An EMG and Biomechanical Investigation of Co-activation of Antagonistic Muscles during High-Speed Movements of Male Lower Limbs

A Thesis Submitted For the Degree of Doctor of Philosophy in the Institute of Biomedical and Life Sciences

by

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Author's Declaration

I declare that this thesis embodies the results of my own special hard work, that I have composed it and that it does not include work forming part of a thesis presented successfully for a degree in this or another University.

Dedication

This thesis is dedicated to my wife and my children, Ali and Salman, for all sacrifices they have made during my study. I would like to express my extraordinary love to them for their never ending support and encouragement to achieve success.

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I would like to especially thank my supervisor Dr.R.H.Baxendale, who has provided helpful advice and patient support throughout my studies.

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I am also grateful to Joseph Wylie for inviting junior football players from Dundee United and Celtic Football Clubs and for his participation with Michael Duncan in football experiments.

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Abstract

Modern sport has progressed quickly largely because of improvements in the technology and equipment available to improve the quality of the athlete's technique. This is particularly true for events that require high-speed movements for successful performance such as sprinting or jumping. However, muscle injuries present an obvious problem and they severely limit the performance of many athletes. There is a poor understanding of the causes of muscle injuries across the whole spectrum of sport.

An interesting observation in the context sports activities is co-activation of antagonist muscles. This may be observed in a range of movements associated with high-speed sports such as Football. Co-activation of antagonist muscles requires one muscle in the pair to develop force under eccentric conditions i.e. as it is stretching. This in turn opens up the possibility of the development of large forces since muscles can develop up to twice the maximum isometric force during eccentric activity. Such large forces may be responsible for muscle damage an injury.

Biomechanical analysis of movements may contribute to the understanding of high-speed movements. When this includes multi-channel electromyography it is possible to study muscle co-activation

during high-speed and high-power movements. To date, the majority of analyses of movements like jumping or sprinting have used video analysis without electromyography or have tested skilled athletes with electromyography under artificial conditions such as making single joint movements on dynamometers. The main aim of this study is to use electromyography to study muscle activation during natural, unrestrained movements.

At total of fifty-seven male volunteers participated in the experiments. There were three main studies: vertical jumping, kicking a tethered football and isokinetic dynamometry. These experiments were designed to investigate the hamstrings activity during high-velocity knee extension movements in an attempt to relate the magnitude of hamstrings co-activation and the timing of hamstrings activity to the speed or power of the movements. In the author's opinion this thesis reports the first electromyographic study of co-activation of the knee extensor and flexor muscles during vertical jumping. It is the first study of co-activation of these muscles during kicking in young semi-professional football players. It is also the first study of repeated high-speed movements made on an isokinetic dynamometer.

It is clear that there is substantial co-activation of the three muscles in hamstrings and vastus lateralis in all three studies. Co-activation is present in almost all volunteers even in the slowest speed and lowest power movements studied. Co-activation has been reported by others during single knee extension movements on isokinetic dynamometers. This thesis reports for the first time that the extent of co-activation changes during repeated movements. Co-activation occurs during unrestrained vertical jumps across the whole range from the lowest power jumps in which the volunteer barely leaves the ground to maximum power jumps. In addition, it is commonly observed even in professional football players capable of producing very fast knee extensions during powerful kicks.

Previous papers by Barratta (1988) and also by Enoka (1997) propose the idea that muscle co-activation is protective and that it acts to stabilize a joint by slowing movements and reducing net torque at the joint. Enoka (1997) has shown that co-activation is relatively stronger when new movements are introduced. Others have shown a reduction in the magnitude of co-activation during short training periods of a few weeks.

This thesis does contain data that is consistent with this idea. The duration of co-activation of hamstrings during kicking was significantly shorter in the highly trained 15-year-old footballers that in their 11-year-old counterparts or in untrained adults. It is possible that this reflects changes in the way their kicking movements have developed with prolonged training. This is the first study of age related changes in co-activation. Interestingly, there is anecdotal evidence from the club coaches that injuries are far more frequent in the 15 year olds than in the younger teams. It may be that the increase in speed of movement achieved by reducing co-activation, places the limb at more risk.

This project has identified the frequency of co-activation of antagonist muscles acting at the knee and shown the clear possibility of eccentric activity causing muscle damage. In addition, differences in the extent of co-activation is clear in young footballers. It will be interesting to develop future projects that incorporate more biomechanical analyses of how their skill develops, with the longer-term aim of introducing training methods which will deliver the high-speed performance required whilst reducing the risk of injury.

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Abbreviations

Sec: Second.

cm: Centimetre.

VL: Vastus Lateralis.

BF: Biceps Femoris.

ST: Semitendinosus.

SM: Semimembranosus.

EMG: Electromyogram.

Hz: Hertz.

Kg: Kilograms.

BH: body height.

BW: boy weight.

Yr: Year.

T: Time.

ANOVA: Analysis of Variance.

JP: Jump power.

MKEV: Maximum knee extension velocity.

msec: Millisecond.

Hams: Hamstrings.

SD: Standard deviation of Mean.

MN: Mean.

Nm: Newton meter.

RMS: Root mean square.

1. Introduction and General Literature Review Section

High-level performance in many sports depends on the physical ability of athletes to produce high power output from muscle. Power is the product of force produced by a muscle and velocity of length change. An understanding of power and biomechanics is useful in coaching to improve performance.

The risk of injury is a worry to athletes and coaches during training or competition. The risk of injury is greater during high speed or high power movements. These may occur in training or in competitions. They may be the result of poor technique or accidents caused by unavoidable circumstances such as ground conditions or collisions (Norton, Schwerdt & Lange, 2001; White, Lee, Cutuk, Hargens, and Pedowitz, 2003). Athletes warm up by light running or some stretching exercises, which are often related to the type of sport performed (Bishop, 2003). Warm up is recommended prior to exercise, training or competition, because muscle physiology performs better and it is thought to reduce the risk of injury. This is because of the increase in temperature of the tissues, increased blood flow to muscles and also for increased muscle elasticity (Shellock and Prentice, 1985).

However, pre-exercise stretching has not been shown to reduce or avoid injury during sports activity (Gleim and McHugh, 1997; Shrier, 1999). Coaches believe that better technique will reduce injury risk without detriment to a performance where high force or high velocity movement is required. A sports injury is defined as any physical damage caused by an accidental movement during physical activity or sport (Backx, Beijer, Bol and Erich (1991)). Researchers found muscular flexibility to be a major risk factor (Shellock & Prentice (1985), Glein & McHugh (1997), Shrier 1999)). Whilst growing, young people have more natural flexibility than older people, but at the same time are prone to strains and muscle tightness (Ekstrand and Gillquist, 1983).

The frequency of particular injuries depends on the sport. Several authors have investigated the injury rate associated with types of sport. De Loes (1995), found the highest incidence of injuries in ice hockey, handball and soccer. Wrestling, hiking and basketball were found to be safer.

The absolute risks of each sport cannot easily be compared with one another. Even fewer studies have compared the related incidences of injury. Backx, et al (1991), found the most common types of sports injuries were contusions (43%), joint sprains (21%), muscle strains (9%) and fractures with other soft tissues damage (1-7%).

There are many possible causes of muscle injury such as excessive exercise; strain; fatigue and cramp or muscle weakness or pain.

Eccentric action caused by muscle stretching by high force development in filaments and damage, appears in muscle sarcomere (Armstrong, (1984), Nosaka, Newton& Sacco (2002), Newham, Jones & Clarkson (1987)). On the other hand, the damage occurs in the musculotendenous junction (Rothwell (1994)). Co-activations of two antagonist muscles cause eccentric stretch and damage to the smaller muscle in the pair. For example, during knee extension caused by concentric shortening of quadriceps and any failure of hamstring to relax, will cause eccentric lengthening with high forces and that may lead to damage. This will be a bigger problem during high velocity extensions such as those made in kicking, jumping or sprinting (Osternig, Hamill, Lander and Robertson, 1986; Osternig, Caster and James 1995; Carpentier, Duchateau and Hainaut, 1996).

Many sports require participants to make fast movements, to produce fast acceleration or to deliver high power. For example, these features are required for successful sprinting or jumping. Attempts to study these features fall into two main categories: in some studies the athlete moves freely or is lightly constrained and the analysis consists principally of video analysis. Alternatively, the movement is studied with devices such as an isokinetic dynamometer and this delivers more accurate information, albeit from a rather artificial movement.

1.1. Studies of Kicking in Football Players

There have been many studies of the power output of the knee extensor muscles of footballers, presumably because of the obvious importance of powerful kicking in that game and perhaps also because of the frequency of injuries to joints and muscles.

One type of experiment uses isokinetic dynamometers to measure the knee extension force or power at one or more knee extension velocities. Studies of this sort have been performed many times. (Oberg, Moller, Gillquist and Ekstrand 1986; De Proft, Cabri, Dufour and Clarys, 1988; Rochconger, Morvan, Jan, Dassonville and Beillot, 1988; McLean and Tumilty 1993; Mognoni, Narici, Sirtori and Lorenzelli, 1994; Orchard, Marsden, Lord and Garlick, 1997; Bennell, Wajswelner, Lew, Schall-Riaucour, Leslie, Plant and Cirone, 1998; Kellis, Kellis, Manou and Gerodimos, 2000; Kellis, Gerodimos, Kelli and Manou, 2001). These studies have used a range of knee extension velocities from 30–300 degrees per second. The details are summarised in Table 1.1, shown below. These experiments have had a variety of aims, mostly to investigate power differences or some modification to their training or rehabilitation after injury.

Authors	**Year**	**Category of Player**	**Knee Extension Velocity (°/sec)**
Oberg et al	1986	Senior male league	30 & 180
De Proft et al	1988	Adults & young	200
Rochcongar et al	1988	Junior 12-16 yrs and adult	30, 180
McLean et al	1993	Junior	60, 180, 240
Mognoni et al	1994	National young	60,180, 240, 300
Orchard et al	1997	Professional senior	60, 180, 300
Bennell et al	1998	Professional league	60, 180
Kellis et al	2000	Young male	60, 120, 180
Kellis et al	2001	Young	30, 90, 120, 180

Table1.1. The table lists studies of muscle power in experienced footballers. These studies did not use EMG analysis.

Another group of experimenters has used video analysis of unrestrained kicking movements, sometimes in combination with measurements of ground reaction forces. Day (1987) reported maximum knee extension velocities of over 330°/sec (5.9 rads/sec) in children. Putnam (1993) reported knee extension velocities of just over 300°/sec (5.4 rads/sec) and knee flexion velocities at 160°/sec (2.8 rads/sec) in adults.

A later study by Anderson and Sidaway (1994) gave much higher maximum knee extension velocities of 1146 – 1287°/sec and hip extension velocities of 670 – 685°/sec. These data are so much greater than the other authors and from the values to be reported later in this thesis (see results section), that the data processing must be fundamentally different, probably in the amount of smoothing applied.

In his study, Luhtanen (1988) performed high-speed video analysis of kicking. This was aimed at analysis of energy transfer from kicker to the ball rather than analysis of the movement of limb.

None of the studies of high speed kicking movements has used electromyography to study muscle activity during the kicks. This is surprising since most studies aimed to measure muscle strength and so it is important to estimate how large the contribution of antagonist muscle might be.

1.2. Previous Studies of High-Speed Movement Using EMG to Investigate Muscle Co-activation

There is a long history of experiments using isokinetic dynamometers to investigate knee extension torque. Examples of these studies are listed in Table 1.2. These studies have examined both concentric and eccentric movements (Steiner, Harris and

Krebs, 1993; Li, Wu, Maffulli, Chan and Chan 1996; Kellis and Baltzopoulos, 1996a and 1996b; Kellis et al 2001).

Author	Year	Velocity deg/sec	Knee movement	Comment
Ronnie et al	1987	60, 180	Ext & Flex	Peak torque
Alexander	1990	30, 180, 230	Extension	Peak torque
Steiner et al	1993	60, 180	Con & Ecc	Average peak torque
Li et al	1996	60, 120	Con & Ecc	Peak torque
Dvir	1996	30, 120, 210		Peak force
Aagaard et al	1996	30, 120, 240		Peak moment
Kellis & Baltzopoulos	1996a	30, 150		Maximum moment
Kellis & Baltzopoulos	1996b	30, 150, 270	Ecc & Con	Maximum moment
Wilson et al	1997	60, 180		Peak torque
Kellis and Kellis	2001	30, 90, 120, 150	Con & Ecc	Maximum force
Siqueira et al	2002	60, 240		Peak torque
Tsiokanos et al	2002	60, 120, 180		Maximum force

Table 1.2. The table shows the previous studies that have used isokinetic dynamometers to investigate extension and flexion movements. These authors did not use EMG. The investigation used a range of concentric and eccentric velocities.

The maximum speed of movement currently available on dynamometers is 300°/sec. It can be seen that none of the authors in Table 1.3 used the maximum available velocity. Some such as Li et al (1996), restricted the fastest speed to quite moderate values such as 120°/sec. Thus, these experiments have not used the full range of the dynamometer and they have tested speeds of movement much slower than natural speed of movement (Day, 1987; Putnam, 1993; Anderson et al, 1994). This is a surprising difference between natural free performance and restricted single joint movement under dynamometer conditions. In addition, space associated with the free movement, together with the involvement of more joints in the sports activities could have approximately doubled the speed to twice of the dynamometer.

A second group of papers, listed in Table 1.3 has used surface electromyography to investigate the hamstring activity during knee extension movements. Kellis and Baltzopoulos (1996c, 1996d, 1997, 1998 and 1999) have made major studies of this. Almost all of the papers listed use the same modest range of knee extension velocities described above. The exceptions are Amiridis, Martin & Morlon (1996); Miller, Croce and Hutchins (2000) who used 300 degrees per second.

Authors	Year	Isokinetic velocity (°/sec)	Hamstring co-activation
Baratta et al	1988	15	YES
Kellis & Baltzopoulos	1996c	30, 60, 90, 120, 150	YES
Kellis & Baltzopoulos	1996d	30, 60, 90, 120, 150	YES
Amiridis et al	1996	(-120, 300)	YES
Kellis & Baltzopoulos	1997	30	YES
Kellis & Baltzopoulos	1998	30, 90, 120, 150	YES
Kellis & Baltzopoulos	1999	30	YES
Miller et al	2000	60,180,300	YES
Aagaard et al	2000	30	YES

Table1.3. The table shows the previous studies of antagonist muscle co-activation using isokinetic dynamometers with concurrent EMG recording. The movement is knee extension. The hamstring results show consistent co-activation through low and medium range velocities.

All nine of the papers listed in Table 1.3 report significant hamstring EMG during knee extension. The experiments cover a range of velocities from 30 to 300 deg / sec. Only Kellis and Baltzopoulos (1997) have made an attempt to estimate how much force may be delivered by such hamstring activity. Their paper reports a maximum hamstring force of 42 Nm during knee extension. It is not easy to relate surface EMG to muscle force during movement and other authors have avoided this issue.

1.3. Studies of Vertical Jump

A number of biomechanical studies of jumping techniques have been published. These have used a variety of techniques such as the measurement of ground reaction forces or video analysis to study different jumping styles. Table 1.4 gives a list of a variety of jumps (Baca, 1999; Kellis, Arabatzi and Papadopoulos, 2003) where volunteers jump from a platform and land on a force plate. In a video analysis of long jumping, Luhtanen and Komi (1980) report knee extension velocities between 286 and 653°/sec.

The table 1.4 shows vertical jump performance by a variety of sportsmen and women, compared with untrained people and that a variety of techniques have been used. However, only two authors (Viitaselo, Hamalainen, Mononen, Salo and Lahtinen, 1993; Bobbert, Gerritsen, Litjens and Van Soest, 1996) make specific reference to the maximum knee extension velocity during jumps. Viitaselo et al (1993) gives a maximum value of 403°/sec and Bobbert et al (1996) measurement is 394 – 404°/sec.

Authors	Year	Instrumentation	Performance	Knee velocity deg/sec	Comments
Clutch	1983	GRF goniometer	Vertical jump		Male untrained or trained
Viitasalo et al	1993	EMG, GRF, goniometer, video	Vertical jump	403	Male volleyball players
Bobbert et al	1996	video, GRF, EMG	Vertical jump	394 to 404	Male volleyball players
Goodwin et al	1999	Video, EMG	Vertical jump		Female untrained or trained
Kettunen et al	1999	Clinical examinations, X ray, MRI	Vertical jump		Male runners, soccer players, weightlifters.
Nagano and Fukashiro	2000	video, GRF, EMG	Vertical jump		Male untrained or trained
Van Zanelwijk et al	2000	GRF	Vertical jump		Male untrained or trained
Hunter and Marshall	2002	GRF, goniometer	Vertical jump		Basketball &Volleyball
Rodacki et al	2002	Video, EMG	Vertical jump		Male untrained or trained
Toumi et al	2004	Video, GRF, EMG	Vertical jump		Male Trained & control groups
Luhtanen and Komi	1980	Video	Long jump	286 to 653	Athletes
Baca	1999	Video, GRF	Drop Jump		Male volunteers
Kellis et al	2003	Video, GRF, EMG	Drop Jump		Trained male long jump

Table 1.4. The table shows the previous studies of vertical, long and drop jumps. It also shows the techniques used and the groups of athletes studied.

In an investigation of the consistency of jumping technique and the reliability of surface EMG as a tool for investigating high-speed movements, Goodwin, Koorts, Mack, Mai, Morrissey and Hooper (1999) reported that the mean angular velocity of the knee has a mean percentage change of 8.8% between two tests, two weeks apart. Whilst they do not give the angular velocities of the knee directly, the percentage change quoted is 8.8% and the magnitude of the changes 25.9°/sec, suggesting their mean velocity must be about 294°/sec. This agrees well with values given by Viitalaso et al (1993) and Bobbert et al (1996).

Goodwin et al (1999) examined the surface EMG from Rectus Femoris, Vastus Medialis, Biceps Femoris and Gastrocnemius during the jumps. They found that mechanical measures of jump performance such as movement of the centre of mass as the range of motion at joints were the most consistent feature with inter class correlation coefficients (ICC) greater than 0.9. The EMG of RF and VM had ICC of 0.88 and 0.70 respectively whilst BF had on ICC of only 0.24. There was a poor correlation between the angular velocity of the knee and the EMG.

These authors made no attempt to examine co-activation of knee extensors and flexors during movement. The maximum knee extension velocity recorded during jumps is higher than that achieved during maximum kicks by Putnam (1993) and Day (1987), analysed 300 and 330°/sec respectively but much less than the maximum kick velocity of 1146 – 1287°/sec reported by Anderson (1994).

A number of the studies of vertical jumps have used electromyography for a variety purposes but none has investigated co-activation of muscles. Bobbert (1996) used EMG signals to define the beginning and end of the movement. In addition, Bobbert (1996) and Nagano (2000) used EMG signals as inputs to algorithms, which use inverse dynamics to predict muscle forces. Goodwin et al (1999) were principally interested in the reliability of biomechanical and EMG signals during repeated movements. Van Zanelwijk, Bobbert, Munneke and Pas (2000) used surface EMG to investigate changes in muscle activation before and after a training programme.

Whilst Rodacki, Fowler and Bennett (2002) used changes in RMS EMG to investigate changes in muscle activity associated with fatigue, Toumi, Best, Martin, F'Guyer and Poumarat (2004) compared EMG activity before and after a training programme. Only Kellis et al (2003) has investigated co-activation of Rectus Femoris and Biceps Femoris but that was during drop jumps, not in vertical jumps. It is interesting to note that co-activation was a consistent finding in these experiments.

1.4. Effect of Training on Surface EMG

It is clear that much of the strength increase observed in the first few weeks of a training programme came from more complete activation of the motor neurons pool supplying a muscle (Sale, 1992). The first who described strength training of the elbow flexors was by Peterson (1960). A similar effect has been observed many times in muscles of the lower limbs.

Strength training of the knee extensors increased the surface electromyogram in experiments reported by Komi, Viitasalo, Rauramaa and Vihko (1978), Hakkinen, Alen and Komi (1985), Rutherford, Greig, Sargeant and Jones (1986), Jones and Rutherford (1987) and Aagaard, Simonsen, Andersen, Magnusson and Poulsen (2002). Sale (1988) also found increased EMG after training of the hamstring flexor muscles of the knee and in gastrocnemius.

