finally, the EMG activity was recorded for the third time after finishing the second half of the simulated game (Figure 6.2.2).

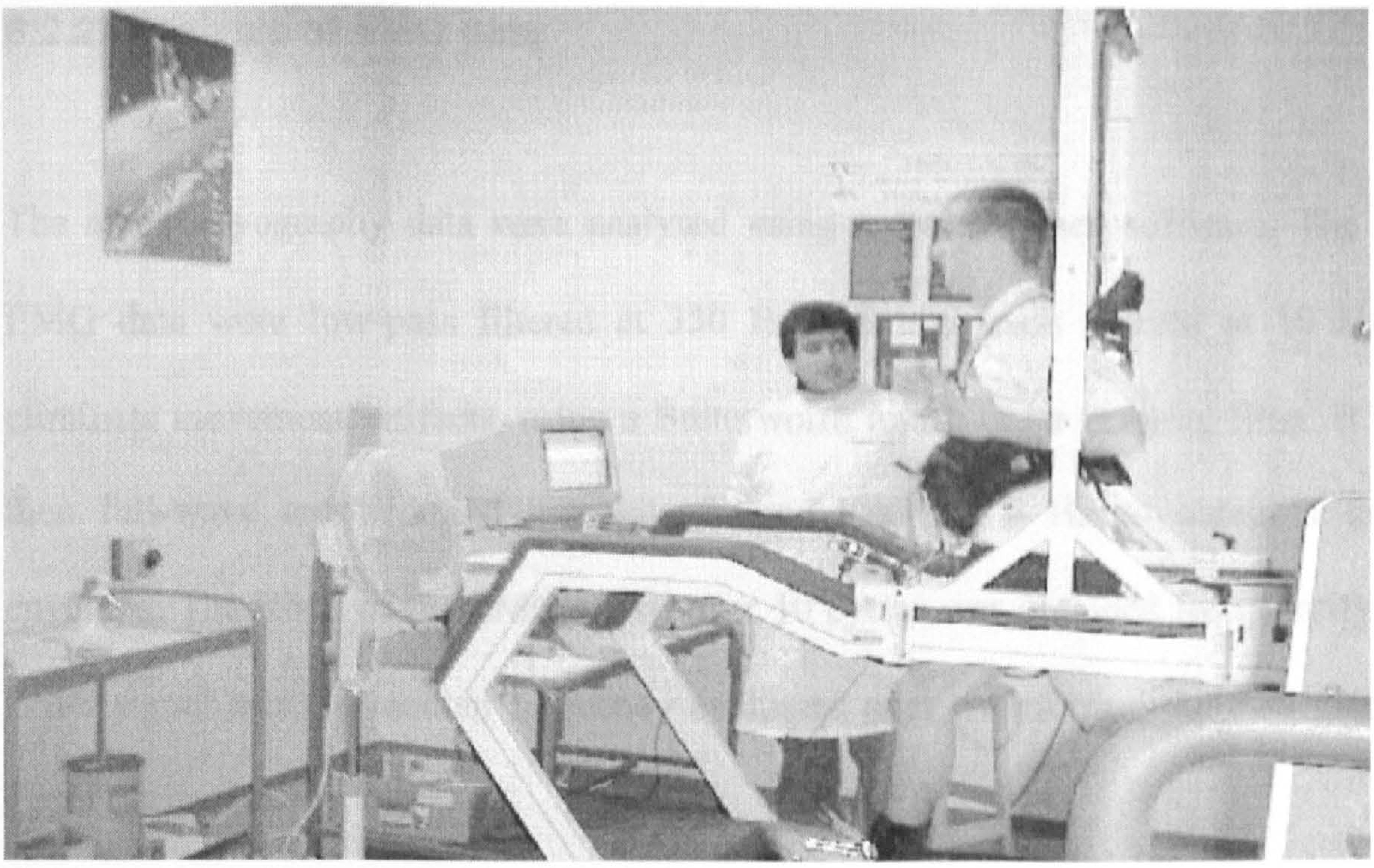


Figure 6.2.2. Recording the subject's EMG activity during the course of the protocol of test.

6.2.1.3. The test procedure for the control group

On the second visit to the laboratory participants performed a control test which consisted of the following:-

1. Warm –up including some specific soccer stretching exercises and running at a slow speed on the treadmill.
2. EMG test
3. 45 minutes rest
4. EMG test
5. 45 minutes rest
6. EMG test.

6.2.2. Analysis of EMG data

The electromyography data were analysed using custom written software. The raw EMG data were low-pass filtered at 350 Hz and high-pass filtered at 10 Hz to eliminate movement artifacts, using a Butterworth fourth-order zero-lag filter. It was then full-wave rectified and low-pass filtered again at 6 Hz to obtain a linear envelope. The RMS of the EMG signal over 10 cycles was obtained for quantify the EMG signal and the median frequency evaluated after transferring the data using a Fast Fourier Transforms.

6.2.3. Statistical analysis (Data analysis)

Analyses of variance (ANOVA) for repeated measures with the Least Significant difference test (LSD) were used where EMG was recorded at three time points (pre-exercise, half-way and post-exercise). The Statistical Package for the Social Sciences (SPSS) and Excel (Windows version 3.1) were used for data analysis. The level of significance on all tests was set at $P < 0.05$.

6.3. RESULTS

The root mean square (RMS) values for the EMG activity per cycle of each muscle [rectus femoris, biceps femoris, tibialis anterior and gastrocnemius] are presented in turn. Each muscle was analysed with a two factor (condition × speed) repeated measure ANOVA. The three conditions were pre-exercise, half-way and post-exercise the simulated game. The 4 speed factors were running at 6 km.h^{-1}, 12 km.h^{-1}, 15 km.h^{-1} and 21 km.h^{-1} on the treadmill.

6.3.1. Experimental group

6.3.1.1. Rectus femoris muscle

A significant main effect was found for condition (using assumed sphericity) ($F_{(2, 18)} = 5.39$, $P < 0.05$). The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\bar{x} = 0.648$ vs 0.594, $P < 0.05$) and between the pre-exercise and post-exercise measures ($\bar{x} = 0.648$ vs 0.587, $P < 005$).

A significant main effect was found for speed (using Greenhouse-Geisser epsilon due to lack of sphericity) ($F_{(1.286, 11.577)} = 106.35$, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 $km.h^{-1}$ speeds ($\bar{x} = 0.214$ vs 0.545 , $P < 0.001$), between the 6 and 15 $km.h^{-1}$ speeds ($\bar{x} = 0.214$ vs 0.682, $P < 0.001$), between the 6 and 21 $km.h^{-1}$ speeds ($\bar{x} = 0.214$ vs 0.997, $P < 0.001$), between the 12 and 15 $km.h^{-1}$ speeds ($\bar{x} = 0.545$ vs 0.682, $P < 0.001$) and between the 15 and 21 $km.h^{-1}$ speeds ($\bar{x} = 0.682$ vs 0.997, $P < 0.001$).

A significant condition × speed interaction was found (using Greenhouse-Geisser epsilon due to lack of sphericity) ($F_{(3.36, 30.25)} = 6.85$, $P < 0.001$). The LSD tests indicated a significant difference between the pre-exercise measures and those obtained after the game ($P < 0.05$) and also between half-way and post-exercise ($P < 0.05$) at 6 and 21 $km.h^{-1}$, 12 and 21 $km.h^{-1}$ and 15 and 21 $km.h^{-1}$ speeds. In effect the data became more divergent with increases in speed and as fatigue developed (Figure 6.3.1).

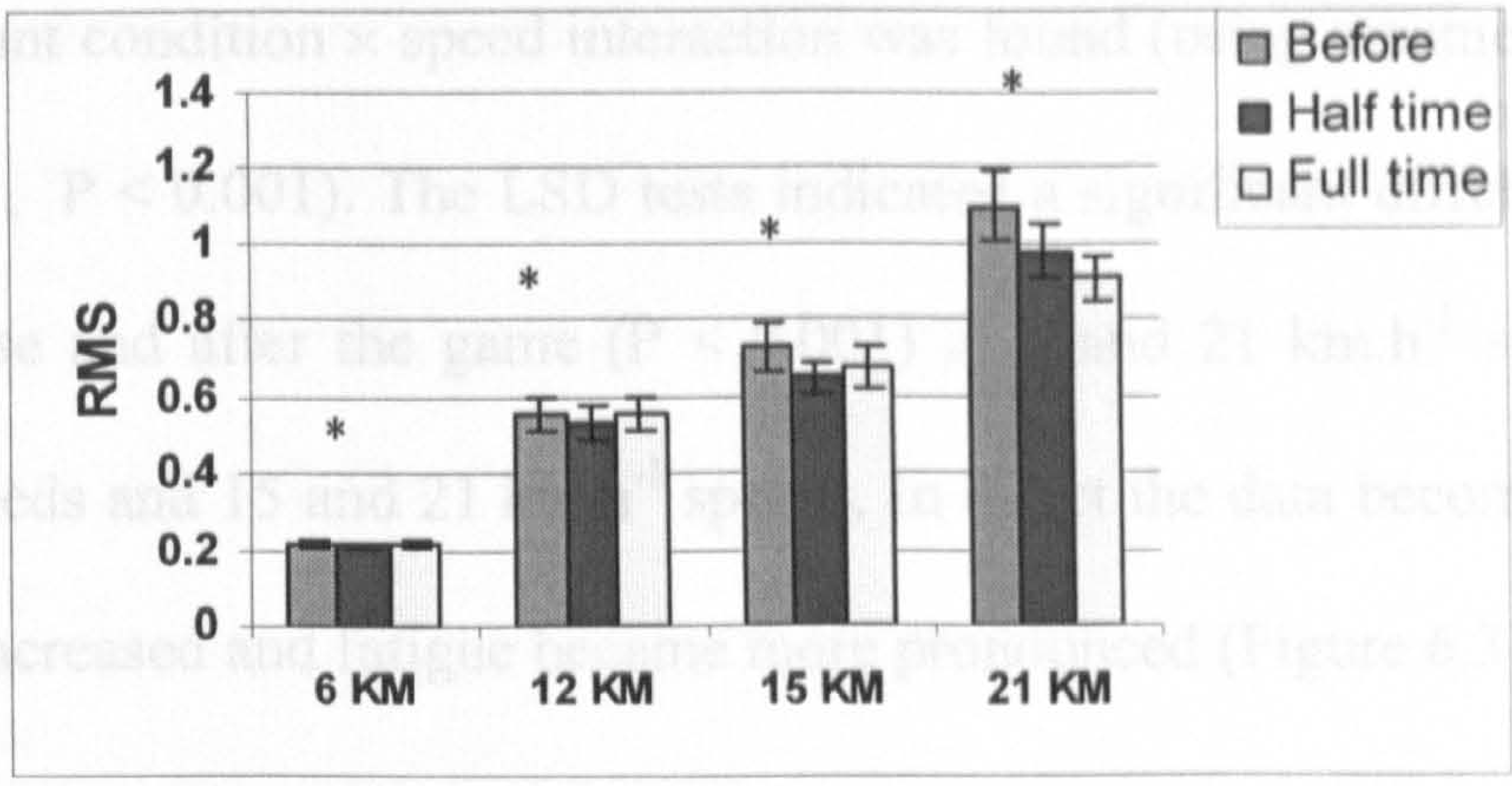


Figure 6.3.1. The mean RMS value of EMG activity for the rectus femoris in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.1.2. Biceps femoris muscle

A significant main effect was found for condition (using assumed sphericity) ($F_{(2, 18)} = 7.57$, $P < 0.01$). The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\bar{x} = 0.559$ vs 0.479 , $P < 0.01$) and between the pre-exercise and post-exercise values ($\bar{x} = 0.559$ vs 0.481, $P < 0.05$).

A significant main effect on the EMG was found for speed (using Greenhouse-Geisser epsilon due to lack of sphericity) ($F_{(1.31,\ 11.79)} = 122.33$, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\bar{x} = 0.184$ vs 0.426, $P < 0.001$), between the 6 and 15 km.h^{-1} speeds ($\bar{x} = 0.184$ vs 0.552, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\bar{x} = 0.184$ vs 0.863, $P < 0.001$), between the 12 and 15 km.h^{-1} speeds ($\bar{x} = 0.426$ vs 0.552, $P < 0.001$) and between the 15 and 21 km.h^{-1} speeds ($\bar{x} = 0.552$ vs 0.863, $P < 0.001$).

A significant condition × speed interaction was found (using assumed sphericity) ($F_{(6, 54)} = 10.81$, $P < 0.001$). The LSD tests indicated a significant difference between the pre-exercise and after the game ($P < 0.001$) in 6 and 21 km.h^{-1} speeds, 12 and 21 km.h^{-1} speeds and 15 and 21 km.h^{-1} speeds. In effect the data become more divergent as speed increased and fatigue became more pronounced (Figure 6.3.2).

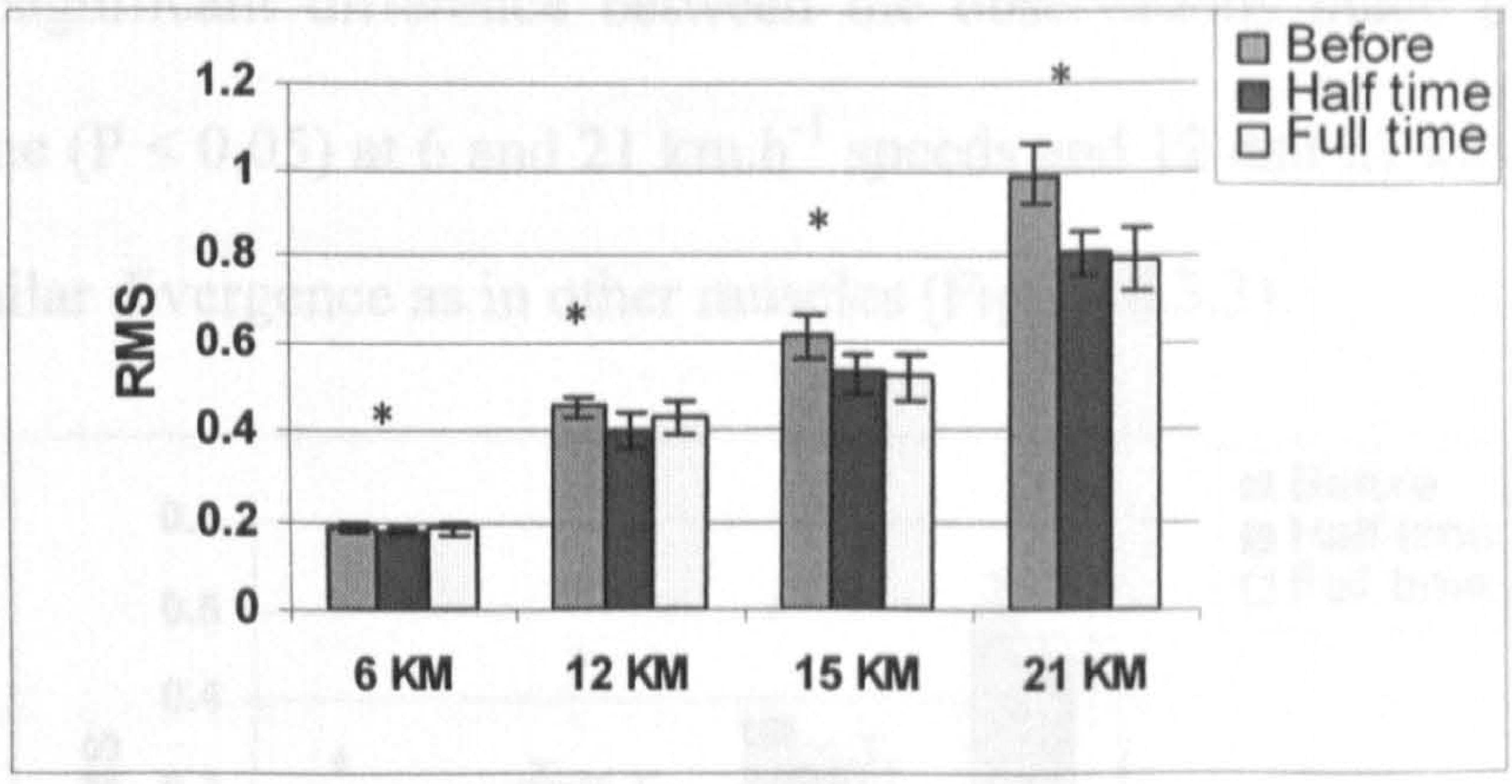


Figure 6.3.2. The mean RMS value of EMG activity for the biceps femoris in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.1.3. Tibialis anterior muscle

A significant main effect on RMS was found for condition (using assumed sphericity) ($F_{(2, 18)} = 4.27$, $P < 0.05$). The LSD tests indicated a significant difference between the pre-exercise and post-exercise measures ($\bar{x} = 0.348$ vs 0.316, $P < 0.05$).

A significant main effect was found for speed (using Greenhouse-Geisser epsilon due to lack of sphericity)($F_{(1.53, 13.79)} = 101.09$, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\bar{x} = 0.202$ vs 0.297 , P <

0.001), between the 6 and 15 km.h^{-1} speeds ($\bar{x}$ = 0.202 vs 0.346, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\bar{x}$ = 0.202 vs 0.464, $P < 0.001$), between the 12 and 15 km.h^{-1} speeds ($\bar{x}$ = 0.297 vs 0.346, $P < 0.001$) and between the 15 and 21 km.h^{-1} speeds ($\bar{x}$ = 0.346 vs 0.464, $P < 0.001$).

A significant condition × speed interaction was found (using Greenhouse-Geisser epsilon due to lack of sphericity) ($F_{(2.60,\ 23.41)} = 3.53$, $P < 0.05$). The LSD tests indicated a significant difference between the observations made pre-exercise and after the game ($P < 0.05$) at 6 and 21 km.h^{-1} speeds and 12 and 21 km.h^{-1} speeds, also showing similar divergence as in other muscles (Figure 6.3.3).

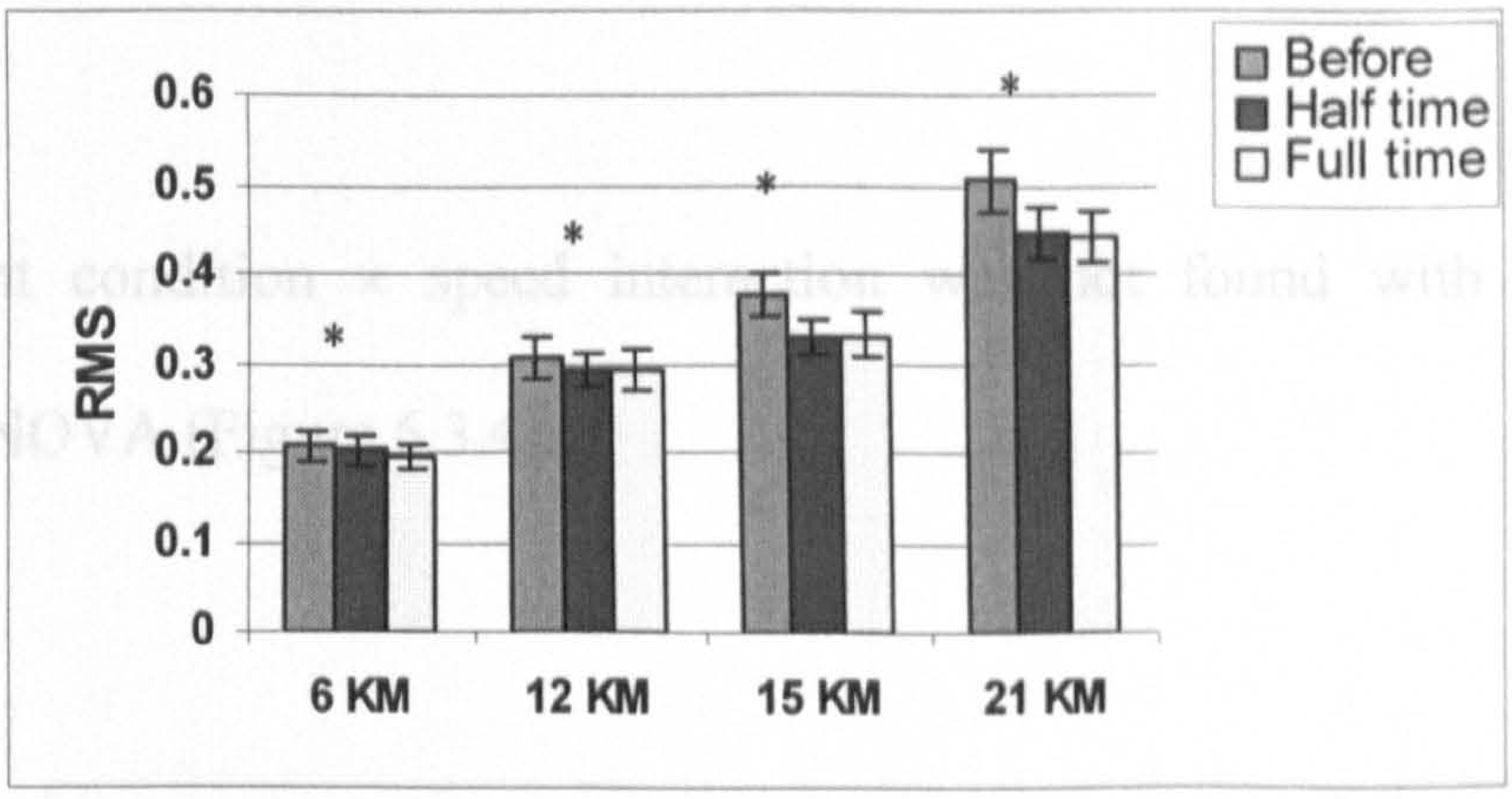


Figure 6.3.3. The mean RMS value of EMG activity for the tibialis anterior in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.4. Gastrocnemius muscle

A significant main effect was not found for condition with using repeated measures ANOVA .

A significant main effect was found for speed (using assumed sphericity) ($F_{(3, 27)}$ = 51.93, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\bar{x}$ = 0.266 vs 0.488, $P < 0.001$), between the 6 and 15 km.h^{-1} speeds ($\bar{x}$ = 0.266 vs 0.511, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\bar{x}$ = 0.266 vs 0.641, $P < 0.001$), and between the 15 and 21 km.h^{-1} speeds ($\bar{x}$ = 0.511 vs 0.641, $P < 0.001$).

A significant condition × speed interaction was not found with using repeated measures ANOVA (Figure 6.3.4).

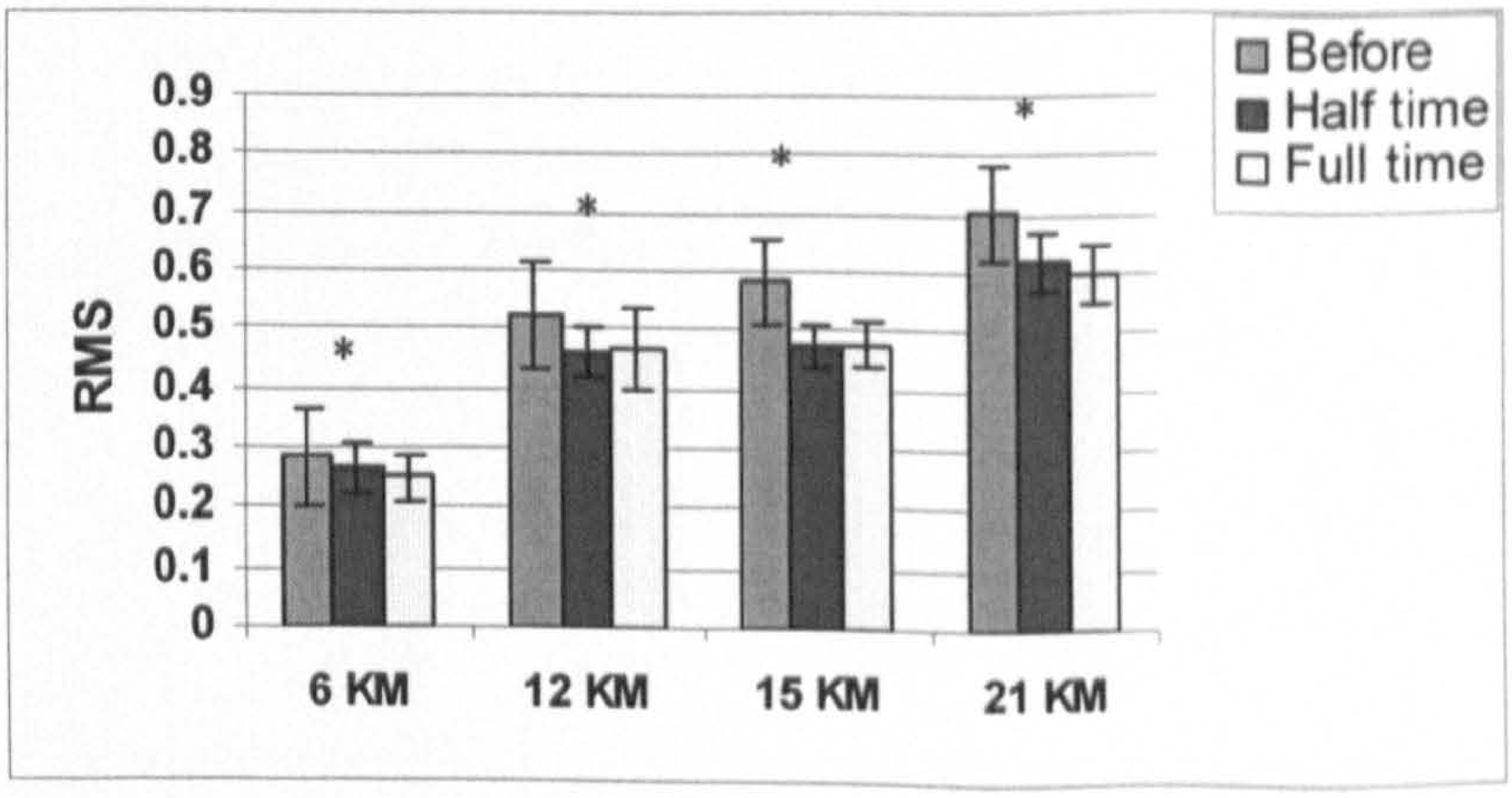


Figure 6.3.4. The mean RMS value of EMG activity for the gastrocnemius in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.2. Control Group

The root mean square (RMS) values for the EMG activity of each muscle [rectus femoris, biceps femoris, tibialis anterior and gastrocnemius] are presented in turn. Each muscle was analysed with a two factor (condition × speed) repeated measures ANOVA. The three condition factors were pre-exercise, half-way and post-exercise the simulated game. The four speed factors were running at 6 $km.h^{-1}$, 12 $km.h^{-1}$, 15 $km.h^{-1}$ and 21 $km.h^{-1}$ on a treadmill.

6.3.2.1. Rectus femoris muscle

A significant main effect was not found for condition with using repeated measure ANOVA.

A significant main effect was found for speed (using Greenhouse-Geisser epsilon due to lack of sphericity) ($F_{(1.371,\ 12.341)} = 83.51$, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\bar{x} = 0.205$ vs 0.514, $P < 0.001$), between the 6 and 15 km.h^{-1} speeds ($\bar{x} = 0.205$ vs 0.661, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\bar{x} = 0.205$ vs 0.980, $P < 0.001$), between the 12 and 15 km.h^{-1} speeds ($\bar{x} = 0.514$ vs 0.661, $P < 0.001$) and between the 15 and 21 km.h^{-1} speeds ($\bar{x} = 0.661$ vs 0.980, $P < 0.001$).

A significant condition × speed interaction was not found with using repeated measures ANOVA (Figure 6.3.5).

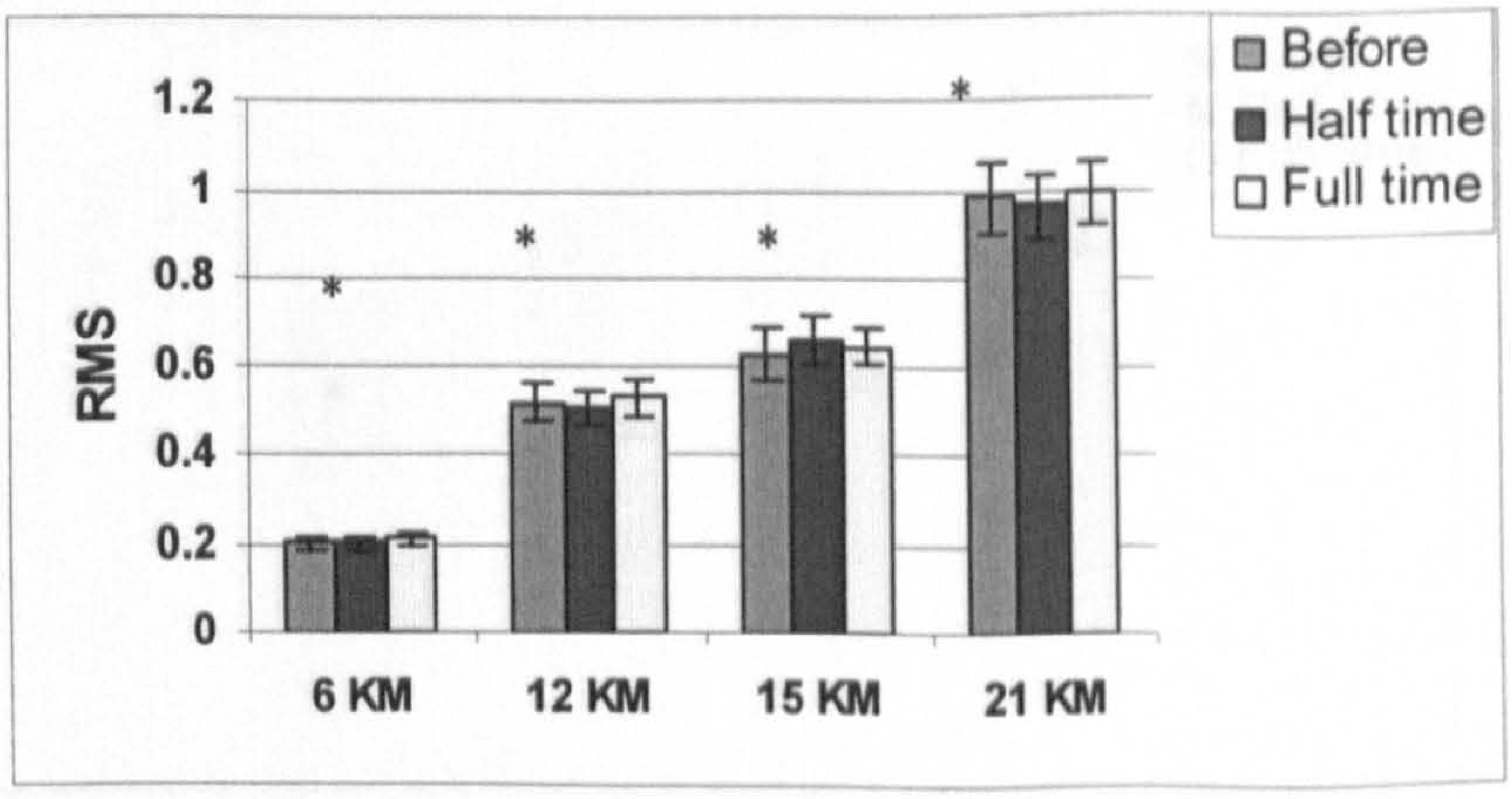


Figure 6.3.5. The mean RMS value of EMG activity for the rectus femoris in different conditions and speed for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.2.2. Biceps femoris muscle

A significant main effect was not found for condition with using repeated measure ANOVA.