There may be differences in the neural phase of training in some of the muscles of the hand. Sale, McComas, MacDougall and Upton (1982) described a reduction in the EMG of the thenar muscles after training by maximum voluntary contraction (Carrolan and

Carfarelli (1987)). This may reflect different motor strategies for muscles in the hand and in the lower limb.

In addition to the question of how fully activated a muscle might be during a maximal effort, there is a second question of how complete the separation of the agonist and antagonist muscles is. A number of papers in the literature describe simultaneous activation of antagonist pairs of muscles. The net effect of this must be a reduction of net torques at a joint i.e. a weaker contraction or a slower movement.

Antagonist co-activation is widespread. It is reported in the upper limb (Paul and David, 1998), in the axial muscles of the trunk (Mirka, Glasscock, Stanfield.and Wilson, 2000) and in the lower limb (Hubley-Kozey and Earl, 2000). In addition, there is the widely reported problem of hamstring co-activation during isokinetic dynamometer tests of knee extension. This was discussed at length earlier in this chapter and there is a volume of published work listed in Table 1.3, page 10.

Co-activation of antagonist muscles is found in men and women (Macaluso, Nimmo, Foster, Cockburn, McMillan and De Vito, 2002), and in children and adults (Kellis and Unnithan 1999). It affects fast and slow contracting muscles (Hubley-Kozey and Earl, 2000; DeVito, McHugh, Macaluso and Riches, 2003). It also persists in the fatigued state where co-activation may be more significant (Weir, Keefe and Eaton 1998; Kellis & Kellis, 2001).

1.5. Training and Co-activation

There have been a number of recent investigations into the question of how a period of training affects the extent of co-activation. This body of literature is summarized in Table 1.5. The generally agreed position is that co-activation decreases with training. Bernardi, Solomonow, Nguyen, Smith and Baratta (1996) and Colson, Pousson, Martin and Van Hoecke (1999) tested the effect of a short period of strength training on the extent of co-activation of biceps femoris and triceps brachii.

The former authors used a conventional 6-week strength-training programme whilst the latter used one week of eccentric training. Both groups observed a reduction in co-activation.

There have been more studies of knee extensor, knee flexor antagonist pairs. Training periods between 3 weeks and 48 weeks show reductions in knee extensor/flexor co-activation (Baratta, Solomonow, Zhou, Letson, Chuinard and D' Ambrosia 1988; Osternig and Robertson 1990; Carrolan and Cafferelli 1992; Kellis and Baltzopoulos 1996a, b; Hakkinen, Kallinen, Izquierdo, Jokelainen, Lassila, Malki, Kraemer, Newton and Alen 1998; Hakkinen, Alen, Kallinen, Newton and Kraemer 2000).

Author	Year	Muscle Pair	Effect on Co-activation	Type of training and duration
Baratta et al	1988	QF, H	Decrease	Strength training 3 weeks
Osternig & Robertson	1990	VL, BF	Decrease	
Carrolan & Cafarelli	1992	VL, BF	Decrease	Strength training 8 weeks
Amiridis et al	1996	VL, VM, ST	Decrease	High jumper
Bernardi et al	1996	BB, TB	Decrease	Strength training 6 weeks
Kellis & Baltzopoulos	1996a	VL, RF, VM, H	Decrease	
Kellis & Baltzopoulos	1996b	VL, RF, VM, Hams	Decrease	
Hakkinen et al	1998	VL, VM, BF	Decrease	Strength training 7 months.
Colson et al	1999	BB, TB	Decrease	Eccentric exercise training 1 week
Hakkinen et al	2000	VL, VM, BF	No change	Strength training 48 weeks
Hortobagyi & DeVito	2000	VL, BF	No fixed pattern	Resistive exercise 7 days
Pinniger et al	2003	SOL, MG, TA	Decrease	

Table.1.5. The table lists the studies of the effect of training on antagonist muscle co-activation. The results show a decrease in co-activation.
BB- biceps brachii, TB- triceps brachii, BF- biceps femoris, QF- quadriceps femoris, H- hamstring, VL- vastus lateralis, VM- vastus medialis, ST- semitendinosus.

This increased separation of muscle activation is also seen with ankle plantar flexors and dorsiflexors (Pinninger, Steele and Cresswell 2003).

All of these studies have tested forms of strength training with large resistance loads. There are no studies which have investigated the effects of other training types. It should be noted that the footballers and jumpers whose co-activation patterns were described earlier are unlikely to have had much experience of strength training.

Enoka (1997) in his invited lecture to the International Society of Biomechanics discussed the functional role of antagonist co-activation. He suggested that co-activation is a strategy adopted by the central nervous system when “there is some uncertainty about a task”. The net effect would be slow movements and reduced joint forces. This idea fits the results reported earlier where exposure to training, involving repetitions of the same task, reduces co-activation and increases forces.

It does not fit the co-activation seen in experienced football players or jumpers unless one supposes that knee extension tasks performed on an isokinetic dynamometer are so unlike kicking or jumping to constitute a novel task.

1.6. Force Development during Eccentric Activity

The earliest experiments on the force-velocity relationship for skeletal muscle showed that the force of contraction falls as the speed of muscle shortening increases (Hill, 1938). When muscle is activated and then stretched, it can develop significantly more force than it does during an isometric contraction, where the velocity is zero. This muscle activation during stretch is termed eccentric activity and as the velocity of muscle stretch increases, so does the force. An early description of this phenomenon was made by Hill (1938) who reported that eccentric forces in the frog sartorius could be 180% of isometric force. Katz (1939) described similar results but gave an eccentric/isometric ratio of 200%. More recent reports of this give ratios of 166% for frog sartorius (Flitney and Hirst, 1978), 120% for frog tibialis anterior (Lombardi and Piazzesi, 1990) and 183% for medial gastrocnemuis of the cat (Gregory, Brockett, Morgan, Whitehead and Proske 2002). In each case the muscle under investigation was maximally activated by tetanic electrical stimulation. The ability to study the mechanical performance of human muscle during eccentric activity is more restricted. In almost every investigation the muscles are activated voluntarily and this introduces the question of motivation and technique. High velocity stretches are often delivered by isokinetic dynamometer whose maximum rotational velocity is limited to about 300 degrees/second and so the displacement of the knee through 100 degrees will take only a little longer than the human reaction time. It is difficult for any volunteer to make a truly maximal effort in these circumstances. A significant advance in this area was made by Westing, Seger, Karlson and Ekblom (1988) who were able to combine maximal electrical stimulation of the quadriceps of human volunteers with muscle stretches. They report an eccentric/isometric force ratio of 233%. This is very similar to the values reported for similar experiments on isolated animal muscle.

The electrical stimulation ensures uniform activation of the muscle and avoids any problems with changing motivation as technique. It must have been very uncomfortable for the volunteers and it is not surprising that there have not been other papers using this approach.

Table 1.6 lists a series of other publications reporting the eccentric force development during stretches of human muscle with voluntary activation. Only the earliest by Komi and Buskirk (1972) shows eccentric/isometric ratios below 100%. This is for elbow flexors in untrained individuals and may be due to low levels of motivation or technique.

Table 1.6A				
Authors	**Year**	**Ratio of Ecc / isometric Force**	**Muscles studied**	**Comments**
Komi & Buskirk	1972	60%	Forearm flexors	Untrained
Eloranta & Komi	1980	113%	Leg extensors	Untrained
Seger et al	1988	98%	Quadriceps femoris	Untrained
Westing et al	1988	233%	Quadriceps femoris	Electrical Stimulation
Alexander	1990	135%	Leg extensors and flexor	Elite sprinters
Westing et al	1990	180%	Knee flexors	Trained athlete
Li	1995	132%	Knee extensors and flexors	Untrained
Donne & Luckwill	1996	122%	Knee extensors	Untrained
Elizabeth et al	1996	151%	Knee extensors	
Kellis & Baltzopoulos	1998	107%	Knee extensors and flexors	Untrained
Kellis	2001	149%	Knee extensors	Untrained

Table 1.6B				
Author	**Year**	**Ratio force**	**Muscle studied**	**Animal**
Hill	1938	180%	Sartorius	Frog
Katz	1939	200%	Vertebrate	Frog
Flitney & Hirst	1978	166%	Sartorius	Frog
Lombardi & Piazzesi	1990	120%	Tibialis anterior	Frog
Gregory et al	2002	183%	Medial gastrocnemius	Cat

Table1.6. The table shows many studies concerned with eccentric contraction force development. A - Human studies . B - Animal studies.

A range of other papers in the last 25 years show eccentric forces up to 180% of isometric force. The values of this ratio tend to be lower than in the animal studies and lower than Westing et al (1988) with electrical activation. This has led to speculation about reflexes, which limit force during eccentric activity (Spurway, Watson, McMillan and Connolly, 2000). It is not known whether these are distinct from volitional effects perhaps related to apprehension about pain or injury, or from volitional failure to excite muscle because of there being too little time to activate long latency stretch reflexes. These will typically have a central delay more than 150msec in the lower limb muscles (Rothwell, 1994).

At any rate it is clear that eccentric stretch of human muscle is capable of delivering forces substantially larger than those seen in isometric conditions or when a muscle shortens. Co-activation will produce activity during stretch i.e. eccentric activation during fast knee extension. This raises the possibility of a co-activation of hamstrings muscle being rapidly stretched. This has the potential to deliver high forces, which may be large enough to damage the muscle (Newham, Jones and Clarkson 1987; Clarkson and Tremblay 1988; Whitehead, Allen, Morgan and Proske 1998; Proske and Morgan 2001).

1.7. Aims: The main aims of this thesis are:

1- To investigate the activity of the hamstrings during high velocity knee extension movements.

2- To attempt to relate the magnitude of the hamstring co-activation to the velocity of the knee extension.

3- To investigate the timing of EMG hamstring co-activation during knee extension.

By doing this, the author hopes to improve the understanding of the hamstrings in high velocity movements and perhaps gain some understanding of why hamstrings are injured so frequently.

2. Materials and Methods Section

This section describes the methods used to undertake the study. The quadriceps and hamstring muscle EMG activity during minimum, median and maximum power were examined. Three series of experiments were carried out in the laboratory.

The first series studied was of free performance of vertical jumps in an untrained adult volunteer. The second studied was in the free kicking of a stationary football by trained young footballers and untrained adult groups. The third series was a study of high-speed isokinetic (200°/sec) knee extensions and flexion on the dynamometer (Kin Com).

2.1. Electrodes Setup of Electromyography

The EMG surface electrodes bipolar configuration was standardized. Each muscle had two electrodes attached, one positive and the other negative, with one electrode earthed.

The volunteer lay face down to facilitate the location of Biceps Femoris, Semitendinosus and Semimembranosus. This was done by asking the volunteer to contract his muscle by strong isometric contraction, to define the bulk location of muscle (see e.g. Kellis and Baltzopoulos, 1996c).

A-

B-

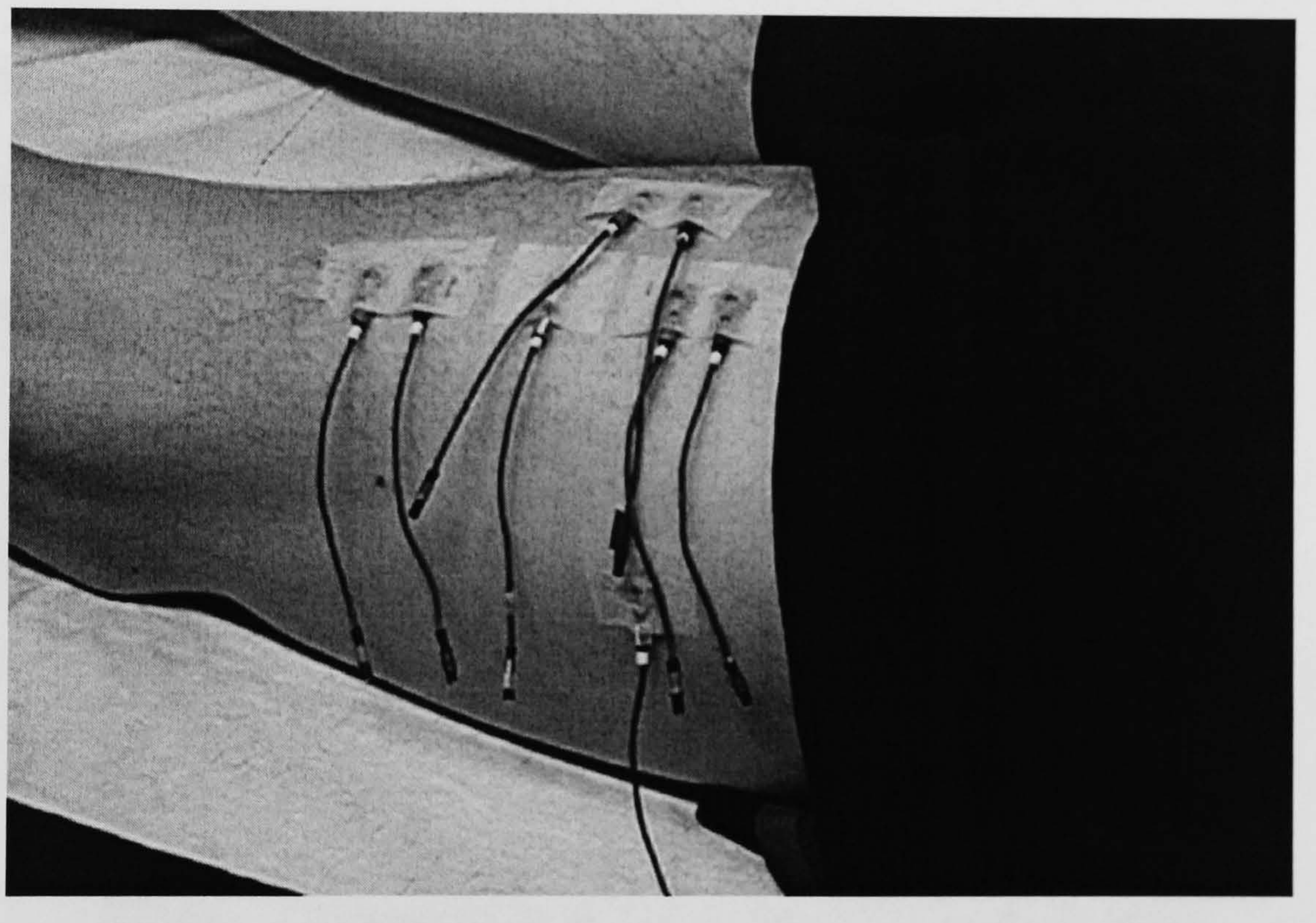


Figure 2.1. The figure shows how the muscle was identified on the posterior view of the thigh. a) Shaved skin cleaned with alcohol. b) Electrodes set up on the muscle.

The skin was marked to identify muscle location and for specific placing of electrodes. In order to improve the EMG recording, a small area of skin was selected and shaved (4 x 2 cm) and swabbed using isopropyl alcohol BP. When the skin dried, the electrodes were coated with conductive gel and attached by tapes, as shown in Figures 2.1a and b. A similar method was used to apply electrodes over Vastus Lateralis.

To avoid excessive electrode wire movement on the superficial muscle during high-speed movements, soft catering cling film was used. The cling film was wrapped round the leg to cover the electrodes after moistening the skin for added adhesion. Cling film is made from nylon elements, which stretch easily when wrapped over electrodes, giving both flexibility, and an accurate fit and allowing easy wire connections through the pierced film

Figure 2.2. The figure shows the subject with cling film covering the electrodes on the upper leg of posterior view.

2.2. Electrogoniometers

This device is made by Biometrics Ltd (Nine Mile Point Ind. Est., Gwent, NP11 7HZ UK). Two electrogoniometers recorded knee flexion and extension. They were attached over the knee and hip on the lateral side of the subject as they stood in a natural standing position on a flat surface. The distal end of the block was mounted laterally on the joint so the axes of the leg and end block coincided when viewed in the sagittal plane (see Figure 2.3).

Figure 2.3. The figure shows the electrogoniometer fixed on the lateral aspect of the knee joint.

This is simple to apply because it crosses the joint without requiring alignment with the axis of rotation. The volunteer made several trial knee or hip flexion and extension movements to ensure the Spike 2 software had registered correctly from electrogoniometers. The electrogoniometer signals were filtered before being digitised at 100Hz by CED 1401 micro A-D converter (Cambridge Electronic Design, Cambridge, UK)

2.3. Electrogoniometers and measurement of joint position

The electrogoniometer calibration was performed on the knee and hip joints for flexion and extension movements in each experiment. The initial calibration set each electrogoniometer at 12 known positions every 15 degrees from, 0 to 180 degrees. The output voltage was sampled with Spike 2. Data was saved for analysis (see Figures 2.4 and 2.5). It is clear that both electrogoniometers have linear correlation with joint positions. Therefore the correlation equation can be used to translate output voltage values into angles.

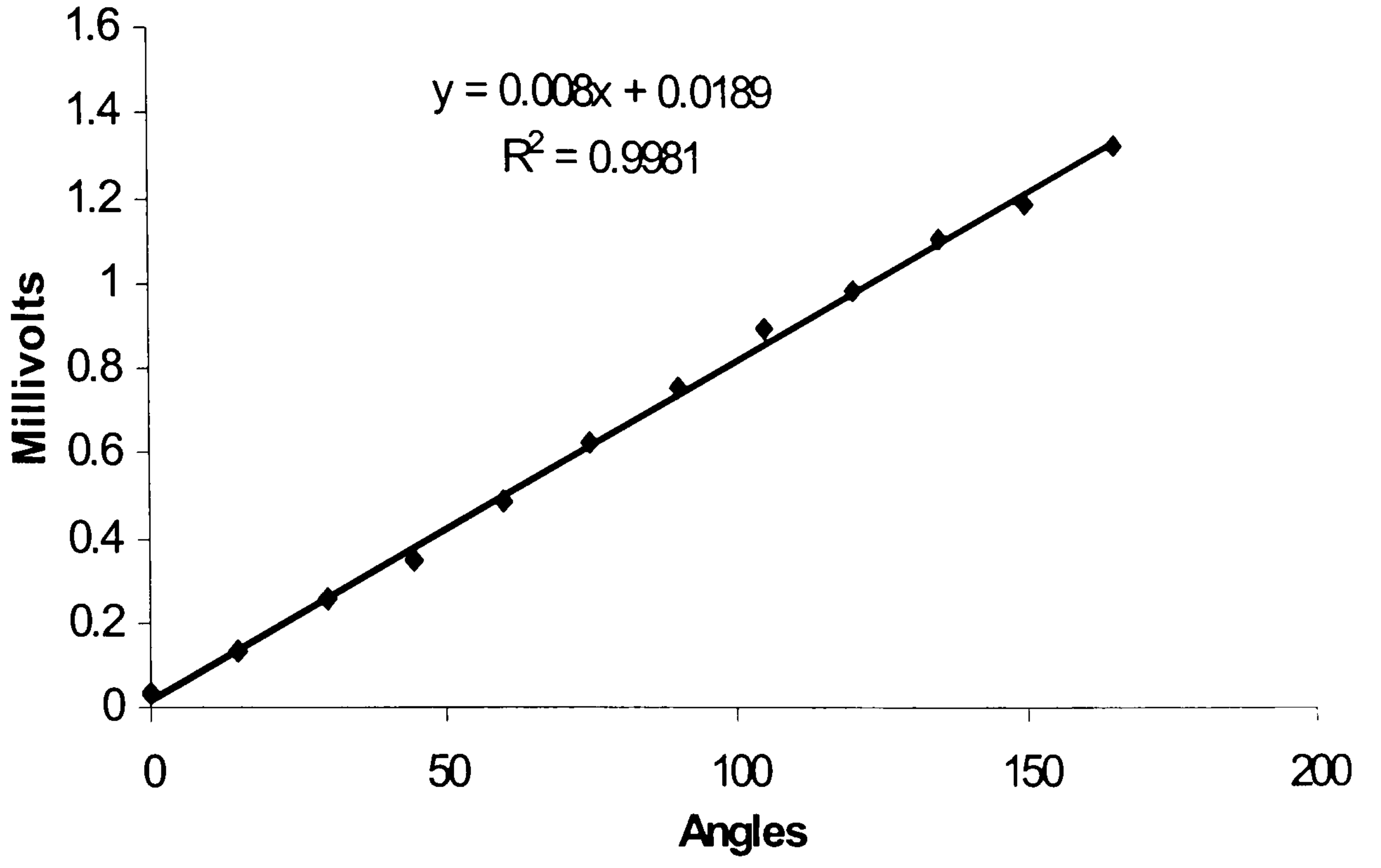


Figure 2.4. The figure shows the calibration of the electrogoniometer used to measure knee joint position.

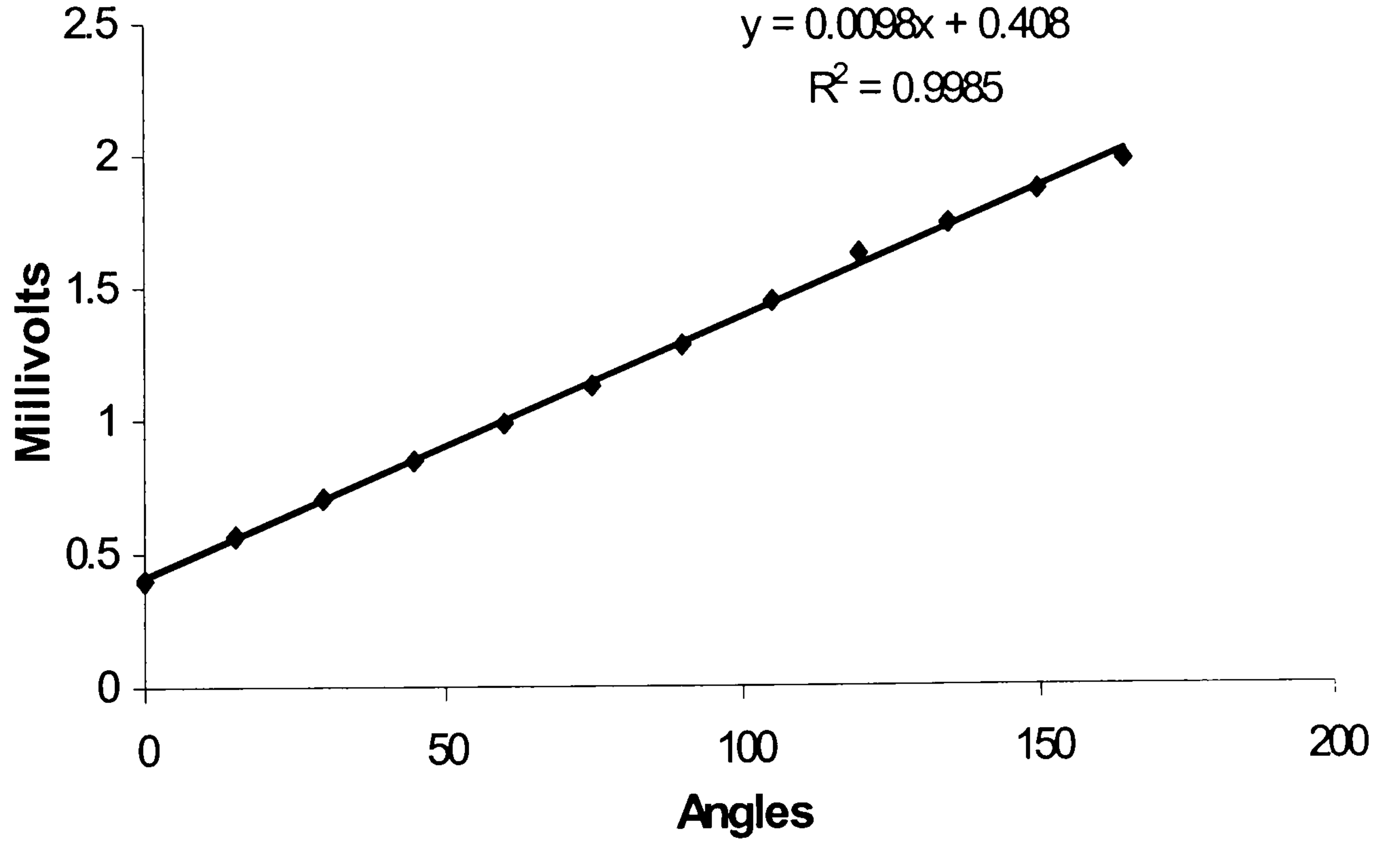


Figure 2.5. The figure shows the calibration of the electrogoniometer used to measure hip joint position.

2.4. Calculation of velocity of angle movement

The electrogoniometer signal was digitised at 100 Hz by the CED 1401 using version 3 of the Spike 2 software. The range of joint movement was identified by placing cursors at the appropriate positions on the traces. The voltage signals measured at the cursors could be converted in angles using the formulae described above. The velocity of joint movement was measured using the 'slope' function of Spike 2. This calculates the best-fit straight line to the curve between two cursors. The cursors were moved along the curve until a maximum gradient was found.

2.5. Electromyography Set-up

Chlorided silver electrodes 9 mm in diameter– (SLE Diagnostics, South Croydon Surrey CR2 6PL UK) were connected to two AC pre-amplifiers and each pre-amplifier has two channels. The amplifiers were fixed to the back of a waist belt (see Figure 2.6).

The NL 822 AC Pre-Amplifier has gain of x1000. This produced amplified signals of up +/- 2.5V. These are illustrated in figures 2.14 and 2.15. This is close to the maximum input range for the 16 bit A/D converter and it ensured good signal conversion.

The NL 822 has a selectable low frequency cut off. This was set at 3Hz to eliminate movement artefacts caused by limb movements or cable movements. This filter rejected the movement artefacts but did not alter the electromyogram which has very little energy in frequencies below 5Hz.

Figure 2.6. The figure shows the subject fitted with the waist belt with two pre-amplifiers set up.

Two of the pre-amplifiers were connected to the T connector [NL 969T] and then to the NL 820 isolator unit. This module was connected into the Neurlog system. The EMG signals were fed to a CED 1401 micro A-D converter (Cambridge Electronic Design, Cambridge, UK). This offers 16 bit analogue to digital conversion on up to 16-waveform channel recordings simultaneously at independent frequencies up to 80 kHz. The input voltages on the EMG channel were up to +/- 2.5 volts after amplification. These signals were well resolved by the converter since they were close to its maximum input range.

The EMG of four thigh muscles (Vastus Lateralis, Biceps Femoris, Semitendinosus and Semimembranosus), were recorded through Spike 2 software. Each channel was digitised at 1000 samples/sec. This is well within the maximum sampling frequency of the 1401. It also provides good temporal resolution of the EMG. The EMG spectrum does not contain frequencies in excess of 400 Hz and so the signal will not be distorted or degraded by inappropriate sampling rates.

The EMG data could be filtered digitally after recording to modify the signal and remove any unwanted frequencies. Spike 2 provides a set of digital filters that can be selected and modified.

Additional high pass filtering was used when movement artefacts were a particular problem. The digital filter was set at 20Hz and it was 3 dB down at 18.3 Hz. In some experiments the electromyogram was recorded with significant noise components from the background mains supply at 50 Hz. These signals were filtered with a band stop filter centred at 50 Hz with a transition gap of 9.7 Hz. It was 3 dB down at 40 and 64 Hz.

2.6. Foot Switches

Two small switches were taped under the shoe, one on the heel side and the other under the toe side of the right shoe. The switch closed when loaded and opened when unloaded. They are shown in Figure 2.8. The switch closures were recorded in Spike 2 and could be used to facilitate the data analysis.

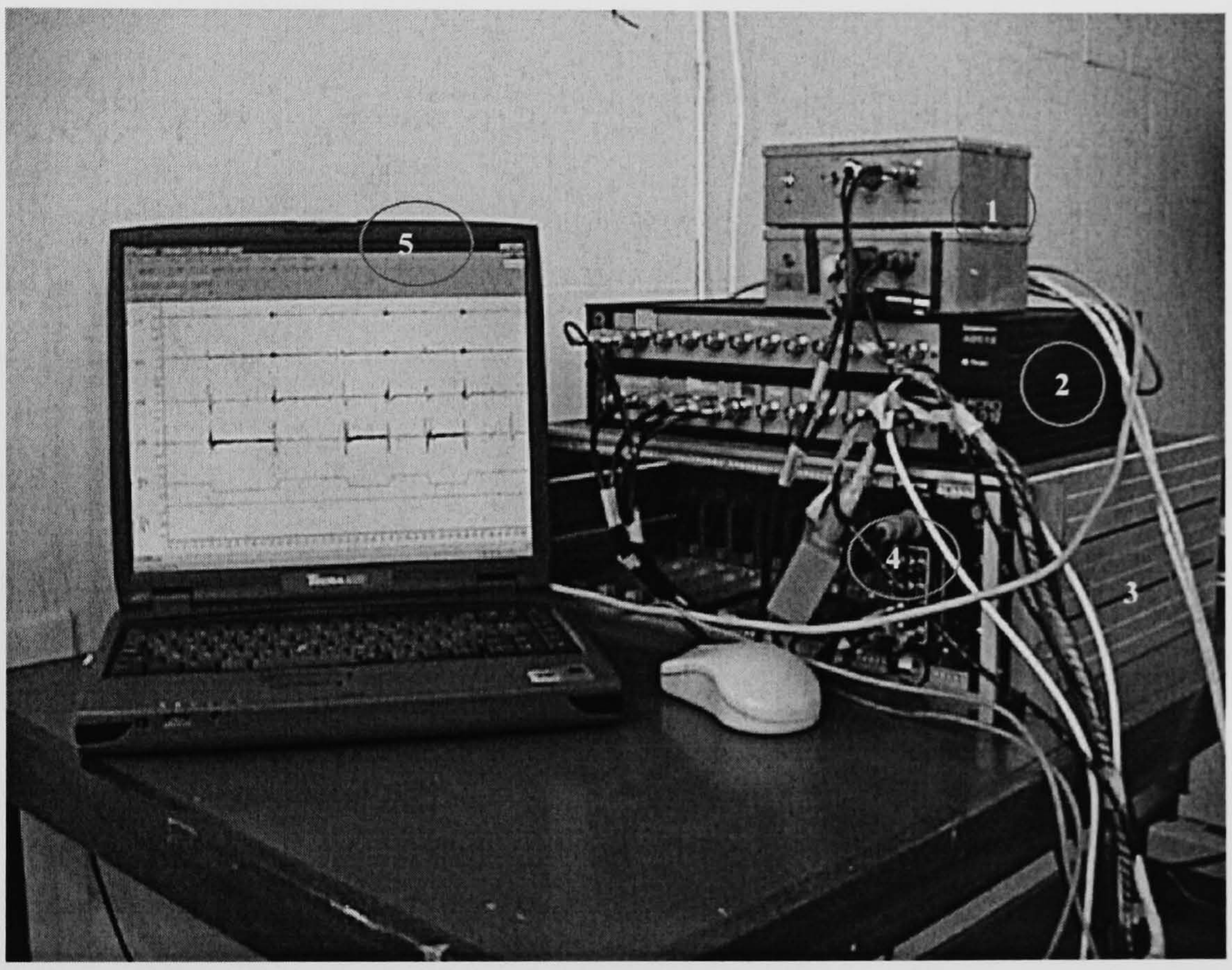


Figure 2.7. The figure shows the equipment. 1- electrogoniometer amplifier. 2- 1401 A/D converter. 3- neurolog system. 4- T Connecter of pre-amplifiers. 5- Laptop with Spike 2 software.

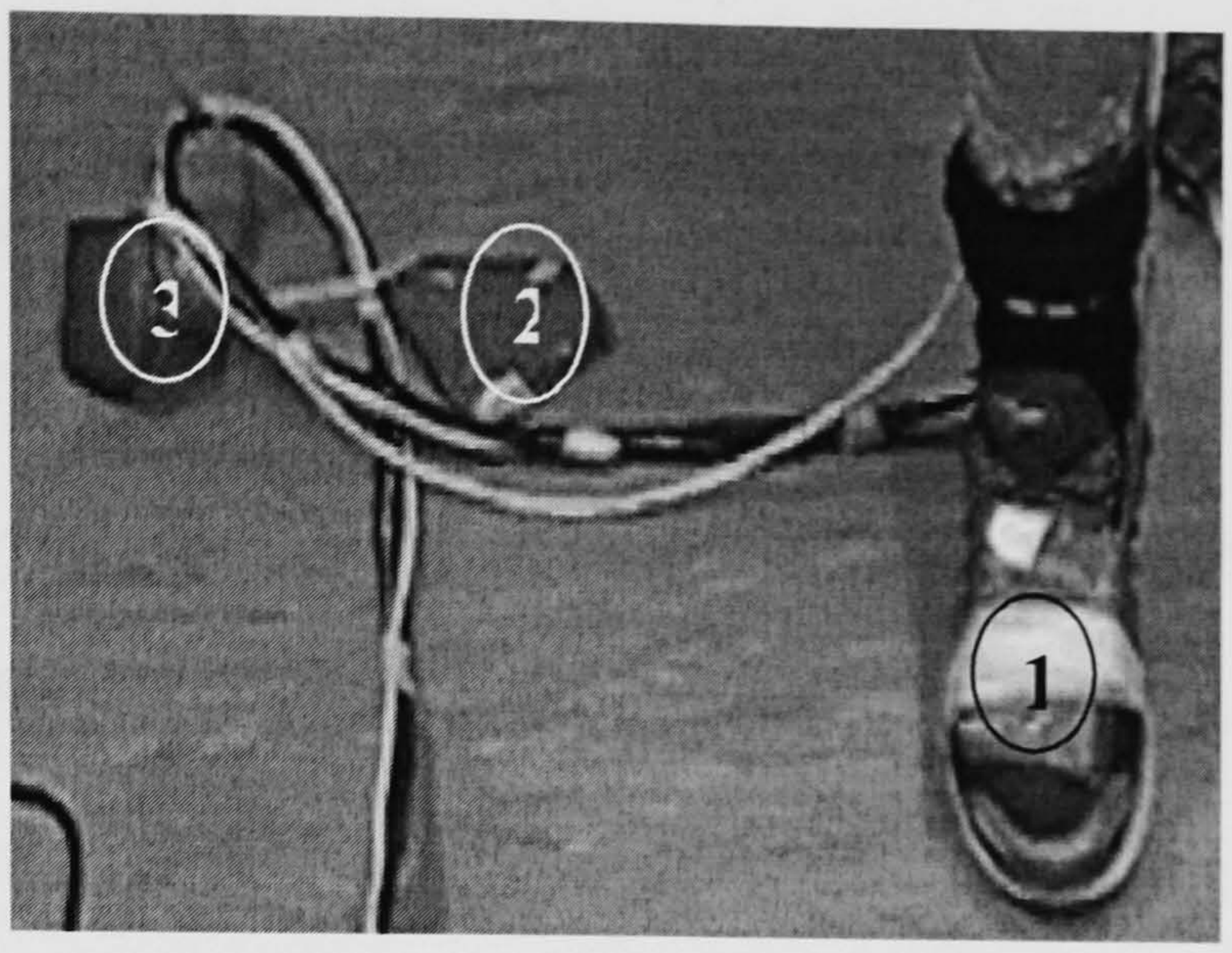


Figure 2.8. The figure shows the foot switch device set up on the shoe.

2.7. Ethical Approval

The design of the experiment was reviewed and approved by the University of Glasgow Research Ethics Committee. Each volunteer was informed of the purpose of the study and given laboratory familiarisation. Volunteers were also made aware of their right to terminate participation at any time and without penalty and were encouraged to ask any questions during any part of the study. They signed statements of informed consent.

2.8. The Vertical Jump Experiment

2.8.1. Volunteers

The volunteers were recruited from the students and employees of the University of Glasgow by an invitation placed on the university web site. In total, fourteen male volunteers participated in the vertical jump study and each of them had an initial visit to the laboratory for familiarisation and an explanation of the nature of the test. They were healthy and recreationally active and had no history of ill health. The volunteers' height was measured with a wall-mounted stadiometer. They were weighed on a standard set of Avery scales. The mean age of the volunteers was 35.7 $\pm$ 6.9 years, the mean height 178.9 $\pm$ 7.0 cm and the mean body mass 80.6 $\pm$ 8.8 kg. Details of the volunteers are summarised in Table 2.1.

Subject	Sex	Age (Year)	Height (cm)	Weight (kg)
1	M	40	166	67
2	M	40	178	69
3	M	35	176	72
4	M	41	178	72
5	M	43	176	75
6	M	28	170	79
7	M	27	171	80
8	M	39	185	83
9	M	25	187	83
10	M	39	185	85
11	M	23	180	87
12	M	42	177	88
13	M	41	186	91
14	M	37	190	97

Table 2.1. The table shows the characteristics of volunteers who completed the vertical jump study. The data is ranked by body weight.

2.8.2. Equipment used in the Vertical Jump Experiment

The experiment requirement for this study was electromyography to examine Vastus Lateralis, Biceps Femoris, Semitendinosus and Semimembranosus. In addition, an electrogoniometer was used to record knee movements and foot switches on the heel and toe of the shoe were used determined take off and landing. In addition, a jump mat was used to show take off and landing. The mat was connected to 1401 system and signals from it were captured by the 1401 using Spike 2 software.

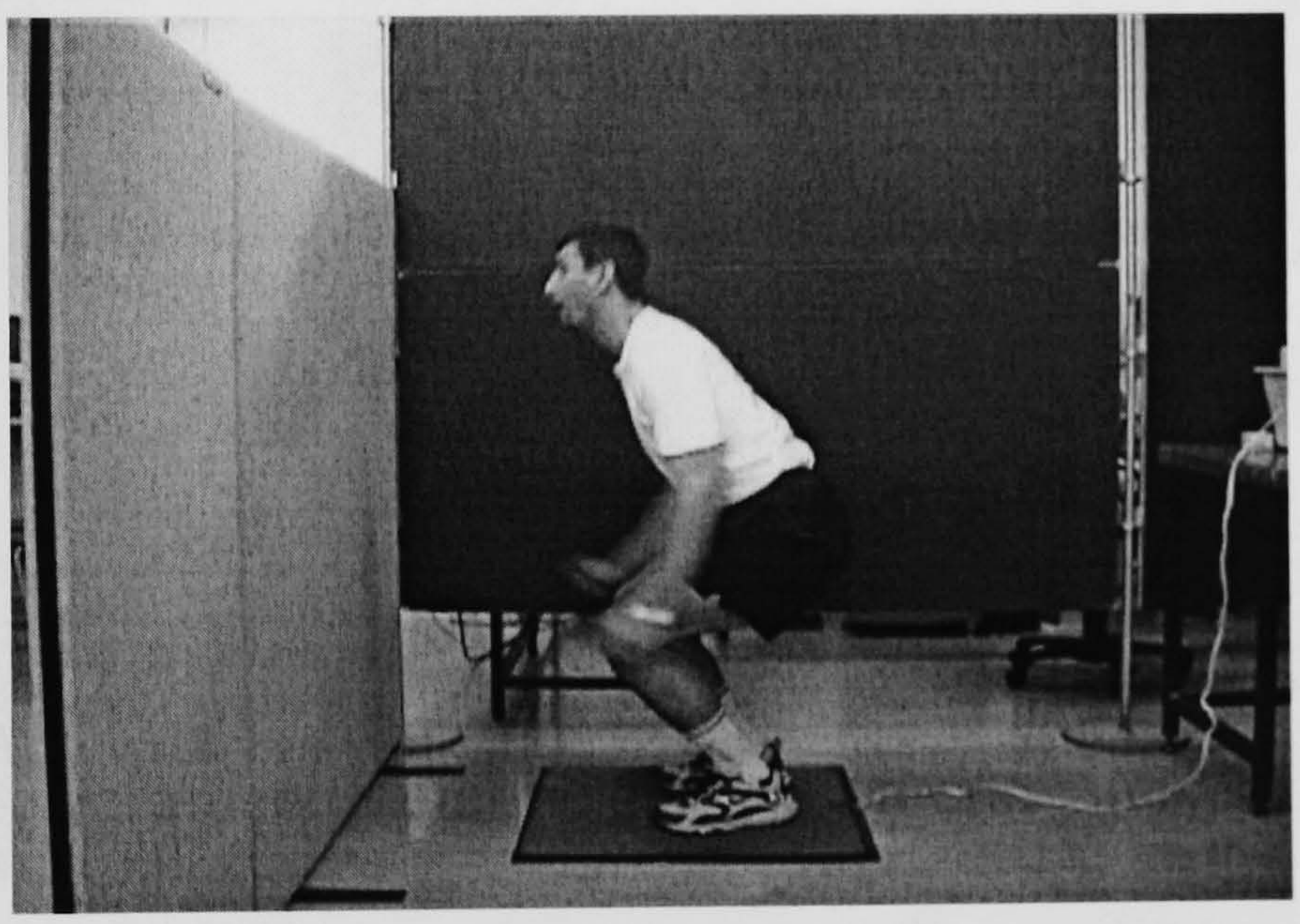


Figure 2.9. The figure shows the position of a volunteer before take-off in vertical jump experiment.