A significant main effect was found for speed (using Greenhouse-Geisser epsilon due to lack of sphericity) ($F_{(1.334,\ 12)} = 80.82$, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\bar{x} = 0.192$ vs 0.470, $P < 0.001$), between the 6 and 15 km.h^{-1} speeds ($\bar{x} = 0.192$ vs 0.593, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\bar{x} = 0.192$ vs 0.938, $P < 0.001$), between the 12 and 15 km.h^{-1} speeds ($\bar{x} = 0.470$ vs 0.593, $P < 0.001$) and between the 15 and 21 km.h^{-1} speeds ($\bar{x} = 0.593$ vs 0.938, $P < 0.001$).

A significant condition × speed interaction was not found with using repeated measures ANOVA (Figure 6.3.6).

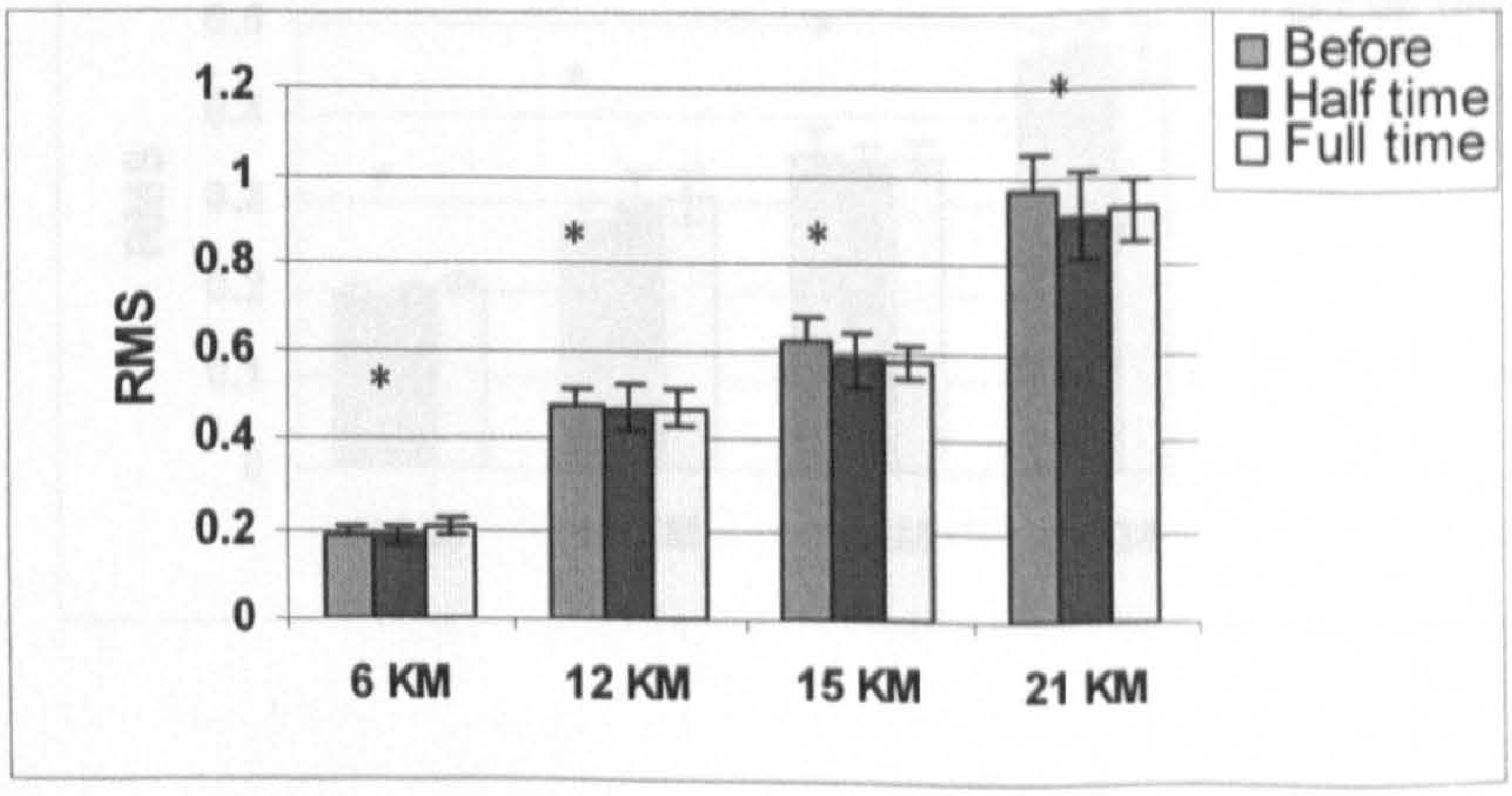


Figure 6.3.6. The mean RMS value of EMG activity for the biceps femoris in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.2.3. Tibialis anterior muscle

A significant main effect was not found for condition with using repeated measure ANOVA.

A significant main effect on RMS was found for speed (using assumed sphericity)($F_{(3, 27)} = 71.19$, $P < 0.001$). The LSD tests indicated a significant difference between 6 and 12 km.h^{-1} speeds ($\overline{x} = 0.202$ vs 0.298, $P < 0.001$), between the 6 and 15 km.h^{-1} speeds ($\overline{x} = 0.202$ vs 0 .354, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\overline{x} = 0.202$ vs 0.470, $P < 0.001$), between the 12 and 15 km.h^{-1} speeds ($\overline{x} = 0.298$ vs 0.354, $P < 0.001$) and between the 15 and 21 km.h^{-1} speeds ($\overline{x} = 0.354$ vs 0.470, $P < 0.001$).

A significant condition × speed interaction was not found with using repeated measures ANOVA (Figure 6.3.7).

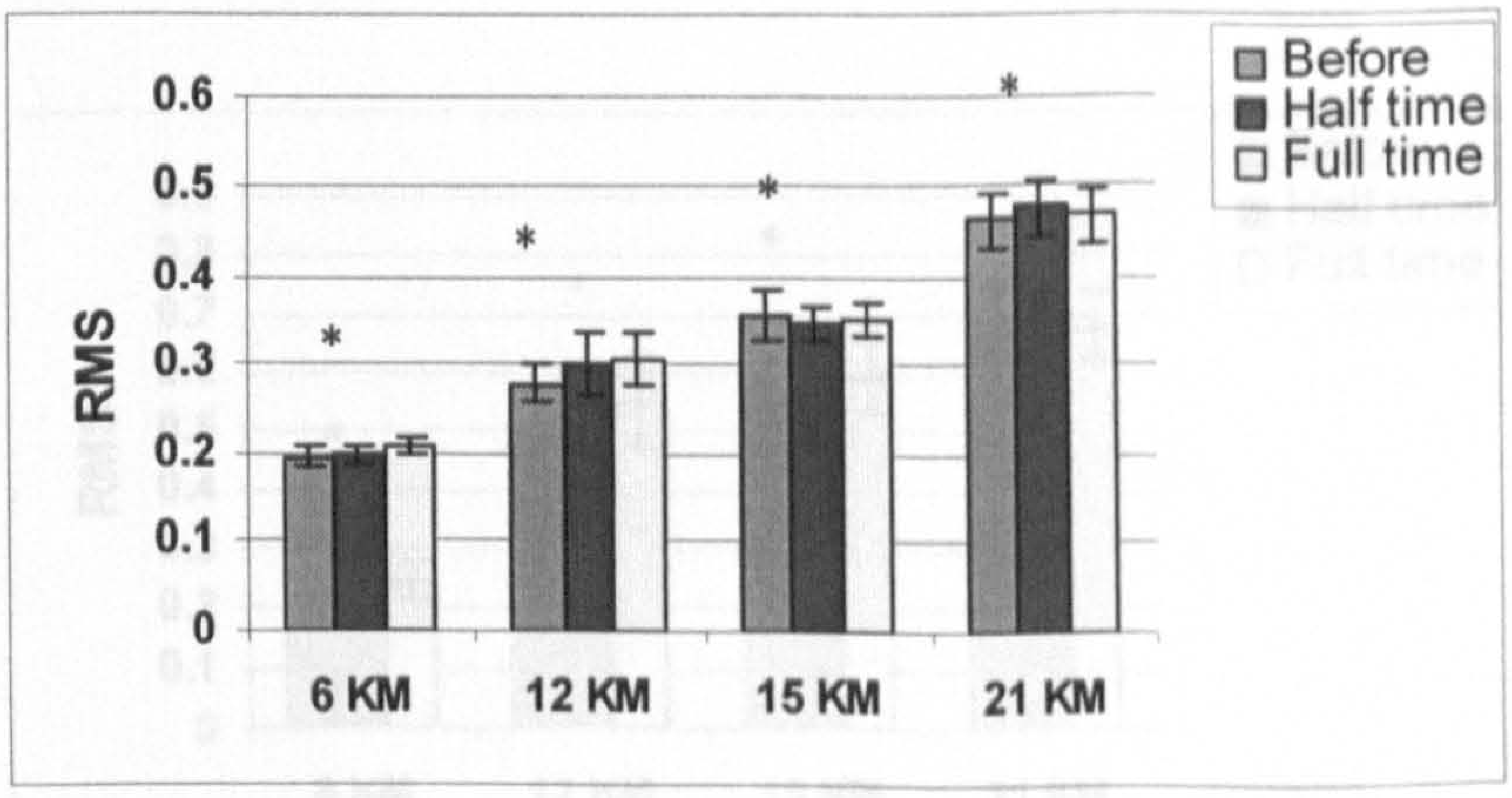


Figure 6.3.7. The mean RMS value of EMG activity for the tibialis anterior in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.2.4. Gastrocnemius muscle

A significant main effect on RMS was not found for condition with using repeated measures ANOVA.

A significant main effect was found for speed (using assumed sphericity) ($F_{(1.330,\ 11.967)} = 57.24$, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\overline{x} = 0.253$ vs 0.536 , $P < 0.001$), between the 6 and 15 km.h^{-1} speeds ($\overline{x} = 0.253$ vs 0.597, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\overline{x} = 0.253$ vs 0.694, $P < 0.001$), between the 12 and 15 km speeds ($\overline{x} = 0.536$ vs 0.597, $P < 0.01$) and between the 15 and 21 km.h^{-1} speeds ($\overline{x} = 0.597$ vs 0.694, $P < 0.001$).

A significant condition × speed interaction was not found with using repeated measures ANOVA (Figure 6.3.8).

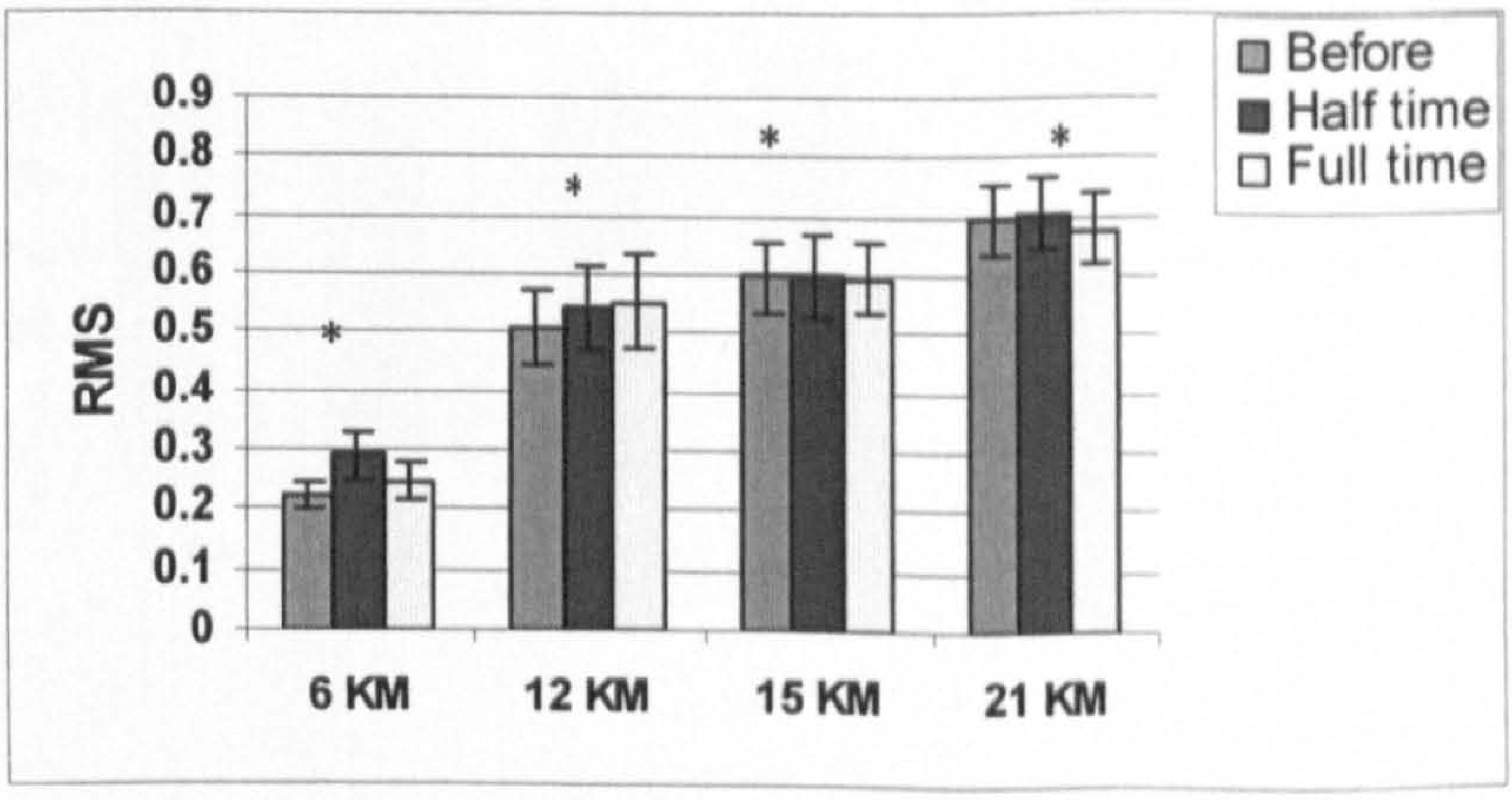


Figure 6.3.8. The mean RMS value of EMG activity for the gastrocnemius muscle in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.3. Median frequency

The median frequency values for the EMG activity of each muscle (rectus femoris, biceps femoris, tibialis anterior and gastrocnemius) are presented in turn. Each muscle was analysed with a two factor (condition × speed) repeated measure ANOVA. The three conditions were pre-exercise, half-way and after the simulated game. The 4 speed factors were running at 6 $km.h^{-1}$, 12 $km.h^{-1}$, 15 $km.h^{-1}$ and 21 $km.h^{-1}$ on a treadmill.

6.3. 3.1. Rectus femoris muscle

A significant main effect was not found for condition with using repeated measures ANOVA.

A significant main effect was found for speed (using assumed sphericity) ($F_{(3,\ 30)}$ =5.84, P < 0.01). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\overline{x}$ = 24.76 vs 26.95, P < 0.05), between the 6 and 21 km.h^{-1} speeds ($\overline{x}$ = 24.76 vs 28, P < 0.01), and between the 15 and 21 km.h^{-1} speeds ($\overline{x}$ = 26.33 vs 28, P < 0.05).

A significant condition × speed interaction was not found with using repeated measures ANOVA (Figure 6.3.9).

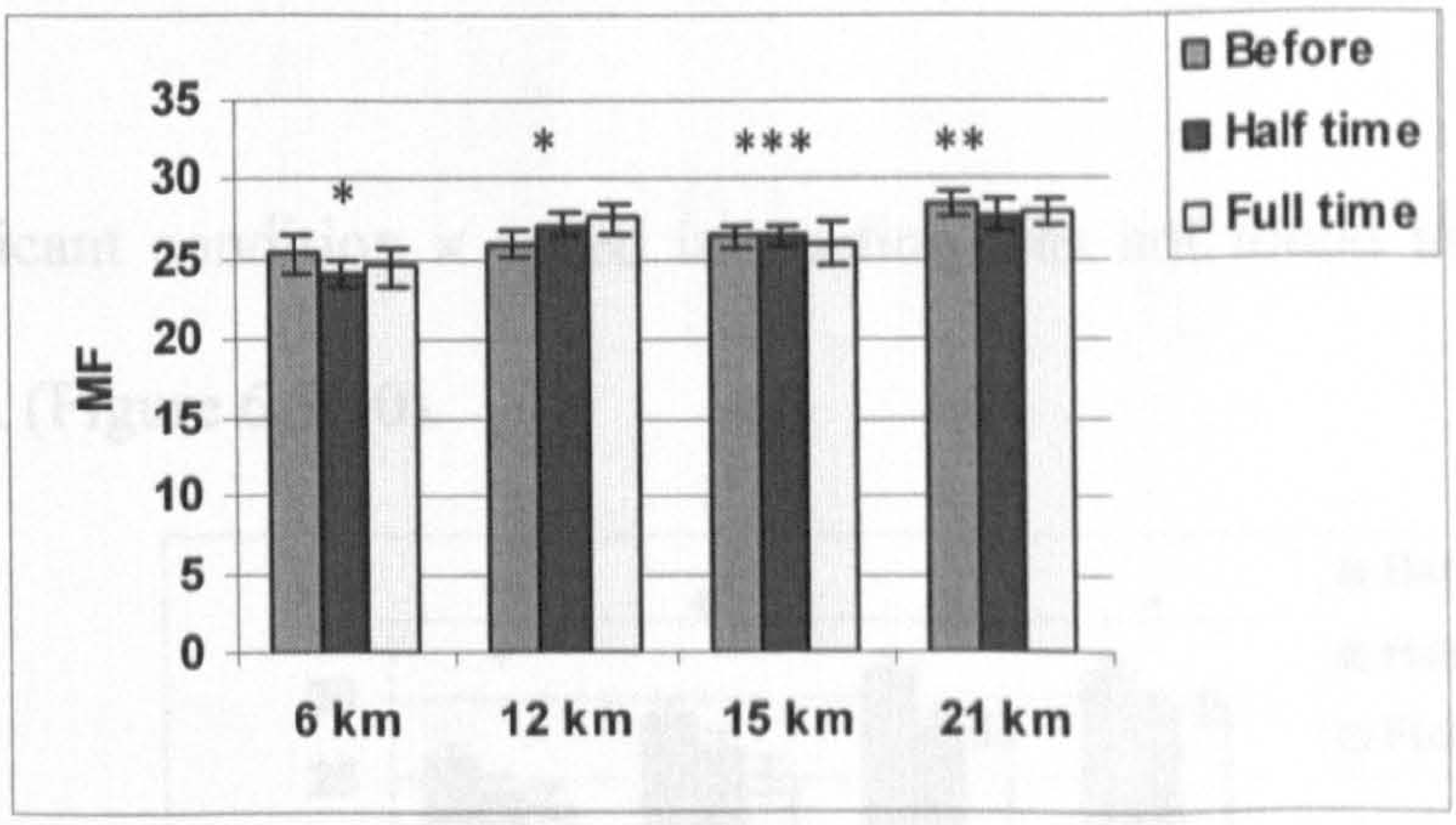


Figure 6.3.9. The MF value of EMG activity for the rectus femoris in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between the 6 and 12 km.h^{-1} speeds

** denote significant differences between the 6 and 21 km.h^{-1} speeds

*** denote significant differences between the 15 and 21 km.h^{-1} speeds

6.3.3.2. Biceps femoris muscle

A significant main effect was found for condition (using assumed sphericity) ($F_{(2, 20)} = 5.30$, $P < 0.05$). The LSD tests indicated a significant difference between the pre-exercise and half-way measures ($\bar{X} = 29.68$ vs 27.20, $P < 0.05$) and between the pre-exercise and post-exercise measures ($\bar{X} = 29.68$ vs 26.5, $P < 0.05$).

A significant main effect was found for speed (using assumed sphericity) ($F_{(3, 30)} = 17.4$, $P < 0.001$). The LSD tests indicated a significant difference between the 6 and 12 km.h^{-1} speeds ($\bar{X} = 24.6$ vs 27 , $P < 0.001$), between the 6 and 15 km.h^{-1} speeds ($\bar{X} = 24.6$ vs 29.35, $P < 0.001$), between the 6 and 21 km.h^{-1} speeds ($\bar{X} = 24.6$ vs 30.12, $P < 0.001$), between the 12 and 15 km.h^{-1} speeds ($\bar{X} = 27.10$ vs 29.35, $P < 0.05$).

A significant condition × speed interaction was not found using repeated measures ANOVA (Figure 6.3.10).

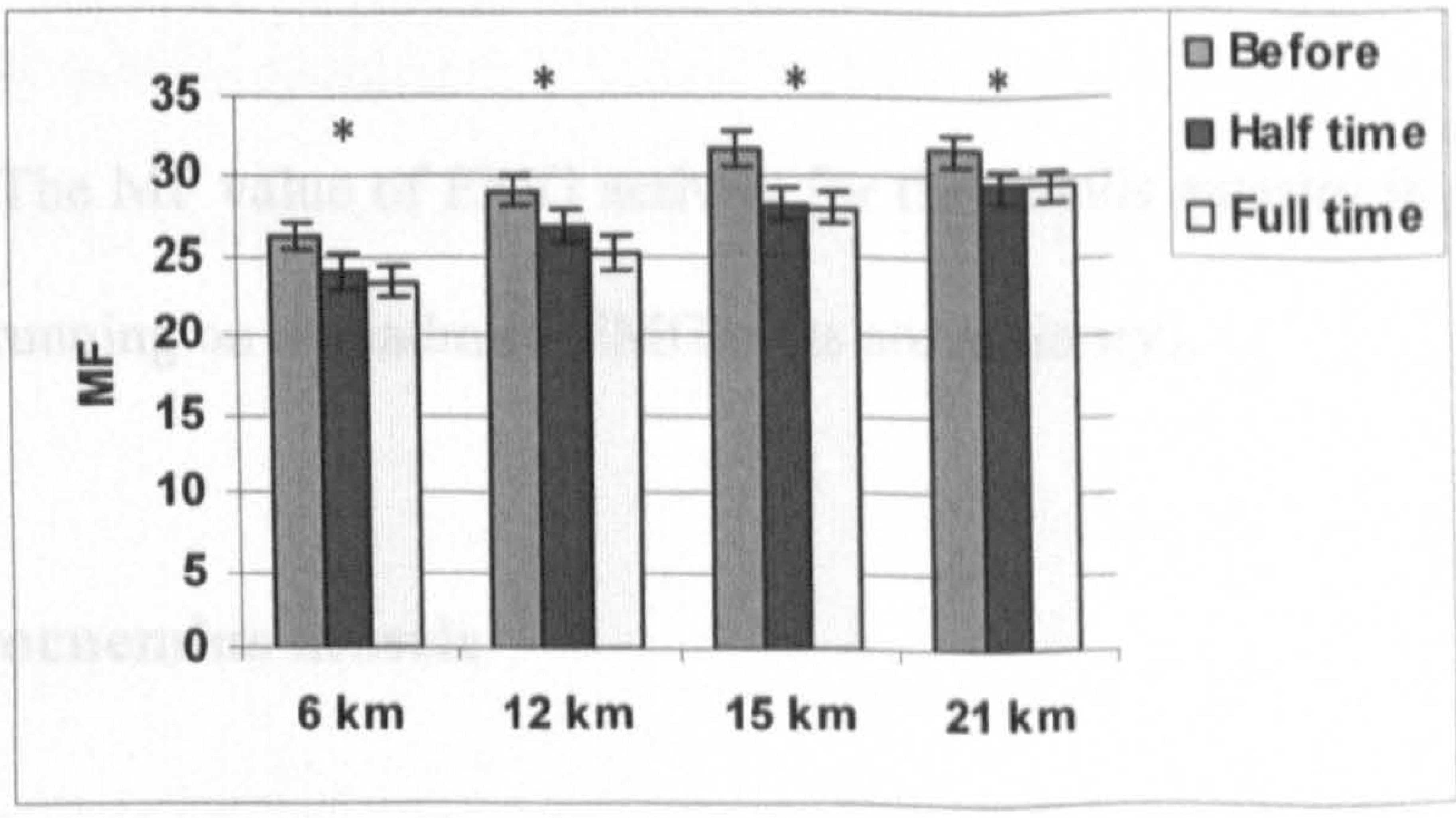


Figure 6.3.10. The MF value of EMG activity for the biceps femoris in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between all speeds

6.3.3.3. Tibialis anterior muscle

A significant main effect was not found for condition using repeated measures ANOVA.

A significant main effect was not found for speed using repeated measures ANOVA.

A significant condition × speed interaction was not found using repeated measures ANOVA (Figure 6.3.11).

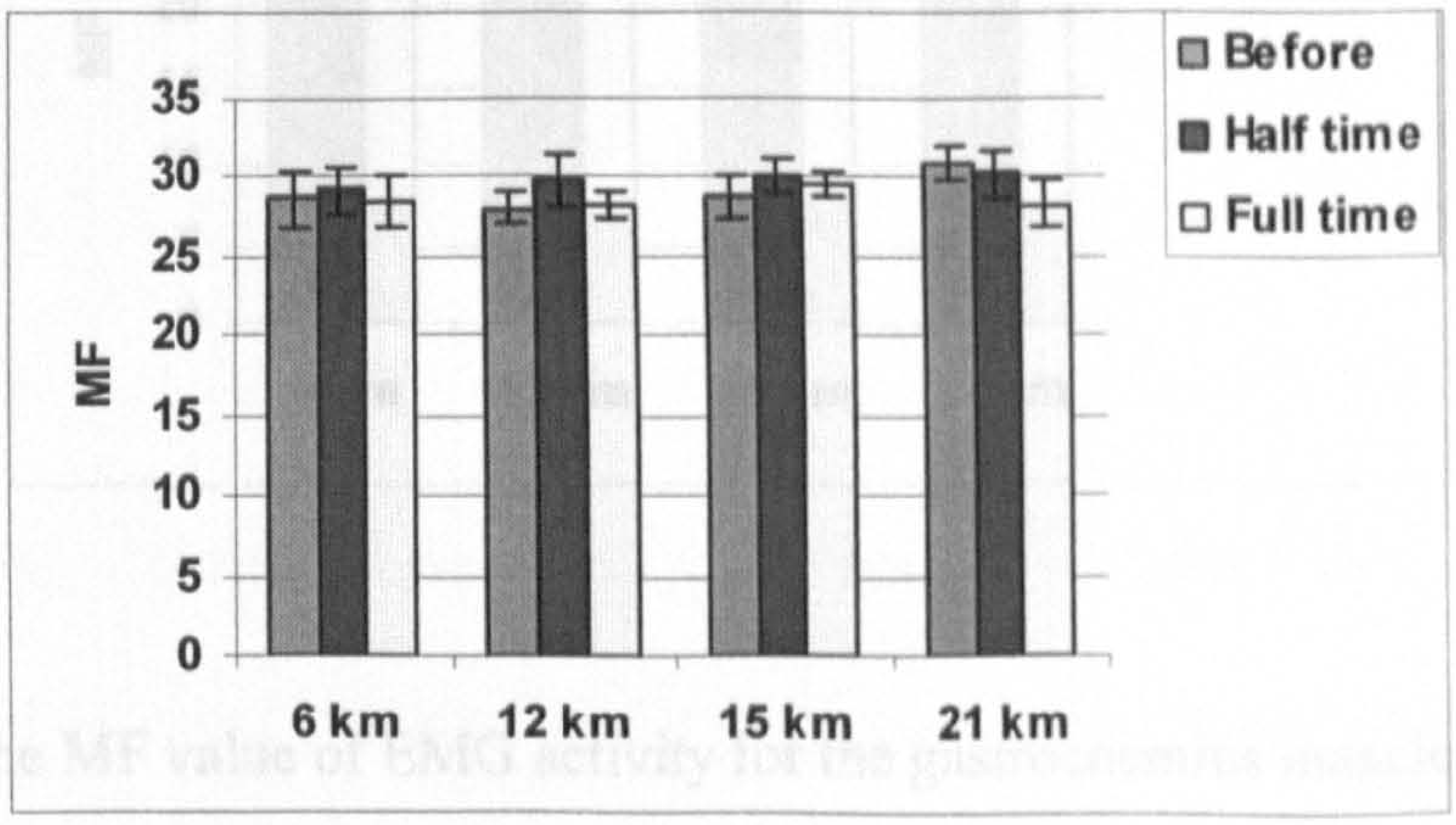


Figure 6.3.11. The MF value of EMG activity for the tibialis anterior in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

6.3.3.4. Gastrocnemius muscle

A significant main effect was found for condition (using assumed sphericity) ($F_{(2, 20)} = 7.75$, $P < 0.01$). The LSD tests indicated a significant difference between the pre-exercise and post-exercise measures ($\bar{x} = 29.13$ vs 25.84, $P < 0.01$) and between the half-way and post-exercise measures ($\bar{x} = 28.88$ vs 25.84, $P < 0.05$).

A significant main effect was found for speed (using assumed sphericity) ($F_{(3, 27)} = 51.93$, $P < 0.001$). The LSD tests indicated a significant difference between the 15 and 21 km.h^{-1} speeds ($\bar{x} = 27.16$ vs 29, $P < 0.05$).

A significant condition × speed interaction was not found using repeated measures ANOVA (Figure 6.3.12).