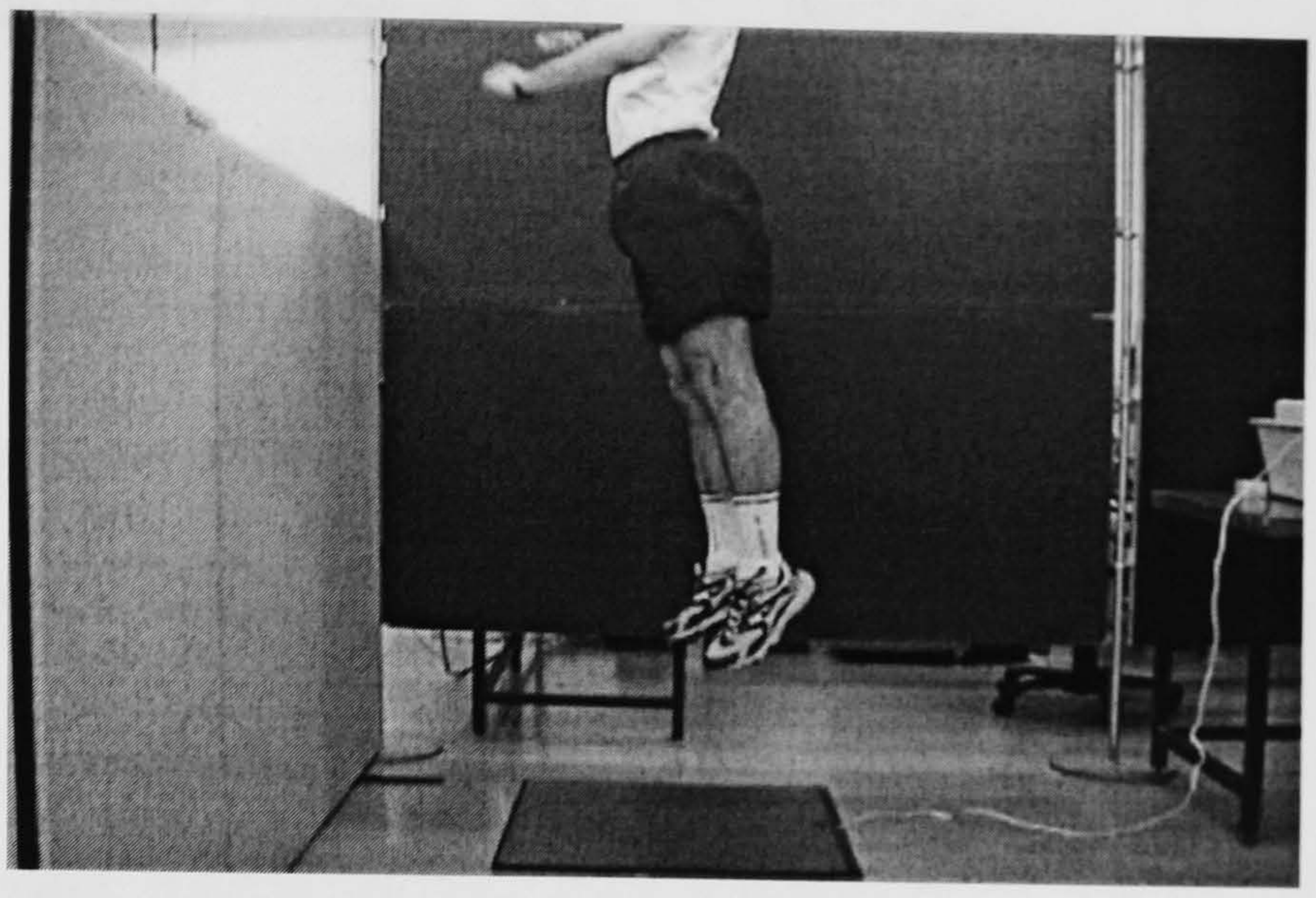


Figure 2.10. The figure shows the volunteer after take-off.

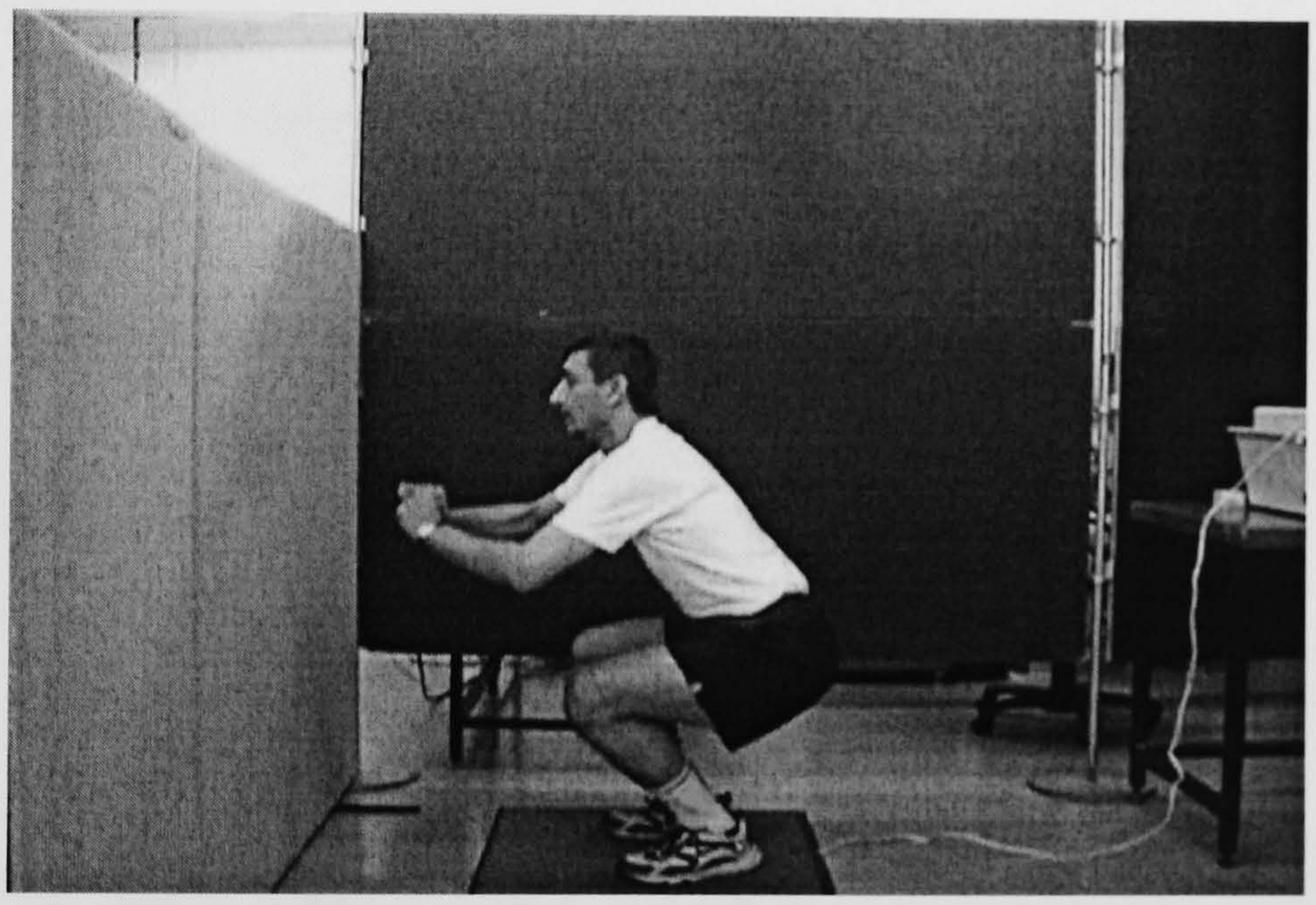


Figure 2.11. The figure shows the volunteer in the landing position.

2.8.3. Design of Experiment

The purpose of this experiment was to investigate EMG activity during vertical jumps at maximum, median and minimum power.

Each volunteer made a series of 10 progressively more powerful vertical jumps, starting with the least powerful. The maximum, median and minimum power vertical jumps were identified later. All volunteers completed vertical jumps at all sessions successfully. The original Spike 2 software recorded EMG activity of Vastus Lateralis, Biceps Femoris, Semitendinosus and Semimembranosus and an electrogoniometer recorded knee movements and a jump mat recorded the take off and landing (see Figure 2.12).

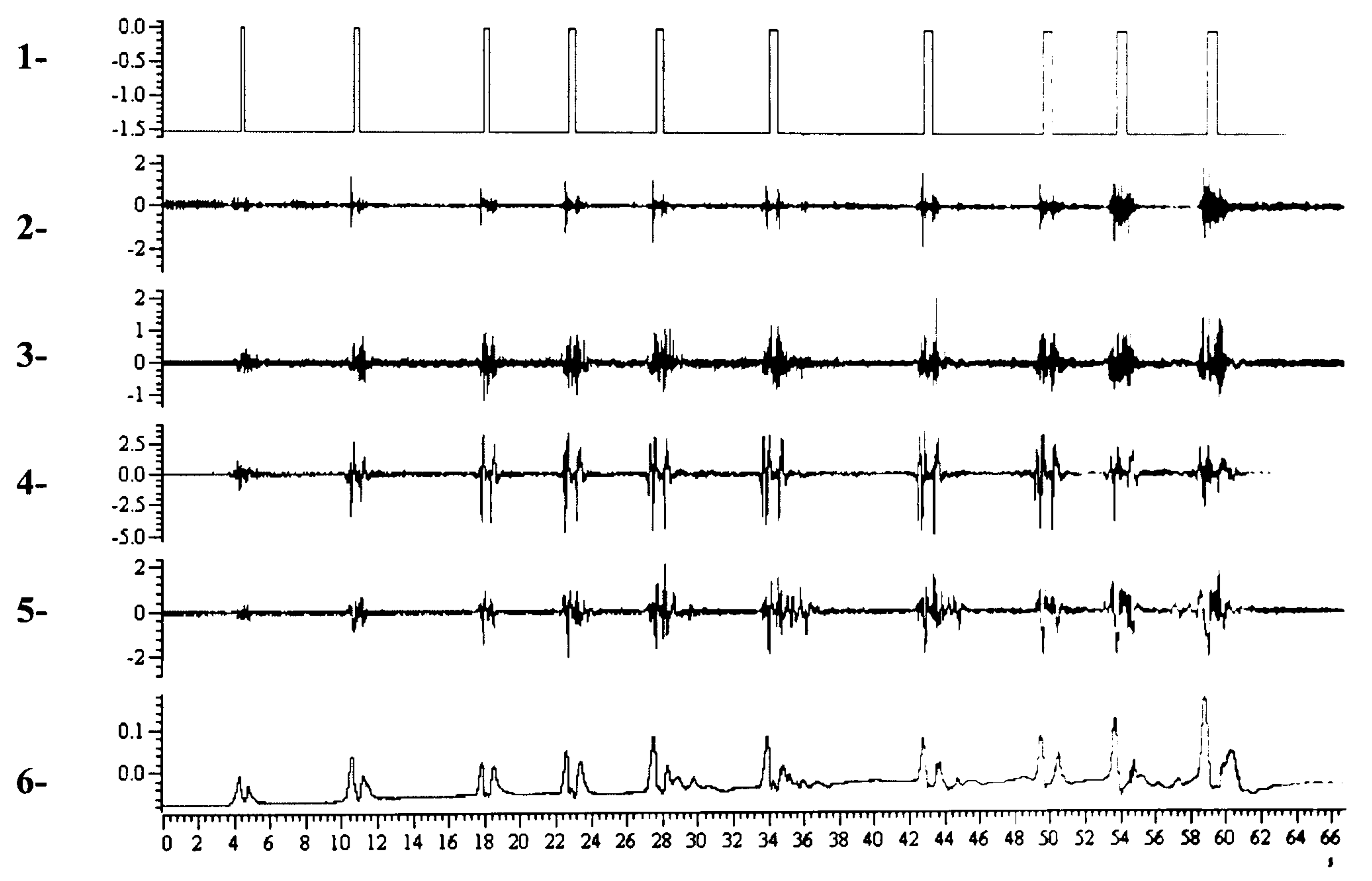


Figure 2.12. The figure shows the sample raw data of EMG from a volunteer performing 10 vertical jumps from minimum to maximum power. The channels show: 1- Jump mat, the signal goes to 0 volts when the jumper is in the air. 2- EMG activity of the biceps femoris muscle (BF). 3- EMG activity of the semitendinosus muscle (ST). 4- EMG activity of the vastus lateralis muscle (VL). 5- EMG activity of the semimembranosus muscle (SM). 6-Knee movement recorded by electrogoniometer.

2.9. Experiments using the Isokinetic Dynamometer

2.9.1. Volunteers

Ten male volunteers participated in Kin Com experiments. All volunteers were healthy recreationally active students recruited from the University of Glasgow student population. The volunteers' heights were measured with a wall-mounted stadiometer and were weighed on a standard set of Avery scales. The means with standard deviations were as follows: age of the volunteers 21 $\pm$ 1yrs; height, 178 $\pm$ 4cm; body weight 85 $\pm$ 7 kg. Details of the volunteers are summarised in Table 2.2.

Subject	Sex	Age (Year)	Weight (kg)	Height (cm)
1	M	21	70	175
2	M	22	80	173
3	M	21	81	184
4	M	21	85	172
5	M	21	87	178
6	M	23	88	180
7	M	20	89	181
8	M	22	90	181
9	M	21	93	182
10	M	22	82	174

Table 2.2. The table shows the characteristics of volunteers who completed the isokinetic study.

2.9.2. Equipment used in the Isokinetic Study

The dynamometer apparatus was built by Kin-Com, (Wellness by Design, Chattanooga Group. Inc. PN 57682. Rev A 06/95). It was set to regulate knee extension and flexion movements at 200°/sec. On the day of the experiment, the volunteer had EMG electrodes placed on the skin over the muscles and covered by cling film wrapped around the thigh (see Figure 2.13). For this experiment, no warm up or specific exercise was required.

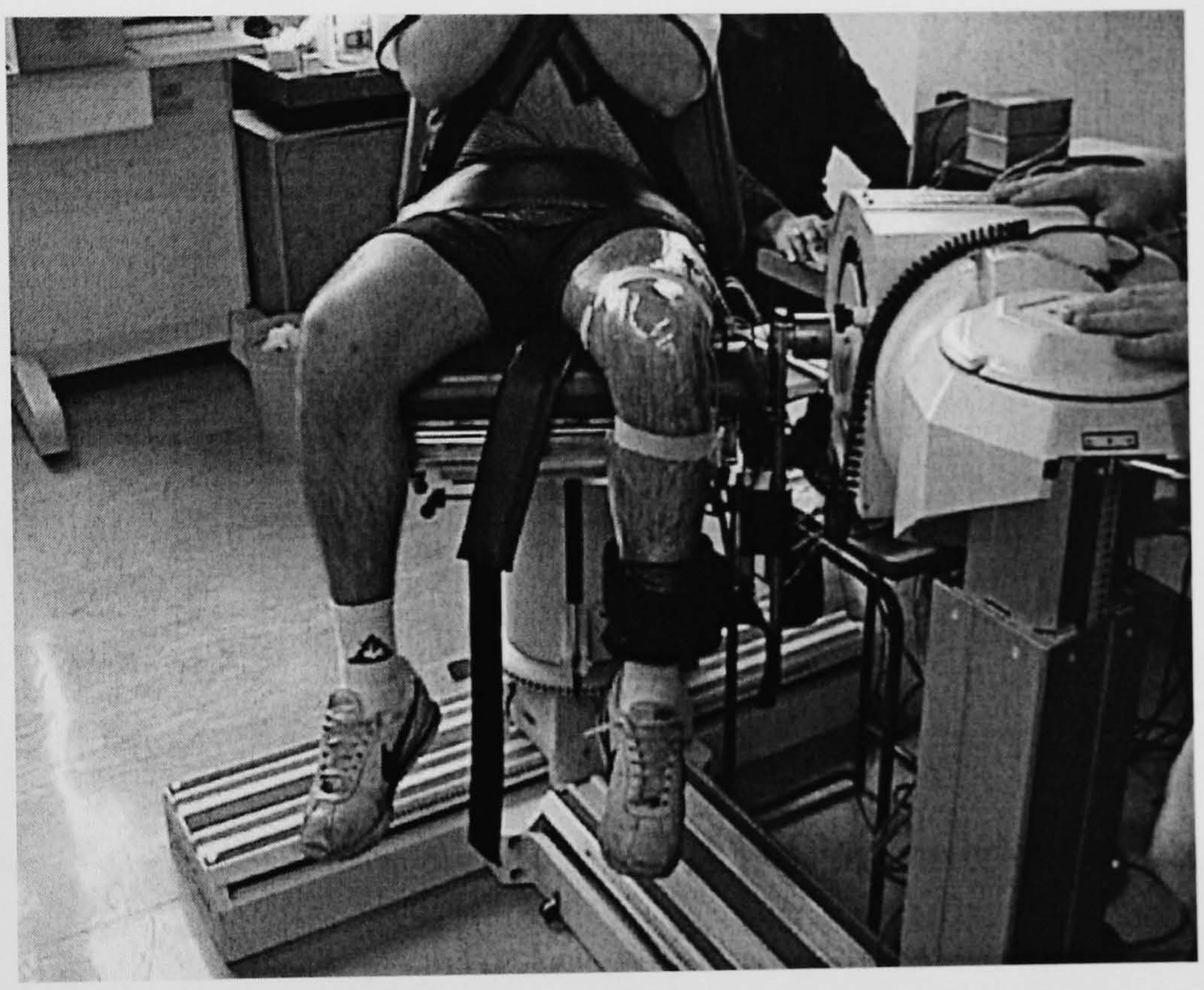


Figure 2.13. The figure shows the subject in a seated position on the Kin Com.

There were two types of isokinetic experiment. In the first series of experiments, the volunteer made three maximal single knee extensions and flexions at 200°/sec. Each volunteer was then allowed a 10 second rest. In the second test they made 5 successive repetitions of knee extension and flexion movement at the same velocity.