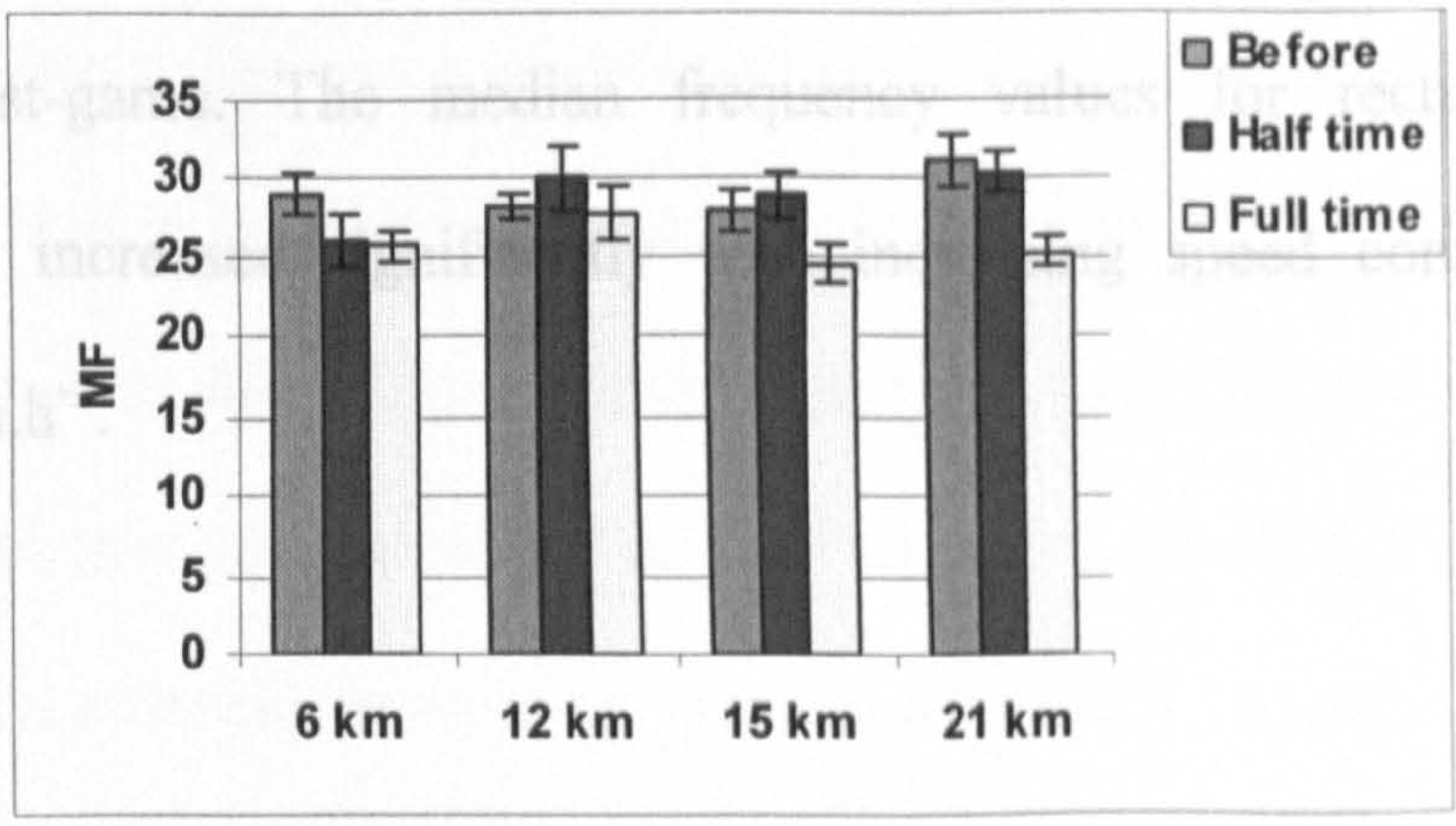


Figure 6.3.12. The MF value of EMG activity for the gastrocnemius muscle in different conditions and speeds for running on a treadmill (EMG units are arbitrary).

* denote significant differences between the 15 and 21 km.h^{-1} speeds.

6.4. Discussion

The purpose of this study was to establish the effect of fatigue on the activity of major lower limb muscles at different speeds running representing a selected fundamental movement appropriate to soccer. In general, the RMS values for rectus femoris, biceps femoris and tibialis anterior significantly decreased as the fatigue protocol progressed. The RMS values for rectus femoris, biceps femoris, tibialis anterior and gastrocnemius increased with increasing speed continually from 6 km.h^{-1} to 21 km.h^{-1}.

The median frequency values for biceps femoris and gastrocnemius were greater pre-game than post-game. The median frequency values for rectus femoris and gastrocnemious increased significantly with increasing speed continually from 6 km.h^{-1} to 21 km.h^{-1}.

Fatigue – RMS

- *Condition:* In the present study, the results indicated that the RMS values decreased as the simulated game progressed. The values for rectus femoris, biceps femoris, and tibialis anterior were greater pre-game than at half-way and greater at half-way than post-game. These findings showed that fatigue has an effect on muscle activity and is likely to be the cause of reduced activity during exercise. The decline in muscle torque during repeated isokinetic efforts has been investigated broadly (Barnes, 1981; Gray and Chandler, 1989; Tesch et al., 1990). This decline in muscle torque has been recognized to be related to both contractile failures (Tesch et al., 1990) and the availability of energy sources within the muscle (Kellis and Baltzopoulos, 1995). Although the studies are fewer in number, changes in EMG activity have also been monitored during repeated dynamic muscular contractions in order to express the effects of fatigue on maximum strength output (Komi and Tesch, 1979; Oberg, 1995; Potvin and Bent, 1997). Previous studies have shown that during exhaustive, repetitive exercise, the power spectrum of the EMG signal and median frequency shifts toward the lower band, which is thought to be caused by a decrease in conduction velocity within muscle fibres during sustained fatiguing contractions (Ament et al, 1993; Potvin and Bent, 1997; Masuda et al., 1999), and the amplitude of the EMG increases (Oberg, 1995; Kellis, 1999; Masuda et al., 1999). The present results (decreases in RMS values as the game progresses) are in agreement with work of Oda and Kida (2001), who found a significant decrease in RMS values of the biceps brachii muscle following maximal concurrent hand grip and elbow extension. This finding is in contrast to work of Psek and Cafarelli (1993), who reported a close relationship between agonist and antagonist increases in EMG activity as a result of fatiguing muscular contractions. Furthermore, the results of this study are contrary to the work of Miller et al. (2000), who found no significant differences in RMS activity as the repetitions progressed for any of the quadriceps and hamstring muscles tested. In addition to these, Yeung et al. (1999) reported an increase in the root mean square in M. vastus medialis following the 30 maximal voluntary isometric contractions.

The contradictory results of the present study and that of Oda and Kida (2001), along with the research of Psek and Cafarelli (1993), Yeung et al. (1999) and Miller et al. (2000) can be attributed to two major differences. First, there were differences in the test protocol. For example, our study involved 90 minutes of intermittent exercise, whereas Psek and Cafarelli (1993) used 3-s contractions at 70 % of maximal effort, with 7-s rest intervals between each contraction, and Yeung et al. (1999) used 30 isometric maximal voluntary contractions while Miller et al. (2000) used 30 continuous extension-flexion maximal efforts. Secondly, there were major differences in the types of movements performed: Psek and Cafarelli (1993) evaluated coactivation patterns during static contractions whereas in this study the EMG activity was evaluated during a 90-min of a soccer simulation game. It is commonly accepted that there are significant differences in mechanisms of torque development and muscle activation between isometric and concentric muscular contractions (Kellis, 1999).

- *Speed:* In the present study, the results indicated that the RMS values for rectus femoris, biceps femoris, tibialis anterior and gastrocnemius, were increased with increasing speed from 6 $km.h^{-1}$ to 21 $km.h^{-1}$. This finding is in agreement with work of Nilsson et al. (1985) who studied the effect of running velocity on EMG. They reported that in absolute terms, the duration of the signal was inversely proportional to velocity, but, in relative terms, muscles were active for a greater percentage of a gait cycle at the higher velocities. In addition, they tended to become active earlier in the cycle. An example of this was the action of the hamstrings in late swing. As the shank velocity increased with increasing running speeds, activity in the hamstrings was required earlier to decelerate the leg effectively. At times these increased demands resulted in an extra burst of activity that was not present at the slower speeds. Vastus medialis and vastus lateralis were normally quiescent in late swing; however, at the faster running speeds they exhibited a burst of activity during this time. Finally, it appears that velocity can also affect the relative magnitudes of activity. This point is demonstrated in rectus femoris as the bursts during the early swing are larger than that during support. It is expected that with increasing running speed, muscle activity will increase.

Fatigue – Median frequency

- *Condition:* Relative to median frequency activity with fatiguing contractions, different patterns of activity were observed among the muscles tested. The biceps femoris and gastrocnemious displayed a decrease in median frequency, whereas the rectus femoris and tibialis anterior displayed no changes in median frequency. These decreased median frequency levels would be indicative of fatigue in the muscle and would be in agreement with the RMS results observed. The present results are in agreement with the previous research such as the work of Masuda et al. (1999), Miller et al. (2000) and Linnamo et al. (2000) who reported similar declines in median frequency values following exhaustive static and dynamic knee contractions. The changes in the EMG activity have also been monitored during consecutive dynamic muscular contractions as a way to describe the effects of fatigue on maximum strength production (Komi and Tesch, 1979; Oberg, 1995; Potvin and Bent, 1997). In summary, the power spectrum of the EMG signal and median frequency shifted toward the lower band, which is thought to be caused by a decrease in muscle fibre conduction velocity during sustained fatiguing contractions (Ament et al., 1993; Potvin and Bent, 1997; Masuda et al., 1999).

- *Speed:* With regard to the median frequency activity, the results indicated that the median frequency values for rectus femoris and gastrocnemious, increased with increasing speed from 6 km.h^{-1} to 21 km.h^{-1}, whereas the tibialis anterior and biceps femoris tended to remain similar. This is in agreement with work of Nilsson et al. (1985) who investigated the changes in EMG with running speed and reported a linear increase in the EMG with increasing speed.

In conclusion, the results indicate that the EMG activity in the major lower-limb muscles was greater before than after a simulated game. Fatigue was reflected in the electrical activity of the active muscle and is likely to be the cause of the reduced strength during prolonged exercise, which was reflected in the reduced work-rate in soccer. The RMS values increased with increasing speed of running on a treadmill, which indicated that greater muscle activity is required to run at higher speeds. The median frequency also decreased as the fatiguing protocol progressed but it increased with increasing speed. As data presented in Chapter 5 showed, muscle strength decreased during and especially towards the end of the game due to fatigue. The hamstring to quadriceps ratio also decreased, and may be a factor in injury. Therefore, it can be suggested that the decreases in force are related to a reduction of neural activation of muscle, and leads to a decrease in muscle performance. The significant decrease in median frequency of biceps femoris may be due to a greater strength loss in this muscle than in the quadriceps as shown in Chapter 5.

CHAPTER SEVEN

GENERAL DISCUSSION

7. 1. SYNTHESIS OF FINDINGS

The studies described in the present thesis were designed to identify the effects of fatigue, typical of a soccer game, on selected extrinsic and intrinsic risk factors related to soccer injuries. Four main investigations were included in this thesis.

In Chapter 3 the injury risk associated with playing actions during competitive soccer were studied. A hand and a computerised notation analysis system were both employed as the injury risk of soccer playing actions were examined by making relevant observations during match-play. No data were previously available regarding the injury risk associated with types of playing action, periods of the game, zones of the pitch, and playing either at home or away in soccer. The results, based upon 10 English Premier games, indicated that an average 1788 events (one every three seconds), 767 events with injury risk (one every six seconds), and 2 injuries per game were recorded. An overall injury incidence of 53 per 1000 playing hours was calculated. Receiving a tackle, receiving a "charge" and making a tackle were categorised as having a substantial injury risk, while goal catch, goal punch, kicking the ball, shot on goal, set kick and heading the ball were all categorised having a significant injury risk. All other actions were deemed low in risk. The first 15 min of each half had the highest number of actions with mild injury potential, because the contest is arguably at its most intense in the initial period of play, compared with later in the game, and the players are fresh and more energetic and wish to "register their presence" with the opposition. The closing 15 minutes of the game had the most frequent actions with moderate injury risk. This may be the result of a fatigue effect on the muscles and other body organs as muscle glycogen stores near depletion (Saltin, 1973) and players become hypohydrated

(Reilly, 1997). At this stage of the game the players are tired but the outcome of contest may still be undetermined. The consequence may be that predisposition to injury is exposed as fatigue sets in or damage incurred earlier in the game becomes more evident as play is sustained. The major conclusions from this study were firstly that playing actions with high injury risk were linked to contesting possession, while other actions had relatively low injury risk. Secondly, injury risk was highest in both the first and last 15-min periods of the game, reflecting the intense engagements in the opening period and the possible effect of fatigue in the closing period.

A practical implication from the injury risk assessment is that since some actions have a higher injury risk than others, more attention should be paid to these by the coach when supervising training, by the referee when judging a match, and by players who may also need to practise avoidance manoeuvres to protect themselves in such instances. Furthermore, more attention should be paid by game officials and players (and the team's medical staff) to the first and last periods of the game if actions including some risk of injury are not to lead to actual injury.

In addition to this investigation which identified effects of fatigue on selected extrinsic risk factors (Chapter 3), further studies were conducted to determine the effects of fatigue on intrinsic risk factors. Firstly a reference database for isokinetic strength was established (Chapter 4) and then the effects of a soccer-game simulation as a fatigue task on muscle strength, and muscle balance (chapter 5) and muscle activation and co-activation (chapter 6) were investigated.

The main findings from the study described in Chapter 4 were that the elite players had the higher values in (i) the peak torque levels of knee extensors, (ii) the peak torque levels of knee flexors, (iii) quadriceps strength relative to body size, (iv) hamstrings strength relative to body size in both dominant and non-dominant legs and in both contraction modes (concentric and eccentric), (v) hamstrings to quadriceps strength ratio in eccentric mode (both legs), (vi) fast-speed to slow-speed ratio in the quadriceps of the dominant leg and (vii) flexibility of the hip joint (both sides). The sub-elite players had a ratio closer to unity at the high speed for both legs. No significant differences were found between these two groups of players for bilateral quadriceps and hamstrings strength ratio or vertical jump. The major conclusions from this research were firstly that elite soccer players differ from sub-elite soccer players in terms of most muscle functional variables; the elite players demonstrated greater absolute strength and also greater strength relative to body mass and greater flexibility. Secondly, they tended to have the better values in the DCR ratio and fast-speed/slow-speed ratio, which suggests they are less at risk of injury than less skilled players. It is thought that several years of soccer training and match-play at a high level improves the strength of knee extensors and knee flexors, irrespective of body size, and also the flexibility in elite players. Finally, this investigation has also established a comprehensive isokinetic strength reference database for English soccer players.

In Chapter 5 the findings of the initial study (Chapter4) were extended. It was evident from the literature that no previous studies have considered the effects of a fatigue task (soccer simulation game) on the potential responses of such muscles. The results from Chapter 5 showed significant reductions in peak torque with fatigue for both quadriceps and hamstrings muscles at all angular velocities (1.05, 2.09, 5.23 rad.s^{-1} (concentric) and 2.09 (eccentric). The levels of peak torque and relative peak torque of knee extensors and knee flexors were greater pre- exercise than at half-time and greater at half-time than post-exercise. For the hamstrings/quadriceps ratio, significant changes were found for both legs, the ratio being greater pre-exercise than post-exercise. For fast/slow speed and left/right ratios, no significant changes were found. The major conclusion from this study was that there is a continuous reduction in muscle strength, which applies across a range of functional characteristics during exercise which mimics the work-rate in soccer.

The decline in muscle strength would have implications for the ability of players to perform their skills towards the end of the game when they may be unable to run, sprint, jump and tackle as vigorously as they would at the start of the game. It may also lead to a higher number of errors, which would affect players' susceptibility to injury as the game progresses. The greater reduction in hamstrings in eccentric mode, might lead to less control and lower stability of the knee towards the end of the game and thus lead to a greater risk of injury. The deficit in hamstrings strength with fatigue is of concern in that it may correspond to a compromised capability for joint stabilisation and so potentially, an increased risk of injury. Local muscle fatigue has been identified as a factor in injury causation (Lieber and Friden, 1988; Davis and Bailey, 1997) and Hawkins et al. (2001) claimed that this could explain the greater injury incidence observed in the second half of competitive matches, especially during the final quarter. Consequently trainers should focus on the eccentric function of the hamstrings as well as the concentric action of the quadriceps in training sessions, to ensure a good bilateral muscle balance over a wide range of playing skills.

In general, this present study showed that fatigue occurred progressively in soccer players' muscles and therefore maximum force decreased progressively from the beginning to the end of the game. A reduction in muscle glycogen and also a decline in body water content or other factors may be involved in the fatigue process but the precise mechanisms of fatigue in the present study can not be isolated. Nevertheless, further research into the role of carbohydrate intake and rehydration in attenuating fatigue is warranted.

The next study described in this thesis was an investigation of the influences of fatigue on muscle activity. In the laboratory-based study described in Chapter 6, the muscle activity of the major lower-extremity muscles was investigated during a simulated soccer game with reference to selected fundamental locomotor movements. The results indicated that the RMS values for rectus femoris, biceps femoris and tibialis anterior decreased significantly as the game progressed. The RMS values for rectus femoris, biceps femoris, tibialis anterior and gastrocnemius increased with increasing speed continually from 6 km.h^{-1} to 21 km.h^{-1}. The median frequency values for biceps femoris and gastrocnemius were greater in pre-game than post-game. The median frequency values for rectus femoris and biceps femoris increased significantly with increasing speed continually from 6 km.h^{-1} to 21 km.h^{-1}. The major conclusions from this research were that the EMG activity in major lower limb muscles was greater before than after a simulated game. It seems that fatigue has an effect on muscle activity and is likely to be the cause of reduced activity during exercise, which mimicked work-rate in soccer. The RMS values increased with increasing speed of running on the treadmill, which confirmed that an increase in muscle activity is required with increasing speed. The median frequency also decreased as the game progressed and it increased with increasing speed.

It is concluded from the completion of the studies in Chapters 3, 4, 5 and 6 that the original aims of this thesis have been realised. A holistic approach was adopted and utilised in order to assess injury risk in soccer. The hand and computerised notation analysis system provided a means to collect epidemiological and aetiological data from injury and injury risk in soccer. The data collected via this method showed a possible effect of fatigue on injury risk in the last period of the game. Further insights into the effects of fatigue on injury were then gained through the use of a laboratory-based study utilising a simulating the work-rate of a soccer game on a treadmill, which provided a well-controlled environment to monitor the players' muscle function.

In summary, in Chapter 3, a highest injury risk in the first and last 15 minutes of the game was recorded, reflecting the intense engagements in the opening period and the possible effect of fatigue in the closing period (aim 1). In Chapter 4 a comprehensive isokinetic strength reference database was established for further investigation (aim 2). The results from Chapter 5 indicated that there is a continuous reduction in muscle strength during a soccer game (aim 3). Finally, in Chapter 6 it was demonstrated that fatigue has an effect on muscle activity and is likely to be cause of reduced activity during exercise, which mimicked work-rate in soccer (aim 4).

It can be concluded that the specific reduction in muscle strength and its influence on muscle balance were documented. One cause of this reduced strength was found to be a reduced level of neuromuscular activity which is linked to progressive central fatigue of the neural system.

7.2. CONCLUSIONS

From the studies described, the main conclusion is that fatigue is evident within 90 min of activity which mimics the exercise intensity of match-play. A reduction in muscle performance is likely to raise injury risk, due to its lowered ability to resist external loading. It is suggested that fatigue is a risk factor, because failure to provide enough muscle strength and maintain suitable muscle balance due to fatigue may lead to an increasing likelihood of injury. Specifically, the observed increases in injury risk toward the end of the game can be linked to the effect of fatigue because of the reduced muscle activity, strength and muscle balance evident at the end of the game.

7.3. RECOMMENDATIONS FOR FURTHER RESEARCH

From conducting the research in the present thesis and from reviewing the literature, the following directions are proposed for further work in this area of soccer studies. The recommendations are limited to the most immediate issues.

It would be of interest to investigate injury, mechanisms of injury and injury risk in lower-skilled (recreational) players and also in youth players. It would also be of interest to study these variables in other countries in which different styles to the English Premier League are employed as players' style may also be a factor affecting injury risk.

Equally, it would be important to perform similar studies on females as their body characteristics are different from males and may also be a factor which influence injury risk. It would also be beneficial to determine whether the menstrual cycle phase in females affects their ability and muscle function responses to a soccer-specific exercise protocol.

Changes in muscle strength in field based soccer-specific protocols should also be investigated, since heat gain during competition and its effects on motivation may influence muscle strength. Due to the possible effects of dehydration and glycogen depletion on fatigue, research into the role of rehydration and carbohydrate intake in attenuating fatigue is warranted.

Performance capabilities, especially with respect to high intensity exercise bouts and specific match actions, need to be maintained close to optimal levels throughout the duration of games. It would be of interest to evaluate the effects of soccer-specific intermittent exercise performance on the maintenance of performance variables such as vertical jump and flexibility as the game progresses.

The effects of fatigue on the kinematics of football skills e.g. kicking, throwing in and sprinting off the mark should be investigated as physiological factors such as muscle strength may be impaired. This study, along with the others recommended, would provide a comprehensive picture of how human capabilities and injury risk alert in a dynamic manner during competitive soccer match-play.

REFERENCES

References

Aagaard, P., Simonsen, E.B., Trolle, M., Bangsbo, J. and Klausen, K. (1995). Isokinetic hamstring/quadriceps strength ratio: influence from joint angular velocity, gravity correction and contraction mode. *Acta Physiologica Scandinavica,* **154,** 421-427.

Aagaard, P., Simonsen, E.B., Magnusson, S.P., Larsson, B. and Dyhre-Poulsen, P. (1998). A new concept for isokinetic hamstring: quadriceps muscle strength ratio. *American Journal of Sports Medicine,* **26,** 231-237.

Abernethy, P. Wilson, G. and Logan, P. (1995). Strength and power assessment: issue, controversies and challenges. *Sports Medicine,* **19,** 401-417.

Agre, J.C. and Baxter, T.L. (1987). Musculoskeletal profile of male collegiate soccer players. *Archives of Physical Medicine and Rehabilitation,* **68,** 147-150.

Aitkens, S., Lord, J., Bernauer, E. and McCrory, M. (1987). Analysis of the validity of the lido digital isokinetic system. *Physical Therapy,* **67,** 757.

Albert, M. (1983). Descriptive three years data study of outdoor and indoor professional soccer injuries. *Athletic Training,* **18,** 218-220.

Albert, M. (1995). Physiologic and clinical principles of eccentrics. In: *Eccentric Muscle Training in Sports and Orthopedics* (ed. M. Albert). Churchill Livingstone, London, pp. 23-35.

Ali, A.H. (1998). A statistical analysis of tactical movement patterns in soccer. In: *Science and Football* (eds. T. Reilly, A. Lees, K. Davids and W.J. Murphy). E. & F. N. Spon, London, pp. 302-308.

Ament, W., Bonga, G.J.J., Hof, A.L. and Verkerke, G.J. (1993). EMG median power frequency in exhausting exercise. *Journal of Electromyography and Kinesiology,* 3, 214-220.

Anglietti, P., Zaccherotti, G., De Biase, P., Latella, F. and Semi, G. (1994). Injuries in soccer: mechanism and epidemiology. In: *Clinical Practice of Sports Injury Prevention and Care* (ed. P.A. Renstrom). Blackwell Scientific Publications, Oxford, pp. 277-284.

Arnason, A., Gudmundsson, A. and Dahl, H.A. (1996). Soccer injuries in Iceland. *Scandinavican Journal of Medicine Science and Sports*, 6, 40-45.

Ball, D.J. (2000). Risks of injury - an overview. In: *ABC of Sports Medicine* (eds. M. Harries, G. Malatchie, C. Williams and J. King). BMJ Books, London, pp. 88-91.

Bangsbo, J. (1994a). Physiology of soccer – with special reference to intense intermittent exercise. *Acta Physiologica Scandinavica,* **151**, 1-155.

Bangsbo, J. (1994b). Energy demands in competitive soccer. *Journal of Sports Sciences,* **12**, S5-S12.

Bangsbo, J., Norregaard, L. and Thorsoe, F. (1991). Activity profile of competition soccer. *Canadian Journal of Sport Sciences,* **16**, 110-116.

Barnes, W.S. (1980a). The relationships between maximum isokinetic strength and isokinetic endurance. *Research Quarterly for Exercise and Sports.* **51**, 714-717.

Barnes, W.S. (1980b). The relationship of motor-unit activation of isokinetic muscular contraction at different contractile velocities. *Physical Therapy,* **60**, 1152.

Barnes, W.S. (1981). Isokinetic fatigue curves at different contractile velocities. *Archives of Physical Medicine and Rehabilitation,* **62**, 62-69.

Basmajian, J.V. and De Luca, C.J. (1985). *Muscle Alive: Their Functions Revealed by Electromyography.* Baltimore: Williams & Wilkins.

Bate, R. (1988). Football chance: tactics and strategy. In: *Science and Football* (eds.T. Reilly, A. Lees, K. Davids and W.J. Murphy). E. & F. N. Spon, London, pp. 293-301.

Bender, J.A., Pierson, J.K., Kaplan, H.D. and Johnson, A.J. (1964). Factors affecting the occurrence of knee injuries. *Journal of American Medical Association,* **18,** 130-134.

Benesh, J. and Benesh, R. (1956). *Reading Dance- The British of Choreology.* Souvenir Press, London.

Bennett, J.G. and Stauber, W.T. (1986). Evaluation and treatment of anterior knee pain using eccentric exercise. *Medicine and Science Sports Exercise*, **18,** 526-530.

Bigland-Ritchie, B., Johansson, R. and Woods, J.J. (1983). Does a reduction in motor drive necessarily result in force loss during fatigue. In: *Biochemistry of Exercise* (ed. H.G. Knuttgen,.). Human Kinetics Publishers, Champaign, III, pp. 864-870.

Blatzopoulos, V. and Brodie, D.A. (1989). Isokietic dynamometry: applications and limitations. *Sports Medicine*, **8,** 101-116.

Brackenridge, C.H. and Alderson, G.J.K. (1985). Match analysis. *National Coaching Foundation,* 1-8.

Brynhildsen, J., Ekstrand, J., Jeppsson, A. and Tropp, H. (1990). Previous injuries and persisting symptoms in female soccer players. *International Journal of Sports Medicine,* **11,** 489-492.

Bollens, E.C., De Proft, E. and Clarys, J.P. (1987). The accuracy and muscle monitoring in soccer kicking. In: *Biomechanics X-A* (ed. B. Jonsson). Human Kinetics Publishers, Champaign, III, pp. 283-288.

Burkett, L.S. (1970). Causative factors in hamstring strains. *Medicine and Science in Sports,* **2**, 39-42.

Campell, D.E. (1979). Generation of horsepower at low and high velocity by sprinters and distance runners. *Research Quarterly for Exercise and Sports*, **50**, 1-8.

Cattermole, H.R., Hardy, J.R. and Gregg, P.J. (1996). The footballer's fracture. *British Journal of Sports Medicine*, **30**, 171-175.

Chaffin, D.B. (1973). Localized muscle fatigue: definition and measurement. *Journal of Occupation and Medicine,* **15**, 346-354.

Chaffin, D.B., Herrin, G.D. and Keyserling, W.M. (1978). Preemployment strength testing: an updated position. *Journal of Occupation and Medicine*, **20**, 403-408.

Chan, K.M., Maffulli, N., Korkia, P. and Li, R.C.T. (1996). Introduction to isokietics. In: *Priciples and Practice of Isokinetics in Sports Medicine and Rehabilitation* (eds. K.M. Chan, N. Maffulli, P, Korkia and R.C.T. Li). Williams and Wilkins, Asia-Pacific, pp. 2-69.

Chapman, A.E. (1976). The relation between length and the force-velocity curve of a single equivalent linear muscle during flexion of the elbow. In: *Biomechanics IV*, (ed. P.V. Komi), University Park Press, Baltimore, p. 434.

Chin, M.K., So, R.C.H., Yuan, Y.W.Y., LI, R.C.T. and Wong, A.S.K. (1994). Cardiorespiratory fitness and isokinetic muscle strength of elite Asian junior soccer players. *Journal of Sports Medicine and Physical Fitness,* **34**, 250-257.

Christensen, H. and Fuglsang, F.A. (1988). Quantitative surface EMG during sustained and intermittent submaximal contractions. *Electroencephalography and Clinical Neurophysiology*, **70**, 239-247.

Clarke, H.H. (1948). Objective strength tests of affected muscle group involved with orthopedic disabilities. *Research Quarterly for Exercise and Sports*, **19**, 118-147.

Clarys, J.P., Bollens, E., Cabri, J. and Dufour, W. (1988). Muscle activity in the soccer kick. In: *Science and Football* (ed. T. Reilly, A. Lees, K. Davids, and W. Murphy). E. & F.N. Spon, London, pp. 434-440.

Clarys, J.P. and Cabri, J. (1993). Electromyogrophy and the study of sports movements: a review. *Journal of Sports Sciences*, **11**, 379-448.

Coldwells, A., Atkinson, G. and Reilly, T. (1994). Sources of variation in back and leg dynamometry. *Ergonomics*, **37**, 79-86.

Cometti, G., Maffiuletti, N.A., Pousson, M., Chatard, J.C. and Maffulli, N. (2001). Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *International Journal of Sports Medicine*, **22**, 45-51.

Coplin, T.H. (1971). Isokinetic exercise: clinical usage. *National Athletic Trainers Association*, **6**, 110-114.

Costain, R. and Williams, A.K. (1984). Isokinetic quadriceps and hamstring torque levels of adolescent, female soccer players. *Journal of Orthopaedic and Sports Physical Therapy*, **5**, 196-200.

Cross, D., Grassino, A. and Ross, W.R.D. (1979). Electromyogram patterns of diaphragmatic fatigue. *Journal of Applied Physiology*, **46**, 1-7

Davies, G.J., Kirkendall, D.T., Leigh, D.H., Lui, M.L., Reinbold, T.R., Wilson, P.K. (1981). Isokinetic characteristics of professional football players: normative relationship between quadriceps and hamstrings muscle groups and relative to body weight (abstract). *Medicine and Science in Sports and Exercise*, **13**, 76-77.

Davis, G.J. (1984). *A Compendium of Isokinetics in Clinical Usage and Rehabilitation Techniques*. S & S publisher, La Crosse, USA.

Davis, J.M. and Bailey, S.P. (1997). Possible mechanisms of central nervous system fatigue during exercise. *Medicine and Science in Sports and Exercise*, **29**, 45-57.

De Luca, C.J. (1979). Physiology and mathematics of myoelectric signals. *Transactions Biomedical Engineering*, **26**, 313-325.

De Luca, C.J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, **13**, 135-163.

De Proft., E., Clarys, J.P., Bollens, E., Cabri, J. and Dufour, W. (1988). Muscle activity in the soccer kick. In: *Science and Football* (eds. T. Reilly, A. Lees, K. Davids and W.J. Murphy). E. & F. N. Spon, London, pp.434-440.

Downey, J.C. (1973). *The Singles Game*. E. P. Publications, London.

Drust, B. (1997). *Metabolic responses to soccer-specific intermittent exercise*. Unpublished Ph.D. Thesis, Liverpool John Moores University.

Drust, B., Cable. N.T. and Reilly. T. (2000a). Investigation of the pre-cooling on the physiological responses to soccer-specific intermittent exercise. *European Journal of Applied Physiology*, **81**, 11-17.

Drust, B., Reilly, T. and Cable, N.T. (2000b). Physiological responses to laboratory-based soccer-specific intermittent and continuous exercise. *Journal of Sports Sciences*, **18**, 885-892.

Dvorak, J., and Junge, A. (2000). Football injuries and physical symptoms. A review of the literature. *American Journal of Sports Medicine*, **28**, S3-S9.