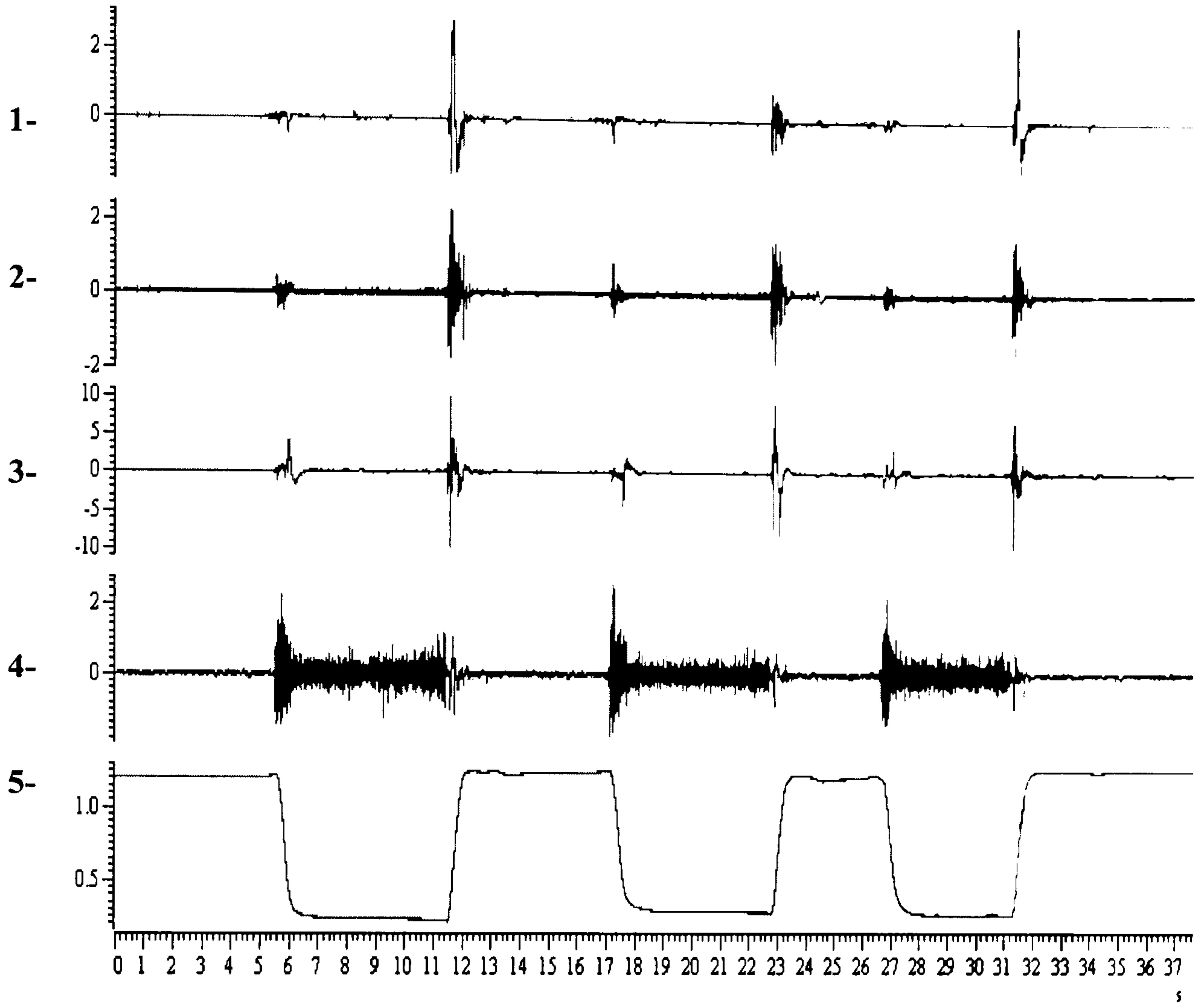


Figure 2.14. The figure shows three single knee extension and flexions at 200 deg/sec. Unprocessed EMG data was recorded during knee extension and flexion movements. The first top three channels express the hamstrings (1- BF, 2- ST, 3- SM), after that (4- VL) recording. The lowest single channel illustrates the knee movement by (5-electrogoniometer). In channel 5 a downward movement of the trace shows extension of the knee.

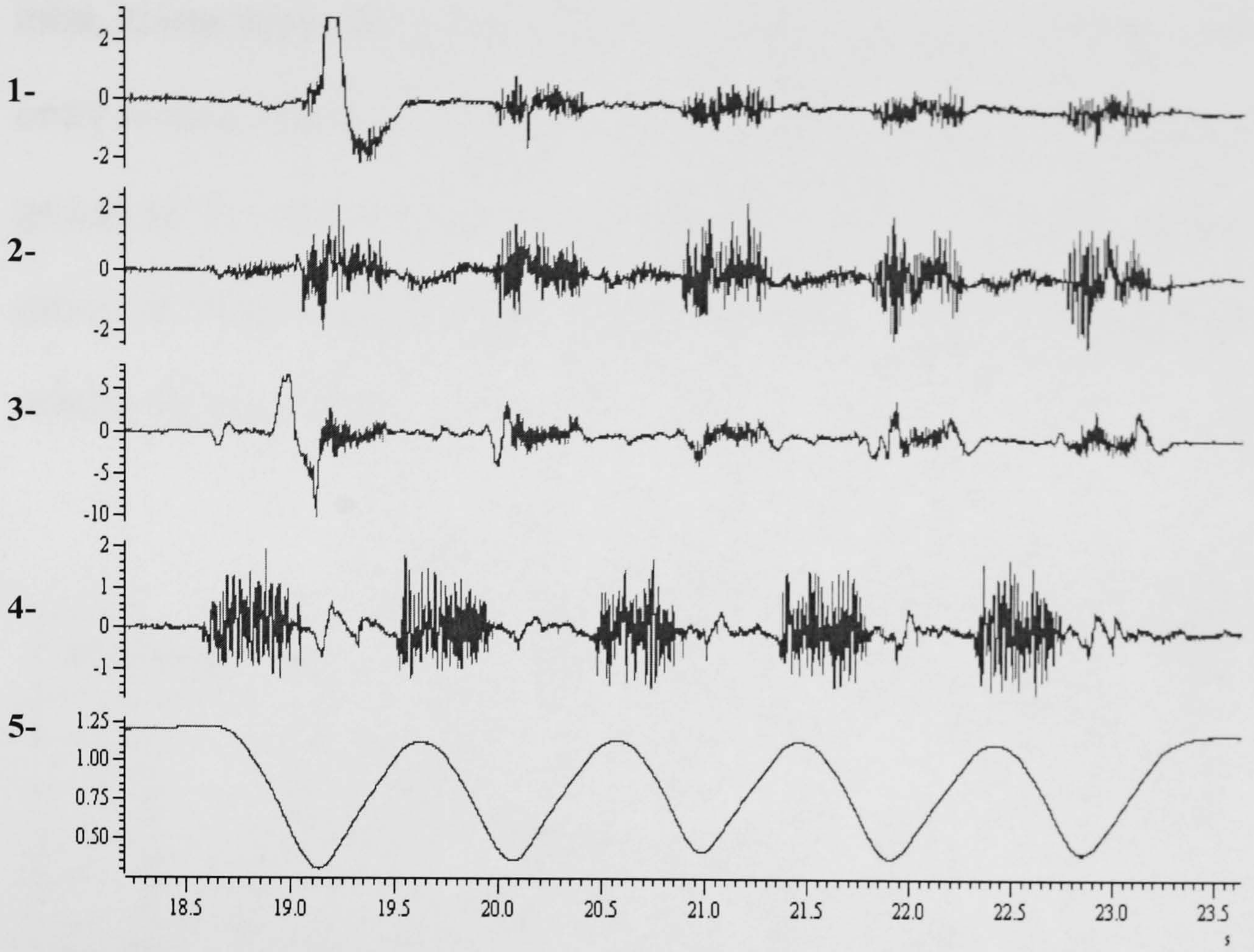


Figure 2.15. The figure shows the five-repetition knee extension and flexions. The channels are as listed in figure 2.14.

2.10. Experiments with Unrestrained Kicks

2.10.1. Volunteers

This study involved three groups. Two groups were trained adolescent soccer players (11 and 15-year-olds) and one group of untrained adults. The adolescent footballers came from Dundee United Football Club. They were recruited by their coach and their parents were invited to attend the experiments. They were healthy and participated in daily football training. Table 2.3 shows the mean with standard deviation of height and weight for all volunteers. In total, thirty-three male volunteers of three groups, who fitted the entry criteria, were recruited for the football kick study: for the first group of 11-year-olds, there were 12 volunteers; for the second group of 15-year-olds, 9 volunteers; for the third group of untrained adults, 12 volunteers.

		11yrs group		15yrs group		Untrained adults group		
Volunteer	**Sex**	**BH (cm)**	**BW (kg)**	**BH (cm)**	**BW (kg)**	**Age (Yr)**	**BH (cm)**	**BW (kg)**
1	M	140	37	157	56	18	164	65
2	M	143	33	170	57	18	164	60
3	M	143	35	167	58	22	170	53
4	M	144	35	169	58	18	172	57
5	M	146	36.5	162	59	18	179	60
6	M	144	38	165	60	18	174	61
7	M	152	39.5	173	61	18	178	63
8	M	159	43	172	62	18	173	63
9	M	153	41	171	62	40	181	69
10	M	145	36	175	64	18	171	70
11	M	163	50	176	67	18	182	73
12	M	145	36	168	63	22	170	77

Table 2.3. The table shows the characteristics of volunteers who participated in the free kick study for trained adolescent footballers and untrained adult groups.

The volunteers' height was measured with a wall-mounted stadiometer. For the 11-year-olds, mean height was 148 $\pm$ 7 cm; for the 15-year-olds, 169 $\pm$ 6 cm; for the untrained adults, 173 $\pm$ 6 cm. They were weighed on a standard set of Avery scales. For the 11-year-olds; mean weight was 38 $\pm$ 5 kg; for the 15-year-olds, 60 $\pm$ 5 kg; for the untrained adults, 64 $\pm$ 7 kg.

2.10.2. Equipment for Kick Study

The material requirement for this study was an electromyograph, to investigate the muscle activities of Vastus Lateralis, Biceps Femoris, Semitendinosus and Semimembranosus muscles. The electrogoniometer provided measurements of knee and hip movements. The foot switches were connected to the shoe to indicate heel and toe contact with the ground or the ball. On the day of the experiment, the volunteer had EMG electrodes placed on the muscles and held by cling film wrapped around the thigh. A Kickmaster trainer device (MV Sports and Leisure Ltd, 35 Tameside Drive, Castle Bromwich Birmingham B35 7AG UK) measured force and velocity of football kicks. A number 4 ball with air pressure at 635 Pascals was used for the junior group. A number 5 ball, at a pressure of 720 Pascals was used for the older juniors and adult groups (see Figure 2.16).

Figure 2.16. The figure shows the Kickmaster device.

The Kickmaster device displays the kick force and the velocity of ball movement. The Kickmaster device was measured in grams and the potential of minimal load was 400 grams and the maximal load was 2000 grams. The Kickmaster showed increases in force and velocity when the load increased. Figures 2.17 and 2.18 show linear suggests this progressive correlation velocity and force increased by increasing load.

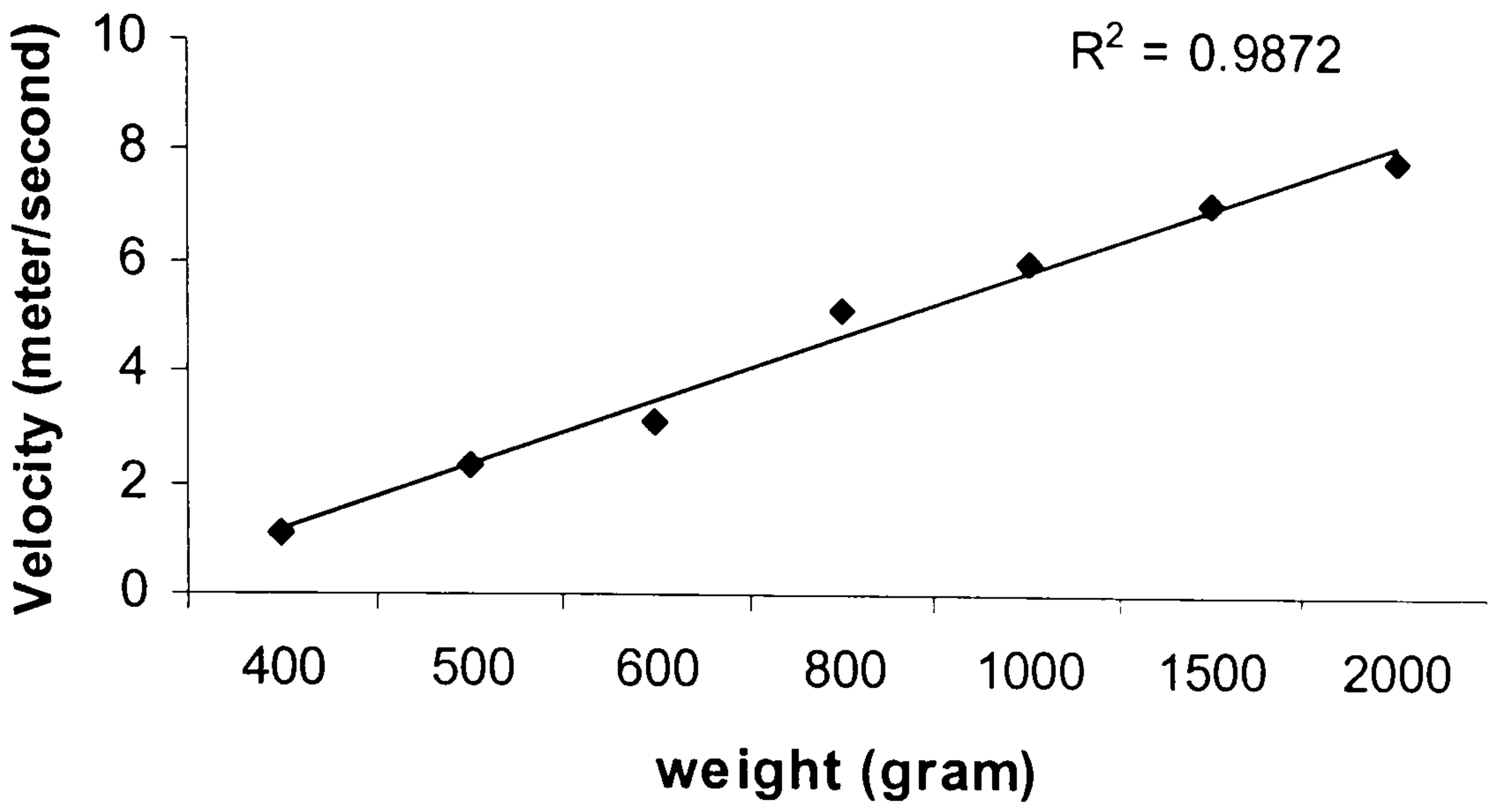


Figure 2.17. The diagram shows the calibration between weight and velocity. The linear correlation reflected the reliability of the measured Kickmaster

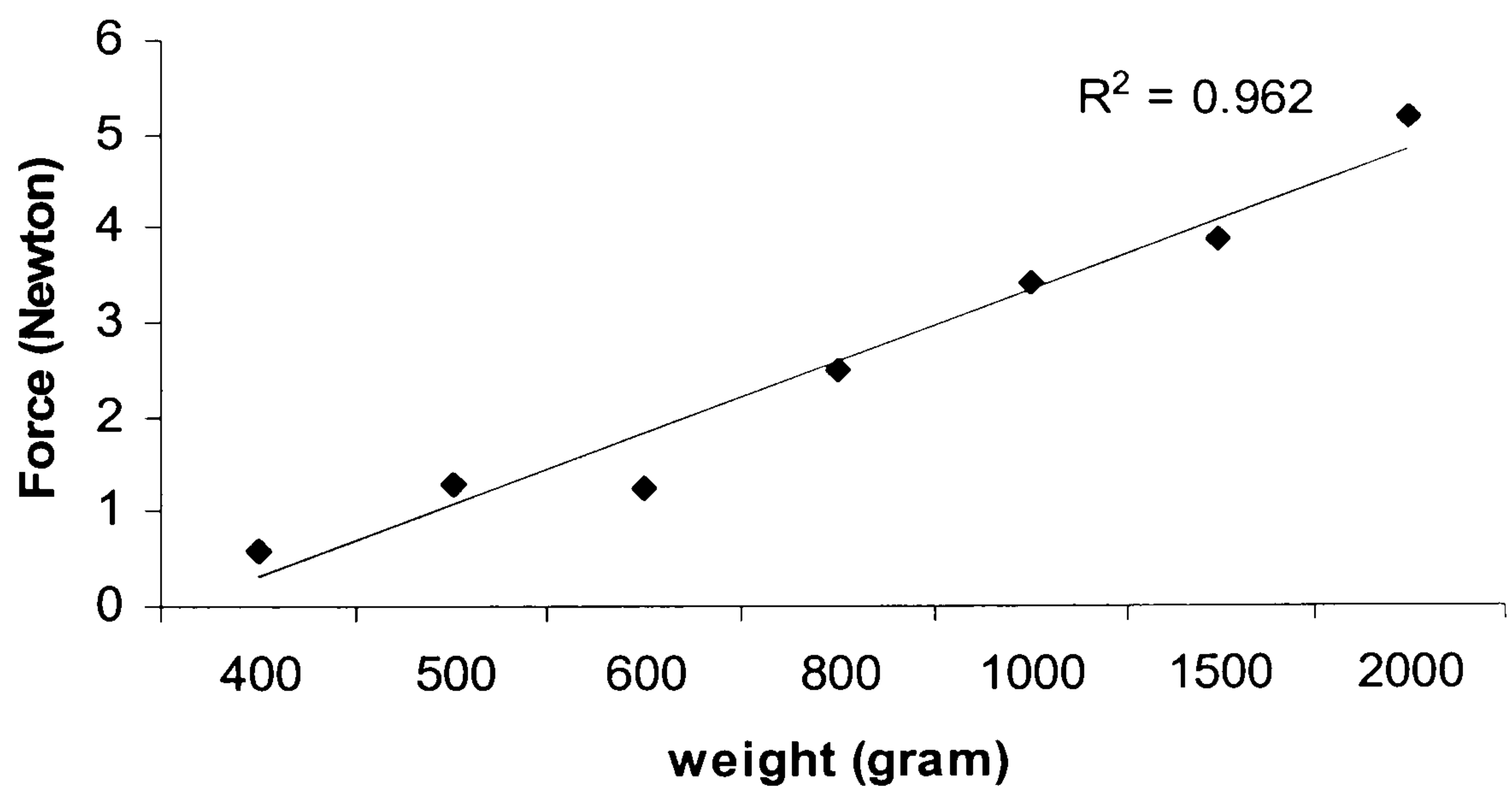


Figure 2.18. The diagram shows the calibration between weight and force.

2.10.3. The Design of Experiment

The purpose of this experiment was firstly to investigate EMG activity at maximum, medium and minimum power when kicking a stationary football and secondly, knee movement in the dominant leg. Three phases of a kick (push off, strike and following through) were identified (see Figures 2.19, 2.20, 2.21).

Each volunteer had 10 kicks of the football, starting from the weakest kick and gradually increasing strength of the kick to reach the strongest. Spike 2 software recorded EMG activity of Vastus Lateralis, Biceps Femoris, Semitendinosus and Semimembranosus. An electrogoniometer recorded movement of knee and hip joints and a foot switch recorded ball contact (see Figure 2.22).

Figure 2.19. The figure shows the push off phase.

Figure 2.20. The figure shows the strike phase.