Ekblom, B. (1986). Applied physiology of soccer. *Sports Medicine*, **3**, 50-60.

Ekstrand, J. (1982). *Soccer injuries and their prevention.* Linkoping University Medical Dissertions, No 130, Linkoping, Sweden.

Ekstrand, J. and Gillquist, J. (1982). The frequency of muscle tightness and injuries in soccer players. *American Journal of Sports Medicine,* **10**, 75-78.

Ekstrand, J. and Gillquist, J. (1983). Soccer injuries and their mechanisms. *Medicine and Science in Sport and Exercise,* **15**, 267-270.

Ekstrand, J., Gillquist, J., Muller, M., Oberg, B. and Liljedahl, S.O. (1983). Incidence of soccer injuries and their relation to training and team success. *American Journal of Sports Medicine,* **11**, 63-67.

Ekstrand, J. and Troop, H. (1990). The incidence of ankle sprain in soccer. *Journal of Foot and Ankle Surgery*, **11**, 41-44.

Elliot, J. (1978). Assessing muscle strength isokinetically. *Journal of American Medicine Association*, **240**, 2408-2410.

Engstrom, B., Forssblad, M., Johansson, C. and Tornkvist, H. (1990). Does a major knee injury definitely sideline an elite soccer player. *American Journal of Sports Medicine,* **18**, 101-105.

Engstrom, B., Johansson, C. and Tornkvist, H. (1991). Soccer injuries among elite female players. *American Journal of Sports Medicine,* **19,** 372-375.

Enoka, R.M. and Stuart, D.G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology,* **72,** 1631-1648.

Esposito, F., Orizio, C. and Veicsteinas, A. (1998). Electromyogram and mechanomyogram changes in fresh and fatigued muscle during sustained contraction in men. *Applied Physiology and Occupational Physiology,* **78,** 494-501.

Essen, B. (1978). Studies on the regulation of metabolism in human skeletal muscle using intermittent exercise as an experimental model. *Acta Physiologica Scandinavica,* **454,** 1-32.

Fenn, W.O. and March, B.S. (1935). Muscular force at different speeds of shorting. *Journal of Physiology,* **85,** 277.

Fowler, N.E. and Reilly, T. (1993). Assessment of muscle strength asymmetry in soccer players. In: *Contemporary Ergonomics* (ed. E. J. Lovesey), Taylor and Francis, London, pp. 327-332.

Franks, I.M. and Goodman, D. (1986). A systematic approach to analysing sports performance. *Journal of Sports Sciences,* **4,** 49-59.

Franks, I.M. and Miller, G. (1986). Eyewitness testimony in sport. *Journal of Sport Behaviour*, **9**, 39-45.

Fried, T. and Lloyd, G.J. (1992). An overview of common soccer injuries. Management and prevention. *Sports Medicine*, **14**, 269-275.

Gilliam, T.H. (1979). Isokinetic torque levels for high school football players. *Archives of Physical Medicine and Rehabilitation*, **60**, 110-114.

Ghena, D.R., Kurth, A.L., Thomas, M. and Mayhew, J. (1991). Torque characteristics of the quadriceps and hamstring muscles during concentric and eccentric loading. *Journal of Orthopaedic and Sports Physical* Therapy, **14**, 149-154.

Gleeson, N., Mercer, T. and Campbell, I. (1995). Effect of fatigue task on absolute and relativeized indices of isokinetic leg strength in female collegiate soccer players. *Journal of Sports Traumatology*, **13**, 502-503.

Gleim, G., Nicholas, J. and Webb, J. (1978). Isokinetic evaluation following leg injuries. *Physician and Sportsmedicine*, **6** (8), 75-82.

Goslin, B.R. and Charteris, J. (1979). Isokinetic dynamometry: normative data for clinical use in lower extremity (knee) cases. *Scandinavian Journal of Rehabilitation and Medicine*, **11**, 105-109.

Grace, T.G., Sweetser, E.R. and Nelson, M.A. (1984). Isokinetic muscle imbalance and knee-joint injuries. *Journal of Bone and Joint Surgery*, **66**, 734-739.

Gray, J.W. and Chandler, J.M. (1989). Percent decline in peak torque production during repeated concentric and eccentric contractions of the quadriceps femoris muscle. *Journal of Orthopedic and Sports Physical Therapy*, **10**, 309-314.

Green, H.J. (1995). Metabolic determinants of activity induced muscular fatigue. In: *Exercise Metabolism* (ed. M. Hargreaves). Human Kinetics, Champaign, Ill, pp. 211-256.

Gregor, R.J., Edgerton, V.R. Perrine, J.J., Campion, D.S. and DeBus, C. (1979). Torque-velocity relationships and muscle controlled fiber composition in elite female athletes. *Journal of Applied Physiology*, 47, 388-392.

Grimby, G. (1985). Progressive resistance exercise for injury rehabilitation: special emphasis on isokinetic training. *Sports Medicine*, **2**, 309-315.

Hagberg, M. (1981). Muscle endurance and surface electromyography in isometric and dynamic exercise. *Journal of Applied Physiology*, **51**, 1-7.

Hansson, G.A., Strömberg, U., Larsson, B., Ohlsson, K., Balogh, I. and Moritz, U. (1992). Electromyographic fatigue in neck/shoulder muscles and endurance in women with repetitive work. *Ergonomics*, **35**, 1341-1352.

Harris, S. and Reilly, T. (1988). Space, teamwork and attacking success in soccer. In: *Science and Football* (eds. T. Reilly, A. Lees, K. Davids and W.J. Murphy). E. & F. N. Spon, London, pp. 322-328.

Hawkins, R.D. and Fuller, C.W. (1996). Risk assessment in professional football: an examination of accidents and incidents in the 1994 World Cup finals. *British Journal of Sports Medicine*, **30**, 165-170.

Hawkins, R.D. and Fuller, C.W. (1998). An examination of the frequency and severity of injuries and incidents at three levels of professional. *British Journal of Sports Medicine,* **32**, 326-332.

Hawkins, R.D. and Fuller, C.W. (1999). A prospective epidemiological study of injuries in four English professional clubs. *British Journal of Sports Medicine*, **33**, 196-203.

Hawkins, R.D., Hulse, M.A., Wilkinson, C., Hodson, A. and Gibson, M. (2001). The association football medical research programme: an audit of injuries in professional football. *British Journal of Sports Medicine,* **35**, 43-47.

Hermans, H.J., Boon, K.L. and Zilvold, G. (1984). The clinical use of surface EMG. *Electromyogeraphy and Clinical Neurophysiology*, **24**, 423-465.

Hill, A.V. (1922). The maximum work and mechanical efficiency of human muscles and their most economical speed. *Journal of Physiology*, **56**, 19-41.

Hill, A.V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London (Bilogy)*, **126**, 136-195.

Hill, A.V. (1950). The series elastic component of muscle. *Proceeding of the Royal Statistical Society, Series, B*, **37**, 273.

Hill, A.V. (1965). Trails and Trails in Physiology. Edward Arnold (publisher) Ltd, London, p. 357.

Hislop, H.J. and Perrine, J.J. (1967). The isokinetic concept of exercise. *Physical Therapy,* **47**, 114-117.

Hoff, G.L., Martin, T.A. (1986). Outdoor and indoor soccer: injuries among youth players. *American Journal of Sports Medicine*, **14**, 231-233.

Hughes, C. (1973). *Football Tactics and Teamwork.* E. P. Publishing, Wakefield.

Hughes, M.D. (1993). Notational analysis of football. In: *Science and Football II* (eds. T. Reilly, J. Clarys and A. Stibbe). E. & F. N. Spon, London, pp. 151-159.

Hughes, M.D. (1996). Notation analysis. In: *Science and Soccer* (ed. T. Reilly). E & F. N. Spon, London, pp. 343-362

Hunter, R.E. and Levi, M. (1988). Sports injury research. *American Journal of Sports Medicine*, **16**, S25-S37.

Haymes, E. M., and Dickinson, A.I. (1980). Characteristics of elite male and female ski racers. *Medicine and Science in Sports and Exercise*, **12**, 153-158.

Inklaar, H. (1994a). Soccer injuries: incidence and severity. *Sports Medicine*, **18**, 55-73.

Inklaar, H. (1994b). Soccer injuries II: aetiology and prevention. *Sports Medicine*, **18**, 81-93.

Inklaar, H., Bol, E., Schmiki, S.L. Mosterd, W.L. (1996). Injuries in male soccer players: team risk analysis. *International Journal of Sports Medicine*, **17**, 229-234.

Jacobs, I., Westlin, N., Karlsson, J., Ramusson, M. and Houghton, B. (1982). Muscle glycogen and diet in elite soccer players. *European Journal of Applied Physiology*, **48**, 297-302.

Jonsson, B. (1978). Kinesiology: with special reference to electromyographic kinesiology. *Electroencephalography and Clinical Neurophysiology*, **34**, S417-S428.

Junge, A. and Dvorak, J. (2000). Influence of definition and data collection on the incidence of injuries in football. *American Journal of Sports Medicine,* **28**, S40-S46.

Kannus, P. (1990). Relationship between peak torque, peak torque angular impulse, and average power in thigh muscle of subjects with knee damage. *Research Quarterly for Exercise and Sports,* **61**, 141-145.

Kannus, P. (1994). Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. *International Journal of Sports Medicine.* **15**, S11-S18.

Kannus, P. (2000). Nature, prevention and management of injury. In: *ABC of Sports Medicine* (eds. M. Harries, G. Malatchie, C. Williams and J. King). BMJ Books, London, pp. 1-6.

Karlsson, J. and Saltin, B. (1971). Diet, muscle glycogen and endurance performance. *Journal of Applied Physiology*, **31**, 203-206.

Katz, B. (1939). The relation between force and speed in muscular contraction, *Journal of Physiology*, **96**, 45.

Kawakami, Y., Kanehisa, H., Ikegawa, S. and Fukunaga, T. (1993). Concentric and eccentric muscle strength before, during and after fatigue in 13 year-old boys. *European Journal of Applied Physiology*, **67**, 121-124.

Kay, D., St, Clair-Gibson, A., Mitchell, M.J. Lambert, M.I. and Noakes, T.D. (2000). Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. *Journal of Electromyography and Kinesiology*, **10**, 425-431.

Keller, C.S., Noyes, F.R. and Buncher, R. (1987). The medical aspects of soccer injury epidemiology. *American Journal of Sports Medicine*, **15**, 230-237.

Kellis, E. (1999). The effects of fatigue on the resultant joint moment, agonist and antagonist electromyographic activity at different angles during dynamic knee extension efforts. *Journal of Electromyography and Kinesiology,* **9**, 191-199.

Kellis, E. and Baltzopoulos, V. (1995). Isokinetic eccentric exercise. *Journal of Sports Medicine*, **19**, 202-222.

Kirkendall, D.T. (1985). The applied sport science of soccer. *Physician and Sports Medicine*, **134**, 53-59.

Kirkendall, D.T. (1993). Effects of nutrition on performance in soccer. *Medicine and Science in Sports and Exercise,* **25**, 1370-1374.

Knapik, J. and Ramos, M. (1980). Isokinetic and isometric torque relationship in the human body. *Archives of Physical Medicine and Rehabilitation*, **61**, 64-67.

Knapik, J.J., Baumann, C.L., Jones, B.H., Harris, J.M. and Vaughan, L. (1991). Pre-season strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *American Journal of Sports Medicine*, **19**, 76-81.

Knapp, B.J. (1963). *Skill in Sport- The Attainment of Proficiency.* Routledge and Kegan Paul, London.

Komi, P.V. (1969). *Effect of eccentric and concentric muscle conditioning in tension and electrical activity of human muscle.* Doctoral Dissertation. University Park, PA, The Pennsylvania State University.

Komi, P.V. and Tesh, P. (1979). EMG frequency spectrum, muscle structure and fatigue during dynamic contractions in man. *European Journal of Applied Physiology*, **42**, 41-50.

Komi, P.V. and Rusko, H. (1974). Quantitative evaluation of mechanical and electrical changes during fatigue loading of eccentric and concentric work. *Archives of Physical Medicine and Rehabilitation*, **3**, S121-S126.

Kranz, H., Williams, A.M., Cassell, J. (1983). Factors determining the frequency content of the electromyogram. *Journal of Applied Physiology*, **55**, 392-399.

Kuhn, J.E., Greenfield, M.L. and Wojtys, E.M. (1997). A statistics primer. Prevalence, incidence, relative risks, and odds ratios: some epidemiologic concepts in the sports medicine literature. *American Journal of Sports Medicine,* **25**, 414-416.

Laird, C.E. and Rozier, C.K. (1979). Toward understanding the terminology of exercise mechanics. *Physical Therapy*, **59**, 287-292.

Lesmes, G., Coyle, E., Costill, D. and Fink, W. (1978). Muscle strength and power changes during maximal isokinetic training. *Medicine Sciences and Sports Exercise*, **4**, 266.

Lewin, G. (1989). The incidence of injury in an English professional soccer club during one competitive season. *Physiotherapy*, **75**, 601-605.

Lieber, R.L. and Friden, J. (1988). Selective damage of fast glycolytic muscle fibers with eccentric contraction of the rabbit tibialis anterior. *Acta Physiologica Scandinavica*, **133**, 587-588.

Lieber, R.L. (1992). *Skeletal Muscle Structure and Function: Implications for Rehabilitation and Sports Medicine.* Williams and Wilkins, London.

Lindstrom, L., Magnusson, R. and Petersen, I. (1970). Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. *Electromyography*, **4**, 341-356.

Lindstrom, L., Kadefors, R. and Petersen, I. (1977). An electromyographic index for localized muscle fatigue. *Journal of Applied Physiology*, **53**, 750-754.

Linnamo, V., Bottas, R. and Komi, P.V. (2000). Force and EMG power spectrum during and after eccentric and concentric fatigue. *Journal of Electromyograhy and Kinesiology*, **10**, 293-300.

Lord, J., *Aitkens, S. and McCrory, M. (1987). Reliability of the Lido isokinetic* system for the measurement of muscular strength. *Physical Therapy*, **67**, 757.

Luthje, P. (1996). Epidemiology and traumatology of injuries in elite soccer: a prospective study in Finland. *Scandinavian Journal of Medicine and Science in Sports*, **6**. 180-185.

Maehlum, S., Dahl, E. and Daljord, O. (1986). A Frequency of injuries in a youth soccer tournament. *Physician and Sportsmedicine*, **14** (7), 73-78.

Mangine, R.E., Noyes, F.R., Mullen, M.P. and Barber, S. (1990). A physiological profile of the elite soccer athlete. *Journal of Orthopaedic and Sports Physical Therapy*, **12**, 147-152.

Masuda, K., Masuda, T. Sadoyama, T., Inaki, M. and Katsuta, S. (1999). Changes in surface EMG parameters during static and dynamic fatiguing contractions. *Journal of Electromyography and Kinesiology*, **9**, 39-46.

McCrudden, M. and Reilly, T. (1993). A comparison of the punt and the drop-kick. In: *Science and Football II* (eds. T. Reilly, J. Clarys and A. Stibbe). E & F. N. Spon, London, pp. 362-366.

McGarry, T. and Franks, I.M. (1995). Modelling competitive squash performance from quantitative analysis. *Human Performance*, **8**, 113- 129.

McGregor, J.C. and Rae, A. (1995). A review of injuries to professional footballers in a premier football team (1990-93). *Scottish Medicine Journal*, **40**, 16-18.

McGregor, S.J., Nicholas, C.W., Lakomy, H.K. and Williams, C. (1999). The influence of intermittent high-intensity shuttle running and fluid ingestion on the performance of a soccer skill. *Journal of Sports Sciences,* **17**, 895-903.