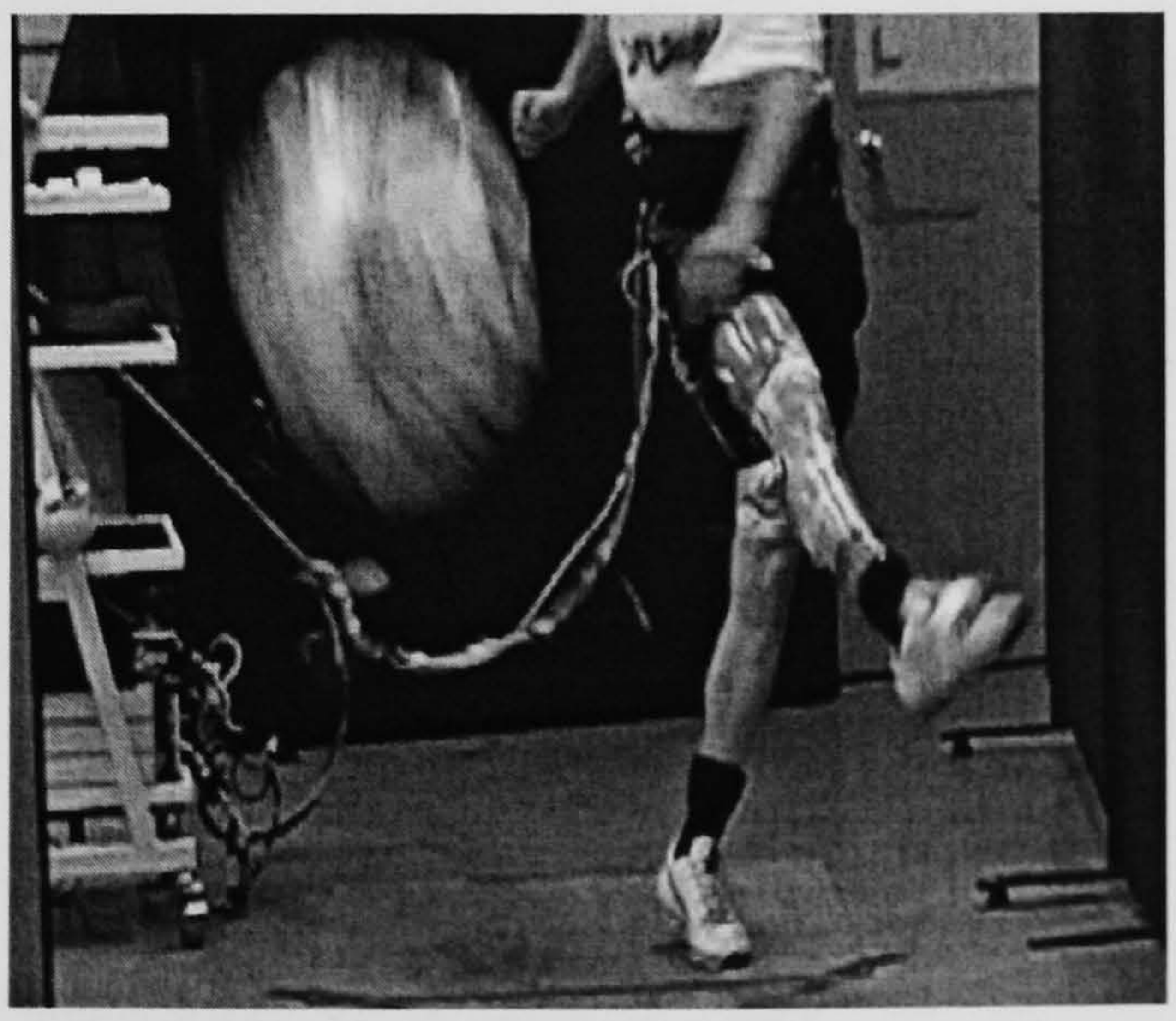


Figure 2.21. The figure shows the following through phase.

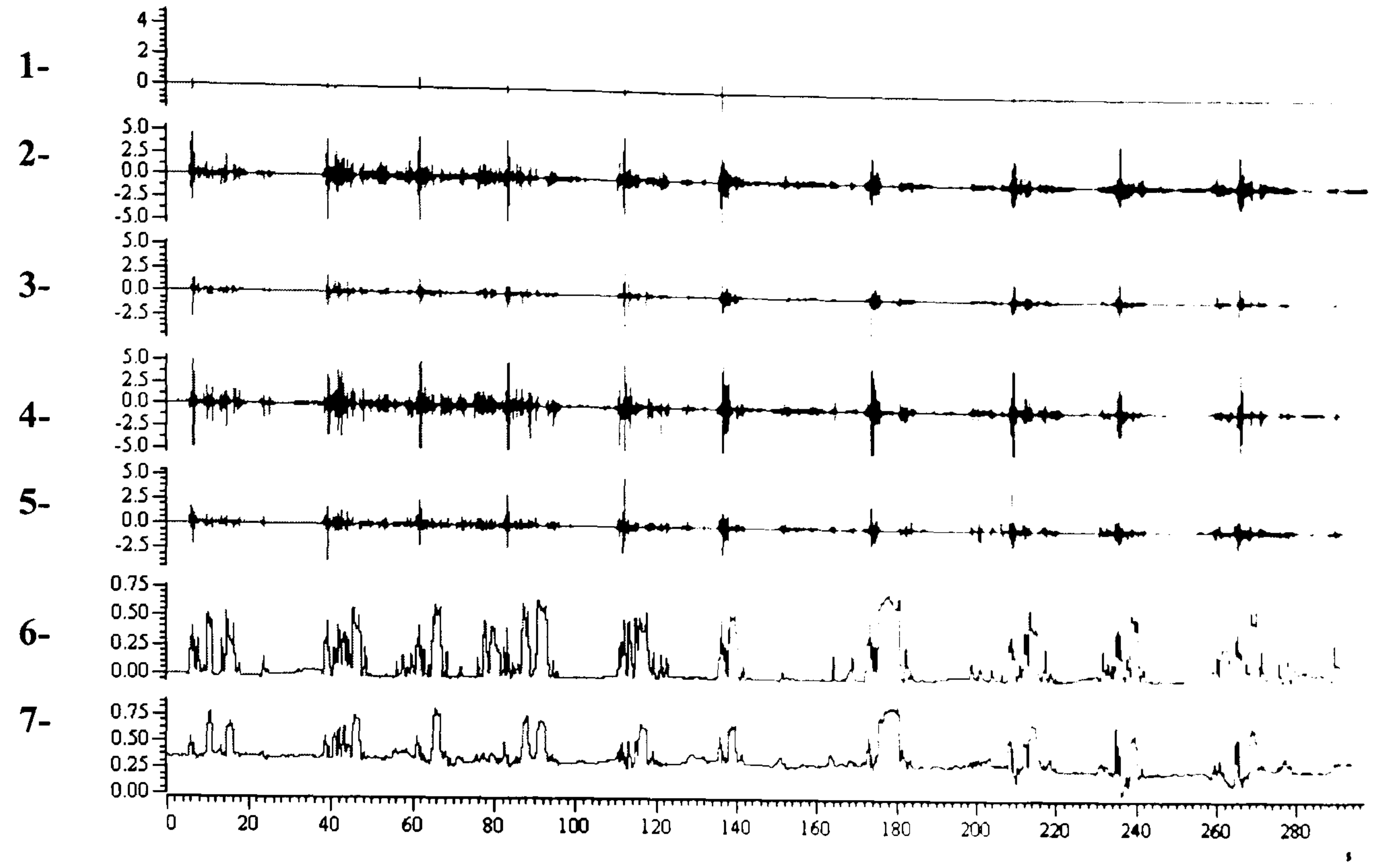


Figure 2.22. The figure shows the 10 kicks of each subject tested from minimal up to maximal and this is data raw of EMG recording and knee and hip movement. 1- Ball kick. 2-Semitendinosus. 3-Biceps Femoris. 4-Semimembranosus. 5-Vastus Lateralis. 6 - Knee joint. 7- Hip joint.

2.11. Data Analysis

2.11.1. General EMG Procedures

The original raw EMG data was not always suitable for analysis because the movement artefacts could be present. In addition some phases of the movements had low EMG activity. The Spike2 software (version 3.15) has a digital filters and these were used to remove artefacts. EMG rectification helped the analysis (see Figure 2.23). The onset of EMG activity was determined by setting a notional threshold five times larger than the mean value of the background EMG.

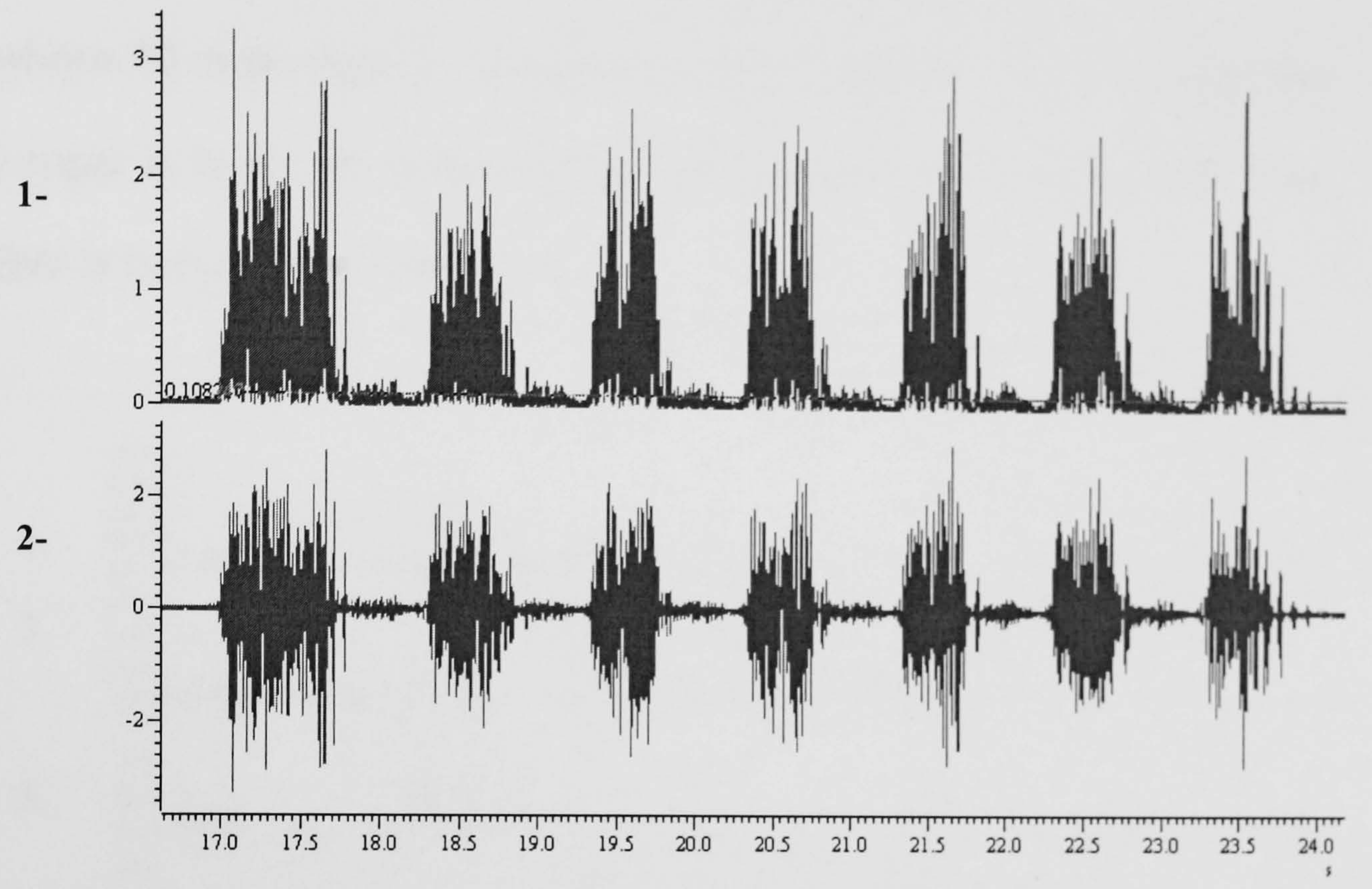


Figure 2.23. The figure shows the EMG pattern after high pass filtering (2) and after subsequent rectification (1).

2.11.2. Electrogoniometer Definitions on the Knee and Hip

Knee and hip movements were measured by electrogoniometers fixed across the joint. The signal was digitised via Spike 2 software. The peak value of the curve identifies most flexed position and the downward movement indicates extension.

Spike 2 software provides manual vertical and horizontal cursors to analyse joint velocity of movement and positions.

2.11.3. Calculation of the Power in Vertical Jumps

The power jump was calculated using the equation:

$$\text{Power} = 0.5 \times 10 \times T^2 \times BW \text{ (watts)}$$

where 10 m/sec/sec is acceleration due to gravity, T^2 is the time the jumper is in the air measured by the switches in the jump mat and BW is body mass in Newtons

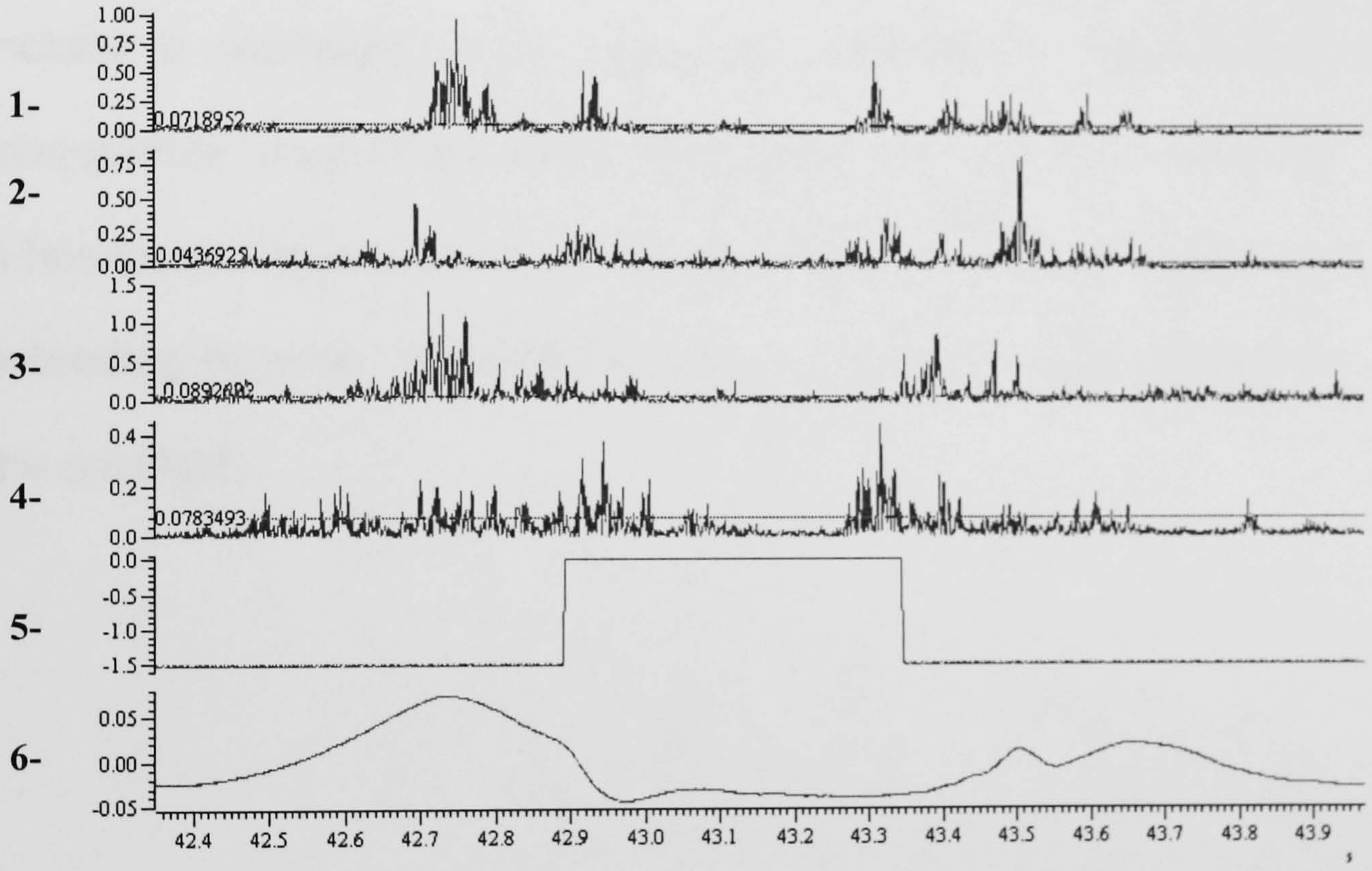


Figure 2.24. A specimen vertical jump performance by one volunteer. It illustrates rEMG of 1 BF 2 ST 3 VL 4 SM. Channel 5 – shows the jump mat signals at take off (first vertical line) and landing (second vertical line). 6 - Knee electrogoniometer

2.12. Statistical Analysis

Data is expressed as mean $\pm$ standard deviation (SD). Statistical analyses were performed using the ANOVA one way unstacked test using Minitab software and two samples paired t-test. (Minitab 13.30 Inc. PA, US). Statistical significance was accepted at $P < 0.05$.

The statistical figures shown by boxplots, for example fig 3.1, include a rectangle which represents roughly the middle 50% interquartile range of the data. The median value is represented by a horizontal line and dark dot indicates the mean. The vertical lines extending to either side indicate range of data from the biggest to the smallest.

3. Results Section

3.1. Vertical Jump Performance in Untrained Adults

A group of 14 fit young adult males with no history of specialised training were invited to make a series of progressively more powerful jumps. During these jumps, the surface electromyography of VL, BF, ST and SM muscles was recorded and the knee extension movement was recorded with a flexible goniometer. Details of these techniques are given in greater detail in the methods section 2.1 and 2.3.

3.1.1. The Effect of Jump Power on the Velocity of Knee Extension

Knee movement velocity was measured by electrogoniometer. The signal was digitised via Spike 2 software. Analysis of these signals involved manual movement of vertical and horizontal cursors. The vertical cursors gave a multifunctional analysis. The slope function measured the gradient between two cursors. Tables 3.1, 3.2 and 3.3 show the results of the vertical jump at maximum extension knee velocity measured during maximum, midrange and minimum jumps power of take off. During maximum jump power, the maximum velocity of knee extension was 384 $\pm$ 68^{o}/sec. During midrange jump power, the maximum velocity of knee extension was 215 ± 46°/sec. During minimum power jumps, the maximum velocity of knee extension was 67 ± 31°/sec. Figure 3.1 shows that there was significant variation in velocity when tested with a one way ANOVA, ($P < 0.0001$).

Vol	BW (kg)	BW (N)	Age (yrs)	Jump time (sec)	Max JP (watts)	MKEV °/s
1	83	830	39	0.423	728	384
2	74	740	35	0.471	805	491
3	67	670	38	0.497	812	386
4	75	750	46	0.494	898	438
5	70	700	26	0.530	964	267
6	88	880	42	0.474	970	442
7	72	720	41	0.527	981	437
8	80	800	28	0.525	1082	322
9	87	870	21	0.512	1119	378
10	85	850	39	0.524	1145	381
11	68	680	40	0.590	1161	391
12	88	880	41	0.531	1217	381
13	97	970	36	0.518	1277	431
14	83	830	24	0.583	1384	246
Mean	**80**	**798**	**35**	**0.514**	**1039**	**384**
SD	**9**	**90**	**8**	**0.043**	**192**	**68**

Table 3.1. The table shows maximum jump power for each volunteer. (BW, kg) body weight in kilograms, (BW, N) body weight in Newtons, (Max JP) maximum power of jump in watts, (MKEV) maximum knee extension velocity in degrees/sec.

Vol	BW (kg)	BW (N)	Jump time (sec)	JP (watts)	MKEV °/s
11	68	680	0.250	208	243
9	87	870	0.230	226	206
3	67	670	0.290	276	281
10	85	850	0.260	282	226
5	70	700	0.290	289	261
7	72	720	0.295	307	186
2	74	740	0.300	327	229
8	80	800	0.290	330	265
4	75	750	0.300	331	169
12	88	880	0.280	338	226
6	88	880	0.290	363	177
14	83	830	0.300	366	182
13	97	970	0.300	428	252
1	83	830	0.330	443	114
Mean	**80**	**798**	**0.286**	**323**	**215**
SD	**9**	**90**	**0.025**	**66**	**46**

Table 3.2. The table shows the jump power achieved in a mid-range jump.

Vol	BW (kg)	BW (N)	Jump time (sec)	MinPJ (watts)	MKEV °/s
1	83	830	0.082	27	69
2	74	740	0.095	33	122
3	67	670	0.118	46	41
5	70	700	0.118	48	46
4	75	750	0.115	49	116
6	88	880	0.118	60	77
7	72	720	0.131	61	61
8	80	800	0.128	64	20
11	68	680	0.16	85	82
9	87	870	0.144	88	103
12	88	880	0.153	101	42
10	85	850	0.158	104	33
13	97	970	0.178	151	47
14	83	830	0.199	161	79
Mean	**80**	**798**	**0.132**	**77**	**67**
SD	**9**	**90**	**0.031**	**41**	**31**

Table 3.3. The table shows the jump power achieved in a minimum power jump in which they barely clear the ground.

There are obvious differences between the three classes of jumps. The power of the minimum jumps is less than 10 % of the maximum jump power. The mid range jumps were closer on the basis of time in the air rather than absolute power. The minimum jumps are the most variable set of data and here the standard deviation is almost half the jump power. Volunteers found very small jumps harder to reproduce consistently than larger jumps.

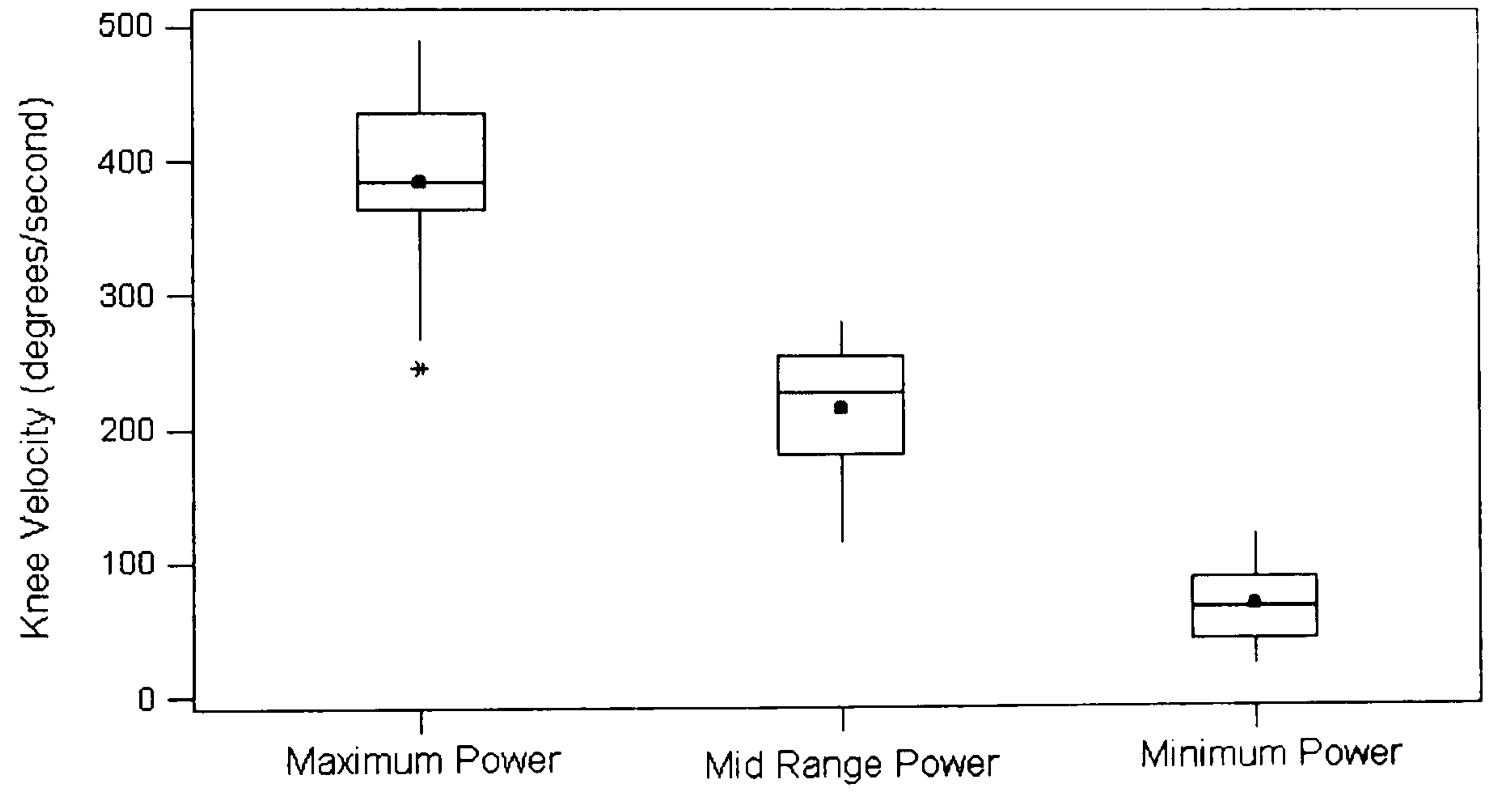


Figure 3.1. The diagram shows the velocity of knee extension during takeoff in vertical jumps for the untrained adult group. The maximum velocity of knee extension during take-off was significantly different between maximum, midrange and minimum jump power ($P < 0.0001$).

3.1.2. EMG Patterns of Activities: Onset and Cessation

The data was also analysed to examine the temporal pattern of electromyography activity during vertical jumps. Details of the EMG recording and digitisation are given in Methods 2.10.1. Specimen data for three individuals are shown in Figures 3.2, 3.3 and 3.4.

It is clear from visual inspection of these traces that the patterns of EMG were complex. For example in Figure 3.2c, a maximum jump, the EMG in Vastus Lateralis begins approximately 600 msec before take off. The EMG amplitude rises progressively to a maximum approximately 200 milliseconds before take off. During this phase, the knee flexes to 64 degrees. As knee extension begins, the VL EMG reduces in amplitude. The VL continues to be active after take off. There is then a period of EMG silence lasting 250 msec before a second phase of activity starts approximately 50 msec before landing.

The EMG in Biceps Femoris starts approximately 380 msec before takes off. The EMG amplitude rises progressively to a maximum approximately 170 msec before take off. The EMG in BF then reduces for 40 msec. As knee extension starts the EMG reactivates at 200 msec before take off and continues until landing.

The EMG in Semitendinosus starts approximately 600 msec before take off. The EMG amplitude rises progressively to a maximum approximately 200 msec before take off. It then falls silent until just after take off when a short burst occurs. There is a second phase of activity, which starts before landing and continues for about 500 msec after ground contact.

The EMG in Semimembranosus starts approximately 400 msec before take off. The EMG amplitude is always less that BF and ST. A prominent EMG burst begins just after take off and whilst in the air, there are several additional short bursts before landing.

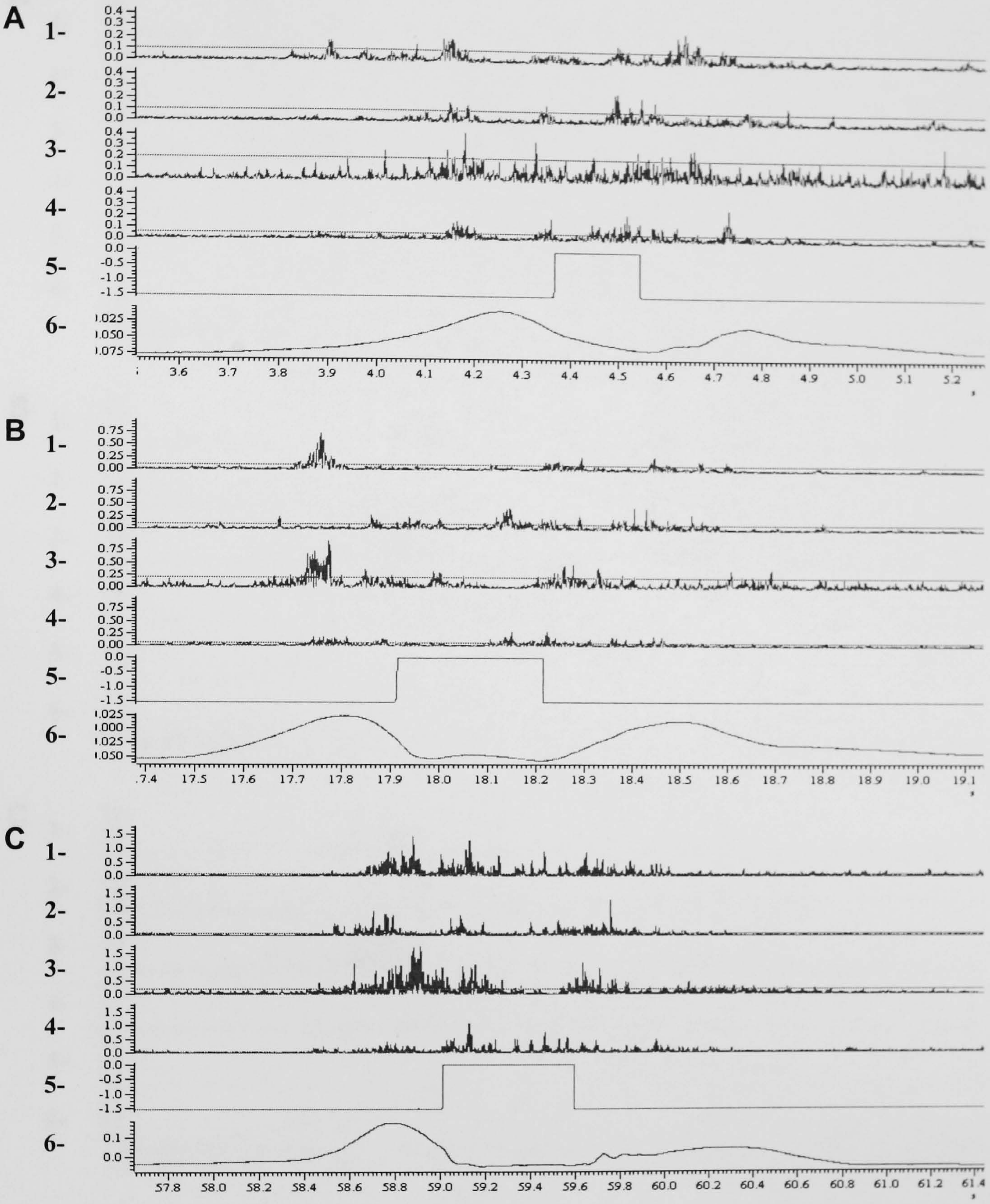


Figure 3.2. The figure shows 3 vertical jumps in the same volunteer A) Minimum; B) Mid power; C) Maximum. Rectified EMG recordings from1- Biceps Femoris; 2- Semitendinosus; 3- Vastus Lateralis; 4- Semimembranosus are shown. 5- Jump mat, the first vertical signal is take off and upper horizontal signal is airtime of the jump and the second vertical signal is landing. 6- Knee angle.

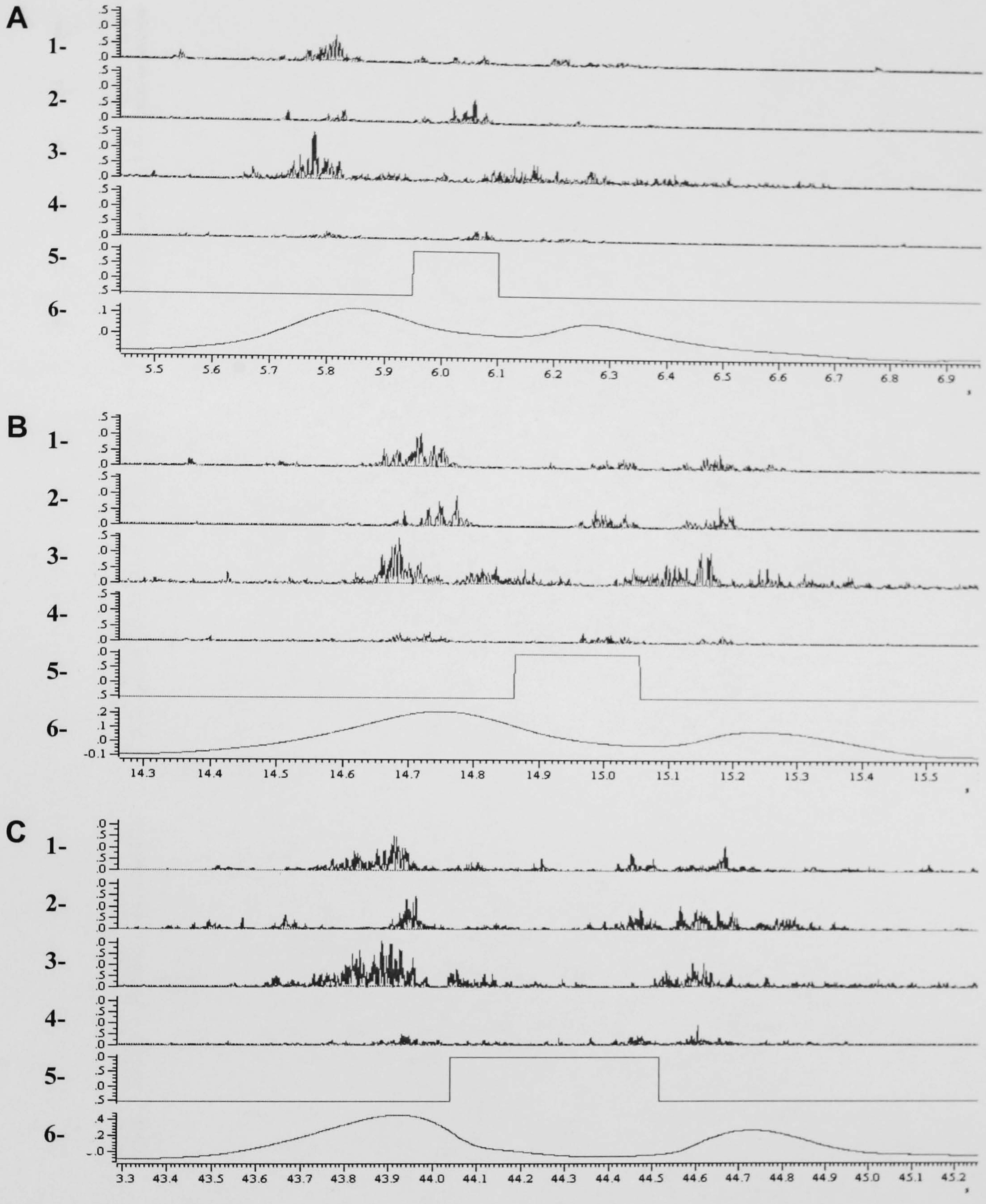


Figure 3.3. The figure shows 3 vertical jumps in a second volunteer A) Minimum; B) Mid power; C) Maximum. Rectified EMG recordings from1- Biceps Femoris; 2- Semitendinosus; 3- Vastus Lateralis; 4- Semimembranosus are shown. 5- Jump mat, the first vertical signal is take off and upper horizontal signal is airtime of the jump and the second vertical signal is landing. 6- Knee angle

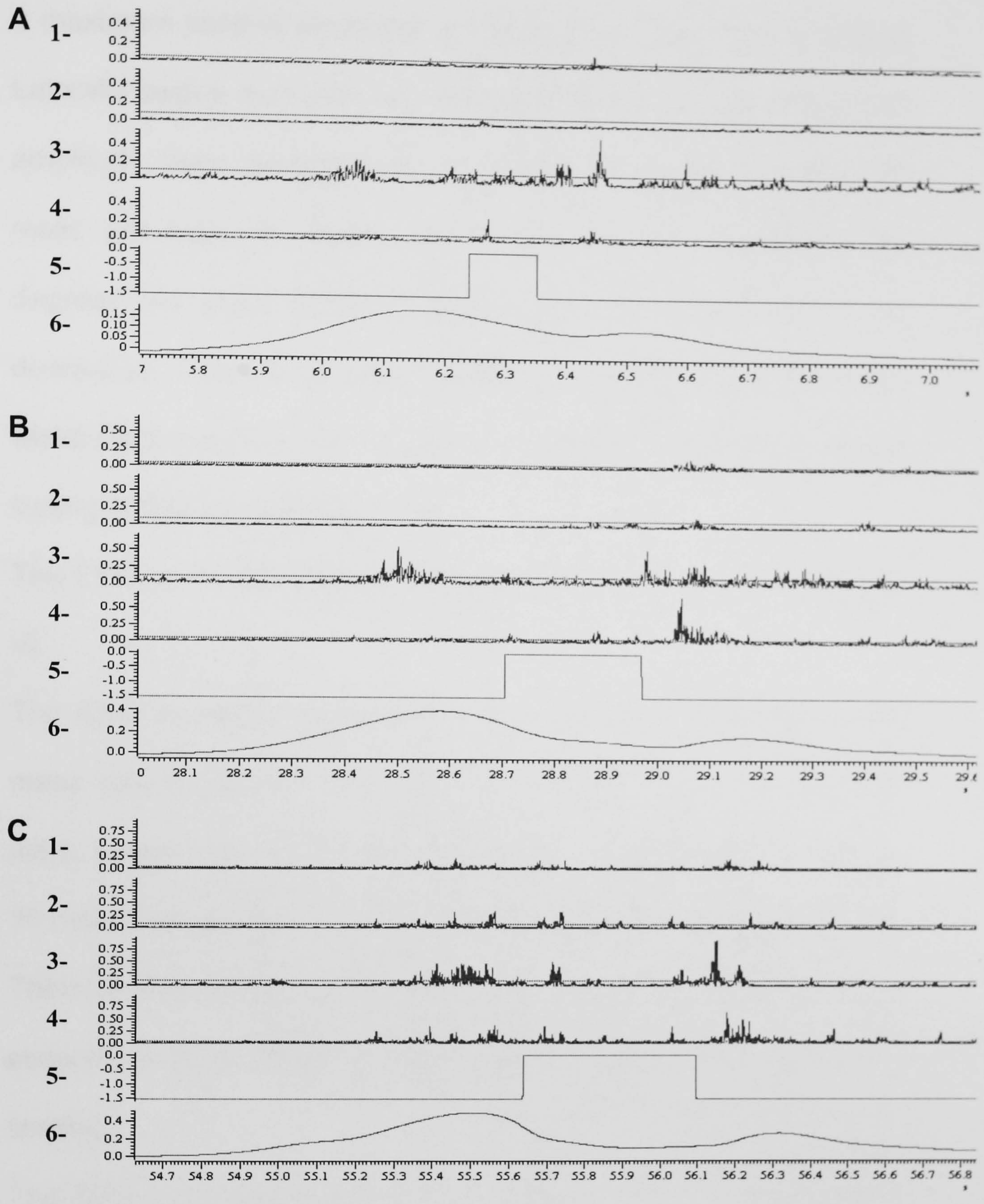


Figure 3.4. The figure shows 3 vertical jumps in a third volunteer A) Minimum; B) Mid power; C) Maximum. Rectified EMG recordings from1- Biceps Femoris; 2- Semitendinosus; 3- Vastus Lateralis; 4- Semimembranosus are shown. 5- Jump mat, the first vertical signal is take off and upper horizontal signal that is airtime of the jump and the second vertical signal that is landing. 6- Knee angle.

a maximum jump is illustrated in Figure 3.3c. The EMG in Vastus Lateralis begins approximately 400 msec before take off. The EMG amplitude rises progressively to a maximum approximately 130 msec pre take off. During this phase the knee flexes to 102 degrees. As knee extension begins, the EMG amplitude in VL decreases. There is a second small burst lasting about 100 msec whilst the jumper is in the air. There is then a period of EMG silence lasting 300 msec before landing.

The EMG in Biceps Femoris follows a profile very similar to that of VL.

The EMG in Semitendinosus shows a few small bursts up to 700 msec before take off. The major activity starts approximately 140 msec before take off. It rises sharply to a maximum approximately 70 msec before take off. The EMG reduces at the instant of take off. There is little EMG activity after take and then there is then a second period of EMG which starts approximately 120 msec before landing.

The EMG in Semimembranosus is always at a low amplitude but it follows the pattern of ST with a short burst before take off and a second burst just before landing.

Data from a maximum jump by a different volunteer is illustrated in Figure 3.4c. The EMG in Vastus Lateralis begins approximately 230 msec before take off. The EMG amplitude rises to a maximum approximately 70 msec pre take off. During the phase of knee flexes to 56 degrees. The EMG then reduces in amplitude for 40 msec. As knee extension begins the VL EMG rises in amplitude for the second short duration phase lasting about 40 msec whilst the volunteer is in the air. There was a second period of EMG silence lasting 300 msec before landing. There is a third phase of EMG activity about 60 msec before landing.

The EMG in Biceps Femoris starts approximately 230 msec before take off. The EMG showed small amplitude bursts and it was difficult to determine the times of activity throughout the take off and landing phases.

The EMG in Semitendinosus begins approximately 270 msec before take off. The EMG shows two bursts before take off. As knee extension begins, the ST there is a third phase of EMG activity. Then ST has a series of three small bursts of EMG activity, before landing.

The EMG in Semimembranosus begins approximately 410 msec before take off. The EMG amplitude rises four times in a series of small bursts. As knee extension begins, the SM EMG is silent. The

SM had a few and small of EMG activities were occur during airtime for 70 msec approximately. Then EMG was silent at landing but shows a large burst of activity 50 msec after landing.

The maximum jumps of all fourteen volunteers were analysed in a similar manner. In all cases, the four muscles under study became active before take off. Table 3.4 shows the times of onset of EMG. These data are illustrated in Figure 3.5 A.