McMaster, W.C. and Walter, M. (1978). Injuries in soccer. *American Journal of Sports Medicine,* **6**, 354-357.

Miller, J.P., Ronald, V., Croce, R.V. and Hutchins, R. (2000). Reciprocal coactivation patterns of the medial and lateral quadriceps and hamstrings during slow, medium and high speed isokinetic movements. *Journal of Electromyography and Kinesiology,* **10**, 233-239.

Milner-Brown, H.S. and Stein, R.B. (1973). Changes in firing rate of human motor units during linearly changing voluntary contractions. *Journal of Physiology*, **230**, 371-390.

Moffroid, M., Whipple, R. and Hofkosh, J. (1969). A study of isokinetic exercise. *Physical Therapy*, **49**, 735-749.

Mognoni, P., Narici, M.V., Sirtori, M.D. and Lorenzelli, F. (1994). Isokinetic torques and kicking maximal ball velocity in young soccer players *Journal of Sports Medicine and Physical Fitness*, **34**, 357-361.

Moritani, T., Muro, M., Kijima, A., Gaffney, F.A. and Parsons, D. (1985). Electromechanical changes during electrically induced and maximal voluntary contractions: surface and intramuscular EMG responses during sustained maximal voluntary contraction. *Experimental Neurology*, **88**, 471-83.

Naeije, M. (1984). Correlation between surface electromyograms and the susceptibility to fatigue of the human masseter muscle. *Archives of Oral Biology*, **29**, 865-70.

Nevill, M.E., Garrett, A., Maxwell, N., Parsons, K.C. and Nowitz, A. (1995). Thermal strain of intermittent and continuous exercise at 10 °C and 35 °C. *Journal of Physiology*, **483**, 1124-1125P.

Nicholas, C.W., Williams, C., Phillips, G., Lakomy, H.K.A. and Nowitz, A. (1995). Influence of ingesting a carbohydrate-electrolyte solution on endurance capacity during intermittent high-intensity shuttle running. *Journal of Sports Sciences*, **18**, 97-104.

Nielson, A.B. and Yde, J. (1989). Epidemiology and traumatology of injuries in soccer. *American Journal of Sports Medicine*, **17**, 803-807.

Nilsson, S. and Roaas, A. (1978). Soccer injuries in adolescents. *American Journal of Sports Medicine*, **6**, 358-361.

Nilsson, J., Thorstensson, A. and Halbertsma, J. (1985). Changes in leg movements and muscle activity with speed of locomotion and mode of progression in humans. *Acta Physiologica Scandinavica*, **123**, 457-475.

Noonan, T.J., Best, T.M., Seaber, A.V. and Garrett, W.E. (1994). Identification of a threshold for skeletal muscle injury. *American Journal of Sports Medicine*, **22**, 257-261.

Oberg, B., Ekstrand, J., Moller, M. and Gillquist, J. (1984). Muscle strength and flexibility in different position of soccer players. *International Journal of Sports Medicine*, **5**, 213-216.

Oberg, B., Moller, M., Gillquist, J. and Ekstrand, J. (1986). Isokinetic torque levels for knee extensors and knee flexors in soccer players. *International Journal of Sports Medicine*, **17**, 50-53.

Oberg, T. (1995). Muscle fatigue and calibration of EMG measurements. *Journal of Electromyography and Kinesiology*, **5**, 239-243.

Oda, S. and Kida, N. (2001). Neuromuscular fatigue during maximal concurrent handgrip and elbow flexion or extension. *Journal of Electromyography and Kinesiology*, **11**, 281-289.

Olson, J.R. and Hunter, G.R. (1985). A comparison of 1974 and 1984 player sizes, and maximal strength and speed efforts for Division I NCAA universities *National Strength & Conditioning Association Journal*, **6**, 26-28.

Ostering, L.R (1986). Isokinetic dynamometry: implications for muscle testing and rehabilitation. *Exercise and Sport Sciences Reviews*, **14**, 45-80.

Ostering, L.R., Hamill, J., Sawhill, J.A. and Bates, B.T. (1983). Influence of torque and limb speed on power production in isokinetic exercise. *American Journal of Physical Medicine and Rehabilitation*, **62**, 163-171.

Parker, M.G. (1982). Calculation of isokinetic rehabilitation velocities for the knee extensors. *Journal of Orthopaedic and Sports Physical Therapy*, **4**, 32-35.

Paton, R, W., Grimshaw, P., McGregor, J. and Noble, J. (1989). Biomechanical assessment of the effects of significant hamstring injury: an isokinetic study. *Journal of Biomechanical Engineering*, **11**, 229-230.

Partridge, D. and Franks, I.M. (1989). A detailed analysis of crossing opportunities from the 1986 World cup (Part I). *Soccer Journal.* May/June, 47-50.

Partridge, D. and Franks, I.M. (1990). Comparative analysis of technical performance: U.S.A. and West Germany in the 1990 World Cup finals. *Soccer Journal*, **35**, 57-62.

Patterson, L.A. and Spivey, W.E. (1992). Validity and reliability of the Lido Active Isokinetic System. *Journal of Orthopedic and Sports Physical Therapy*, **15**, 32-36.

Perrin, D.H. (1993). *Isokinetic Exercise and Assessment.* Human Kinetics Publishers, Champaign, IL.

Perrine, J.J. and Edgerton, V.R. (1975). Isokinetic anaerobic ergometry. *Medicine and Science in Sports and Exercise*, **7**, 78.

Petrofsky, S.J. and Lind, A.R. (1980). Frequency analysis of the surface electromyogram during sustained isometric contractions. *European Journal of Applied Physiology*, **43**, 173-182.

Pollard, R. (1986). Home advantage in soccer: a retrospective analysis. *Journal of Sports Sciences*, **4**, 237-248.

Pollard, R., Reep, C. and Hartley, S. (1988). The quantitative comparison of playing style in soccer. In: *Science and Football* (eds. T. Reilly, A. Lees, K. Davids and W.J. Murphy). E. & F. N. Spon, London, pp. 309-315.

Potvin, J.R. and Bent, L.R. (1997). A validation of techniques using surface EMG signals from dynamic contractions to quantify muscle fatigue during repetitive tasks. *Journal of Electromyography and Kinesiology*, 7, 131-139.

Poulmedis, P. (1988). Muscular imbalance and strains in soccer. In: *Sports Injuries and their Prevention* (eds. C.R. Togt, A.B.C. Kemper, and M. Koornneef), pp. 53-57.

Poulsen, T.D., Freund, K.G., Madsen, F. and Sanvej, K. (1991). Injuries in high-skilled and low-skilled soccer: a prospective study. *British Journal of Sports Medicine,* **25**, 151-153.

Powell, K.E., Kohl, H.W., Caspersen, C.J., Blair, S.N. (1986). An epidemiological perspective on the causes of running injuries. *Physician and Sportsmedicine*, **14** (6) 100-114.

Psek, J.A. and Cafareli, E. (1993). Behavior of coactive muscles during fatigue. *Journal of Applied Physiology*, **74**, 170-175.

Reep, C. and Benjamin, B. (1968). Skill and chance in association football. *Journal of the Royal Statistical Society, Series A*, **131**, 581-585.

Rehrer, N.J. and Burke, L.M. (1996). Sweat losses during various sports. *Australian Journal of Nutrition and Dietetics*, **53**, S13-S16.

Reilly, T. (1993). Introduction. In: *Science and Football II* (eds. T. Reilly, J. Clarys and A. Stibbe). E. & F. N. Spon, London, pp. 3-11.

Reilly, T. (1994). Physiological aspect of soccer. *Biology and Sports*, **11**, 3-20.

Reilly, T. (1996a). Motion analysis and physiological demands. In: *Science and Soccer* (ed. T. Reilly). E. & F. N. Spon, London, pp. 65-81.

Reilly, T. (1996b). Fitness assessment. In: *Science and Soccer* (ed. T. Reilly). E. & F. N. Spon, London, pp. 25-49.

Reilly, T. (1997). Energetics of high-intensity exercises (soccer) with particular reference to fatigue. *Journal of Sports Sciences*, **15**, 257-263.

Reilly, T. and Brooks, G.A. (1986). Exercise and the circadian variation in body temperature measures. *International Journal of Sports Medicine*, **7**, 358-368.

Reilly, T. and Howe, T. (1996). Injury prevention and rehabilitation. In: *Science and Soccer* (ed. T. Reilly). E. & F.N. Spon, London, pp. 161-162.

Reilly, T. and Thomas, V. (1976). A motion-analysis of work-rate in different positional roles in professional football match-play. *Journal of Human Movement Studies*, **2**, 87-97.

Rhodes, E.C., Mosher, R.C., McKenzie, D.C., Frank, I.M. and Potts, J.E. (1986). Physiological profiles of the Canadian Olympic soccer team. *Canadian Journal of Sports Science*, **11**, 31-36.

Rochcongar, P., Morvan, R., Jan, J., Dassonville, J. and Beillot, J. (1988). Isokinetic investigation of knee extensors and knee flexors in young French soccer players. *International Journal of Sports Medicine*, **9**, 448-450.

Rico-Sanz, J., Frontera, W.R., Rivera, M.A., Rivera-Brown, A., Mole, P.A. and Meredith, C.N. (1996). Effects of hyperhydration on total body water, temperature regulation and performance of elite young soccer players in a warm climate. *International Journal of Sports Medicine*. **17**, 85-91.

Roaas, A. and Nilsson, S. (1979). Major injuries in Norwegian football. *British Journal of Sports Medicine*, **13**, 3-5.

Rothstein, J.M. (1985). *Measurement in Physical Therapy: Clinics in Physical Therapy*. Churchill Livingstone Inc, New York.

Saltin, B. (1973). Metabolic fundamentals in exercise. *Medicine and Science in Sports*, **5**, 137-146.

Sandelin, J., Santavirta, S. and Kiviluoto, O. (1985). Acute soccer injuries in Finland. *British Journal of Sports Medicine*, **19**, 30-33.

Scudder, N.G. (1980). Torque curves produced of the knee during isometric and isokinetic exercise. *Archives of Physical Medicine and Rehabilitation,* **61**, 68-72.

Schimidt, S., Bunemann, L.K., Lade, V. and Brassqe, J.O. (1985). Soccer injuries of youth. *British Journal of Sports Medicine*, **19**, 161-164.

Silva, J.M. and Andrew, J.A. (1987). An analysis of game location and basketball performance in the Atlantic Coast conference. *International Journal of Sports Psychology*, **18**, 188-204.

Stafford, M.G. and Grana, W.A. (1984). Hamstring/quadriceps ratios in college football players: a high velocity evaluation. *American Journal of Sports Medicine*, **12**, 209-211.

Stanton, P. and Purdam, C. (1989). Hamstring injuries in sprinting. The role of eccentric exercise. *Journal of Orthopeadic Sports Physical Therapy*, **10**, 343-349.

Sullivan, J.A., Gross, R.H. and Grana, W.A. (1980). Evaluation of injuries in youth soccer. *American Journal of Sports Medicine,* **8**, 325-327.

Svantesson, U., Osterberg, U., Thomee, R., Peeters, M. and Grimby, G. (1998). Fatigue during repeated eccentric-concentric and pure concentric muscle actions of the plantar flexors. *Clinical Biomechanics*, **13**, 336-343.

Taylor, J.L., Bulter, J.E. and Gandevia S.C. (2000). Changes in muscle afferents, motoneurons and motor drive during muscle fatigue. *European Journal of Applied Physiology*, **83**, 106-115.

Tesch, P.A., Dudley, G.A., Duvoision, M.R., Hather, B.M. and Harris, R.T. (1990). Force and EMG signal patterns during repetitive bouts of concentric and eccentric actions. *Acta Physiologica Scandinavica*, **138**, 263-271.

Thistle, H.G., Hislop, H.J., Moffroid, M. (1967). Isokinetic contraction: a new concept of resisted exercise. *Archives of Physical Medicine and Rehabilitation*, **48**, 279-282.

Thomas, V. and Reilly, T. (1979). Fitness assessment of English league players through the competitive season. *British Journal of Sports Medicine*, **13**, 103-109.

Thorstensson, A., Grimby, G. and Karlsson, J. (1976). Force-velocity relations and fiber composition in human knee extensor muscle. *Journal of Applied Physiology*, **40**, 12.

Thorstensson, A., Larsson, L., Tesch, P. and Karlsson, J. (1977). Muscle strength and fibre composition in athletes and sedentary men. *Medicine and Science in Sports*, **9**, 26-30.

Togari, H., Ohashi, j. and Ohgushi, T. (1998). Isokinetic muscle strength of soccer players. In: *Science and Football* (eds. T. Reilly, A. Lees, K. Davids and W.J. Murphy). E. & F. N. Spon, London, pp. 181-185.

Tucker, A.M. (1997). Common soccer injuries. Diagnosis, treatment and rehabilitation. *Sports Medicine*, **23**, 21-23.

Van Gool, D., Van Gervan, D. and Boutmans, J. (1988). The physiological load imposed on soccer players during real match-play. In: *Science and Football* (eds. T. Reilly, A. Lees, K. Davids and W. Murphy). E. & F. N. Spon, London, pp. 51-59.

van Mechelen, W., Hlobil, H. and Kemper, H.C. (1992). Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Medicine*, **14**, 82-99.

Westing, S.H. and Seger, J.Y. (1989). Eccentric and concentric torque-velocity characteristics, torque output comparisons, and gravity effect torque corrections for the quadriceps and hamstring muscles in females. *International Journal of Sports Medicine*, **10**, 175-180.

Whitley, J.D. and Smith, L.E. (1965). Velocity curves and static strength-action strength correlation in relation to mass moved by arm. *Research Quarterly for Exercise and Sports*, **34**, 379-395.

Wilkie, D.R. (1950). The relation between force and velocity in human muscle. *Journal of Physiology*, **110**, 49.

Withers, R.T., Maricic, Z., Wasilewski, S. and Kelly, L. (1982). Match analysis of Australian professional soccer players. *Journal of Human Movement Studies*, **8**, 158-176.

Worrel, T.W., Perrim, D.H., Gansneder, B. (1991). Comparison of isokinetic strength and flexibility measures between hamstrings injured and non-injured athletes. *Journal of Orthopeadic and Sports Physical Therapy*, **13**, 118-125.

Wyatt, M.P. and Edward, A.M. (1981). Comparison of quadriceps and hamstrings torque values during isokinetic exercise. *Journal of Orthopaedic and Sports Physical Therapy*, **3**, 48-56.

Yamanaka, K., Hughes, M. and Lott, M. (1993). An analysis of playing pattern in the 1990 world Cup for association football. In: *Science and Football II* (eds.T. Reilly, J. Clarys and A. Stibbe). E. & F. N. Spon, London, pp. 206-214.

Yamanaka, K., Haga, S., Shindo, M., Narita, J., Koseki, S., Matsuura, Y. and Eda, M. (1988). Time and motion analysis in top class soccer games. In: *Science and Football* (eds. T. Reilly, A. Lees, K. Davids and W. Murphy). E. & F. N. Spon, London, pp. 134-141.

Yeung, S.S., Au, A.L. and Chow, C.C. (1999). Effects of fatigue on the temporal neuromuscular control of vastu medialis muscle in humans. *European Journal of Applied Physiology and Occupation Physiology*, **80**, 379-385.

Zakas, A., Mandroukas, K., Vamvakoudis, E., Christoulas, K. and Aggelopoulou, N. (1995). Peak torque of quadriceps and hamstring muscles in basketball and soccer players of different divisions. *Journal of Sports Medicine and Physical Fitness,* **35**, 199-205.