3.1.2.1. Co-activation before Take Off

It is clear that there is considerable variation in the times when each muscle becomes active before take off. The mean time of VL activation was -582 $\pm$ 160 msec i.e. 582 msec before take off. The mean times for BF were -481 $\pm$ 98 msec, for ST -445 $\pm$ 265 msec and for SM -544 $\pm$ 187 msec (see Table 3.4). No significant differences were found between the times of onset in each muscle when tested with one-way ANOVA (P = 0.220). The data from the midrange and smallest jumps were analysed in a similar way.

The values are shown in Tables 3.5 and 3.6. They are illustrated in Figure 3.5B and C, and the same pattern emerges. In midrange jumps the activation time was: in VL -418 $\pm$ 123 msec, BF -322 $\pm$ 149 msec, ST -277 $\pm$ 239 msec, SM -370 $\pm$ 139 msec. In minimum jumps the time of EMG was in VL -380 $\pm$ 133 msec, BF -322 $\pm$ 169 msec, ST -296 ± 213 msec, SM -357 ± 210 msec. There are no significant differences in the time at which the electromyography starts in each muscle, (midrange jumps P = 0.153, minimum jumps P = 0.635). Thus, in the three ranges of jump power examined, VL, BF, SM and ST became active at the same time.

Subjects	VL msec	BF msec	ST msec	SM msec
14	-410	-446	-277	-458
8	-426	-543	-501	-652
3	-432	-449	-449	-642
10	-503	-532	-579	-633
5	-512	-521	-595	-976
12	-526	-414	-605	-477
13	-533	-551	-610	-592
4	-542	-438	-450	-430
6	-552	-523	-581	-542
2	-567	-367	-254	-343
1	-595	-436	-533	-524
7	-675	-621	-692	-685
11	-863	-623	-479	-503
9	-969	-265	-372	-157
Mean	**-582**	**-481**	**-445**	**-544**
SD	**160**	**98**	**265**	**187**

Table 3.4. The table shows the EMG time beginning before take off for four individual muscles for each subject in maximum power jumps. VL is vastus lateralis, BF biceps femoris, ST semitendinosus and SM semimembranosus.

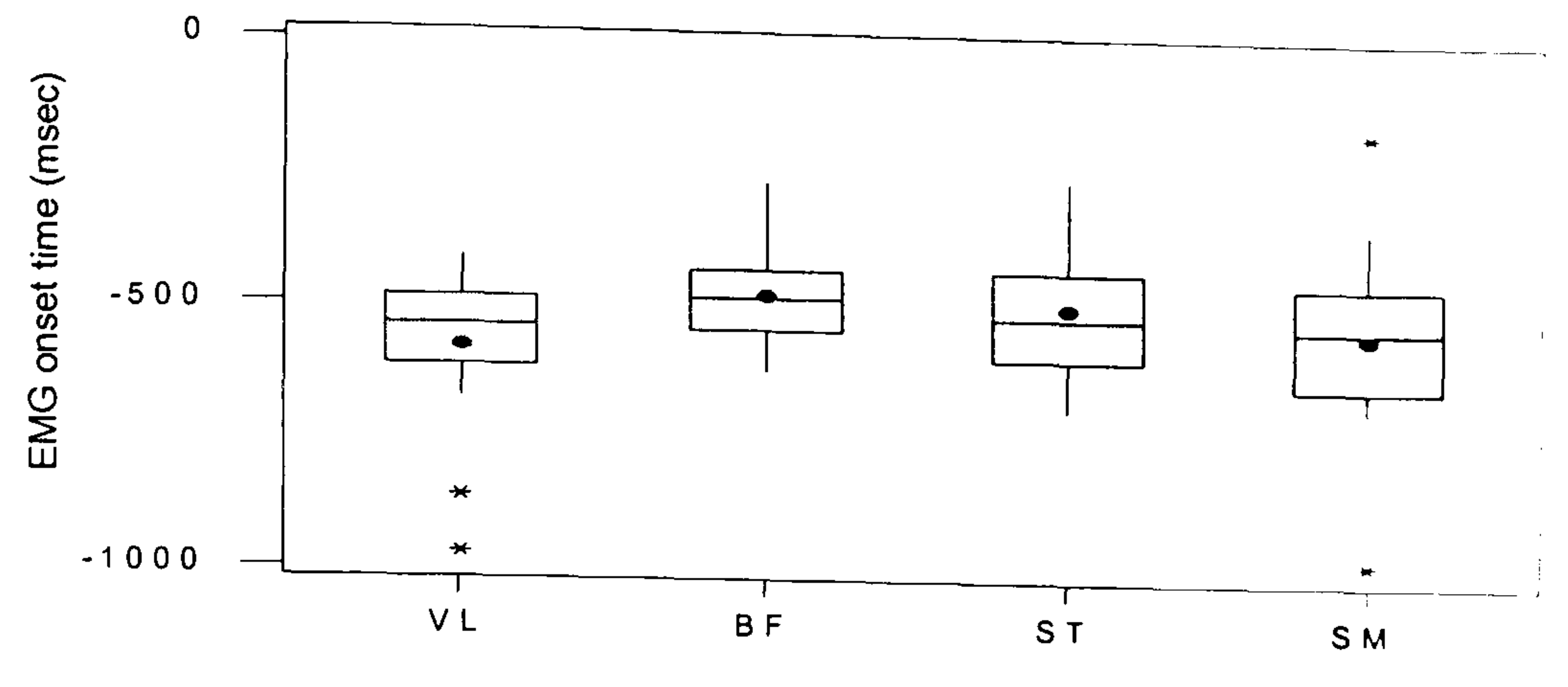
Subjects	VL msec	BF msec	ST msec	SM msec
1	-252	-211	-244	-417
14	-265	-161	-369	-282
8	-272	-477	-403	-386
7	-307	-218	-225	-262
4	-365	-333	-639	-371
12	-377	-246	-305	-580
11	-400	-253	-249	-244
6	-406	-232	-209	-157
2	-459	-480	-233	-361
13	-478	-274	-360	-333
9	-508	-214	-125	-191
5	-532	-223	-227	-464
3	-615	-615	-615	-612
10	-620	-569	-415	-524
Mean	**-418**	**-322**	**-0.277**	**-370**
SD	**123**	**149**	**0.239**	**139**

Table 3.5. The table shows the EMG start times in midrange vertical jumps.

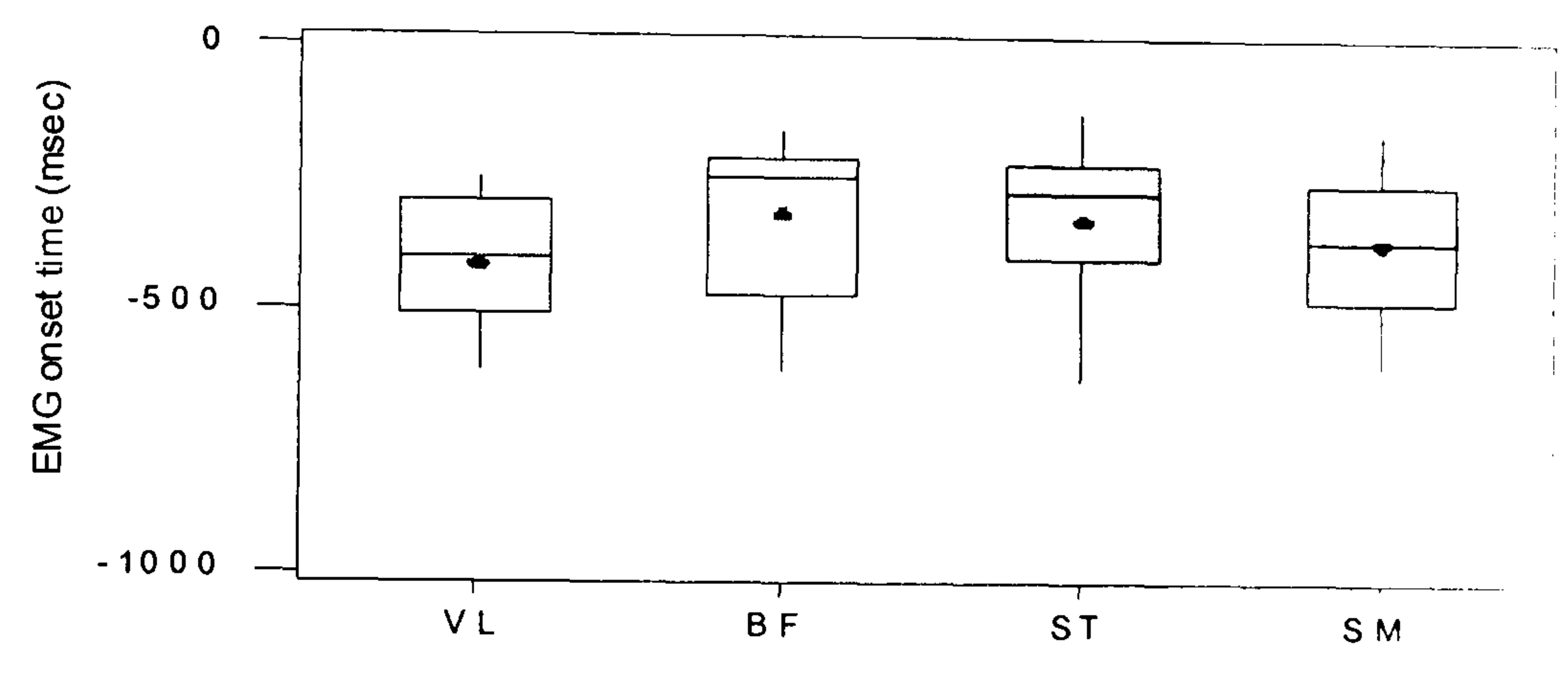
Subjects	VL msec	BF msec	ST msec	SM msec
7	-205	-196	-194	-191
14	-231	-77	-336	-151
5	-257	-246	-182	-198
12	-288	-230	-317	-230
6	-304	-212	-147	-150
4	-317	-372	-169	-241
1	-351	-469	-351	-502
3	-359	-397	-363	-436
2	-365	-386	-346	-395
11	-389	-410	-238	-770
13	-505	-226	-295	-269
10	-550	-309	-689	-608
8	-577	-773	-678	-680
9	-621	-202	-162	-182
Mean	**-380**	**-322**	**-296**	**-357**
SD	**133**	**169**	**213**	**210**

Table 3.6. The table shows the EMG start times in minimum power vertical jumps.

A



B



C

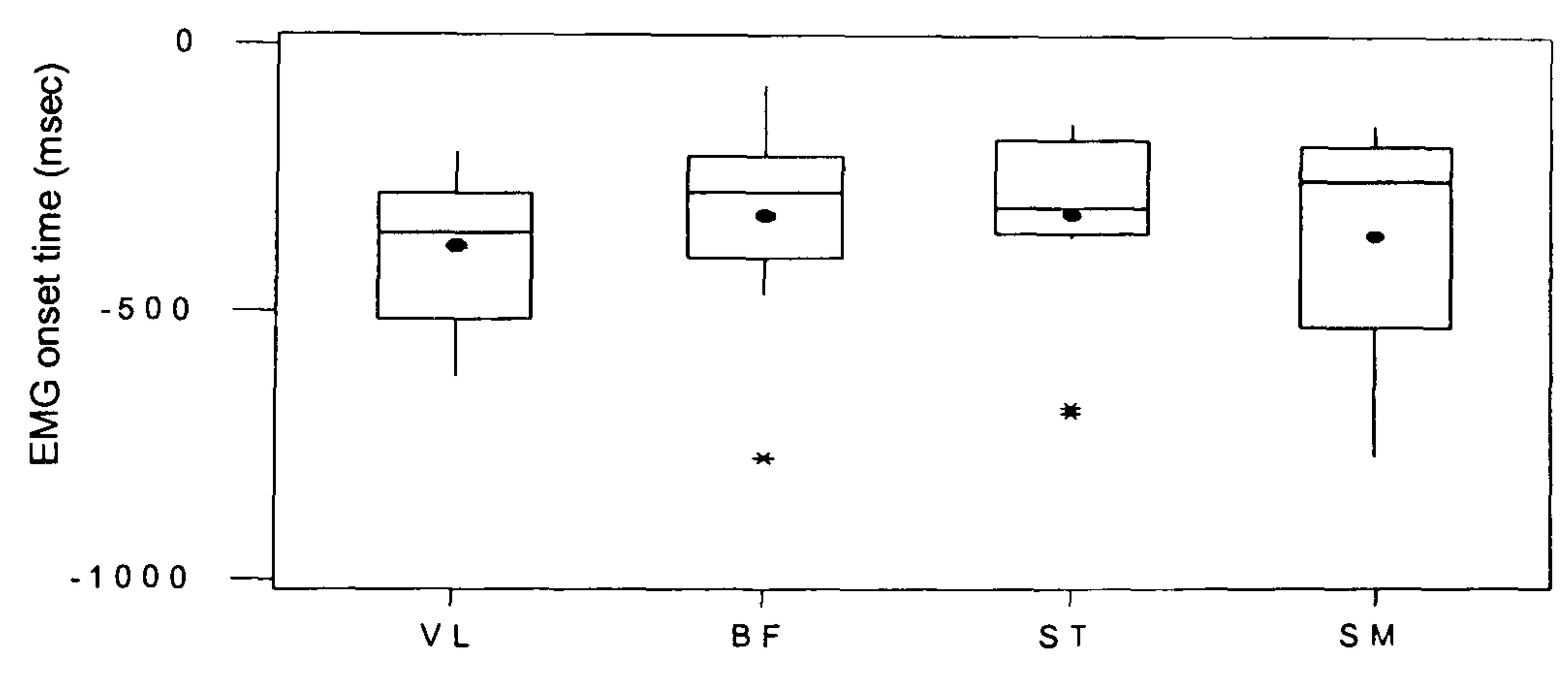


Figure 3.5. The diagram shows summary statistics of the time of EMG onset before take off in Vastus Lateralis, Biceps Femoris, Semitendinosus and Semimembranosus before take off. A) Maximum jump power. B) Mid range jump power. C) Minimum jump power. The changes in A, B and C are not significant A (P = 0.220). B (P = 0.153). C (P = 0.635).

3.1.2.2. Co-activation during Landing

A similar type of analysis was also applied to the identification of the time at which the electromyogram goes silent after landing. Table 3.7 shows data from maximum power jumps. The EMG went silent in VL at 478 $\pm$ 207 msec i.e. 478 msec after ground contact; BF 331 $\pm$ 82 msec; ST 344 $\pm$ 132 msec and SM 394 $\pm$ 179 msec. For midrange power jumps, the EMG went silent in VL at 313 $\pm$ 125 msec; BF 217 $\pm$ 153 msec; ST 221 $\pm$ 158 msec and SM 265 $\pm$ 142 msec, as seen in Table 3.8. For minimum power jumps the EMG times were in VL 322 $\pm$ 190 msec; BF 284 $\pm$ 205 msec; ST 261 $\pm$ 230 msec and SM 288 $\pm$ 243 msec.

Figure 3.6 illustrates the summary statistics. No significant differences were found between the times at which the electromyography of the four muscles ceased in each of the three types of maximum jump power ($P < 0.067$), midrange ($P = 0.270$) and minimum ($P = 0.904$).

Subjects	VL msec	BF msec	ST msec	SM msec
5	976	331	406	786
9	853	149	189	42
11	587	348	204	228
7	526	473	544	537
4	482	339	351	331
2	450	251	138	227
6	417	388	446	407
1	413	255	352	343
10	385	414	462	515
12	382	271	462	335
13	377	395	455	437
3	324	341	341	535
14	265	301	133	313
8	259	376	334	485
Mean	**478**	**331**	**344**	**394**
SD	**207**	**82**	**132**	**179**

Table 3.7. The table shows the time at which the EMG stops after landing from a maximum power vertical jump. VL (vastus lateralis), BF (biceps femoris), ST (semitendinosus) and SM (semimembranosus).

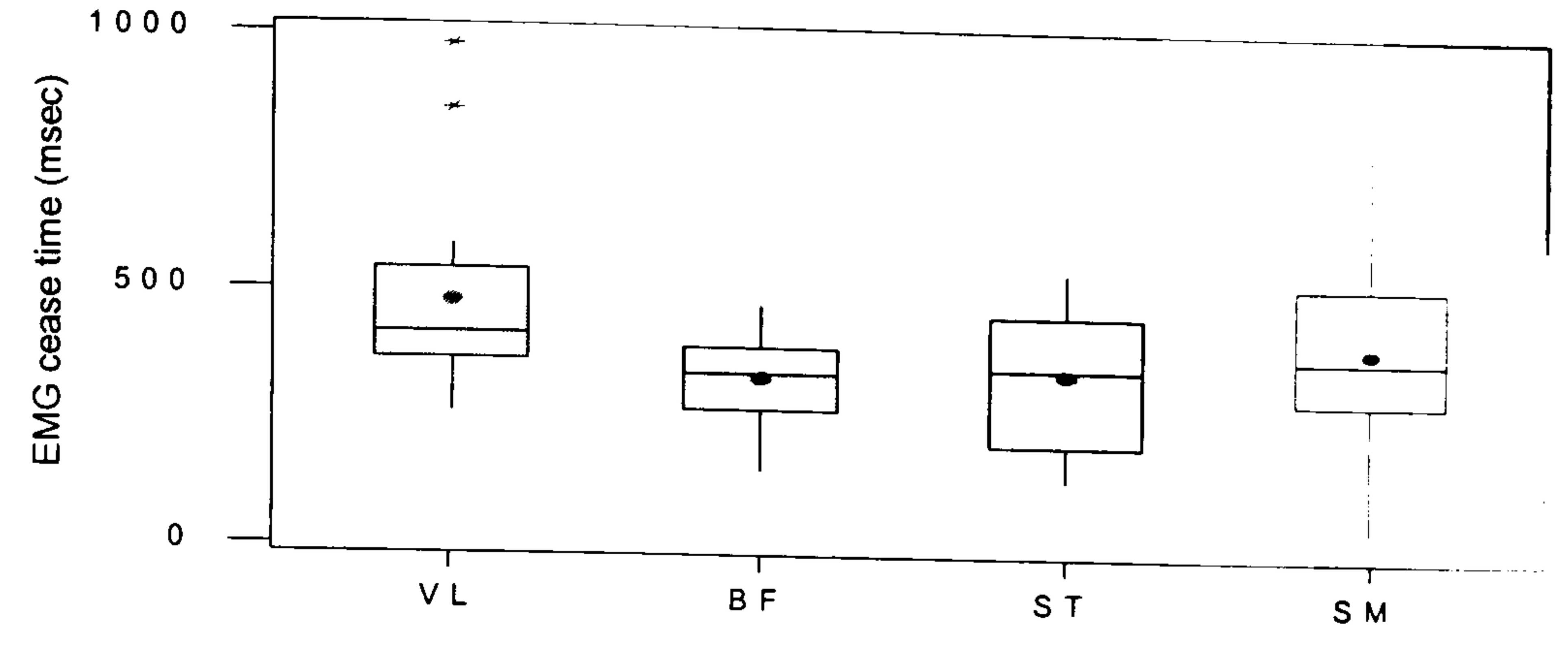
Subjects	VL msec	BF msec	ST msec	SM msec
3	527	527	527	524
10	506	455	302	410
9	412	118	29	96
13	408	204	290	263
5	396	86	90	327
2	349	371	124	252
6	296	122	99	46
4	278	245	552	284
12	276	145	203	479
11	262	115	110	106
7	220	131	139	176
8	168	373	299	282
14	144	040	204	161
1	141	100	132	305
Mean	**313**	**217**	**221**	**265**
SD	**125**	**153**	**158**	**142**

Table 3.8. The table shows the time at which the EMG stops after landing from a mid-range power vertical jump.

Subjects	VL msec	BF msec	ST msec	SM msec
13	671	150	220	193
8	655	653	666	560
9	580	132	122	111
10	454	608	780	710
2	295	316	277	325
11	291	609	480	779
3	278	316	282	355
1	234	352	234	385
4	230	285	81	154
12	202	144	231	144
6	191	99	34	38
5	167	156	92	108
14	138	52	40	59
7	120	111	108	106
Mean	**322**	**284**	**261**	**288**
SD	**190**	**205**	**230**	**243**

Table 3.9. The table shows the time at which the EMG stops after landing from a minimum power vertical jump.

A-



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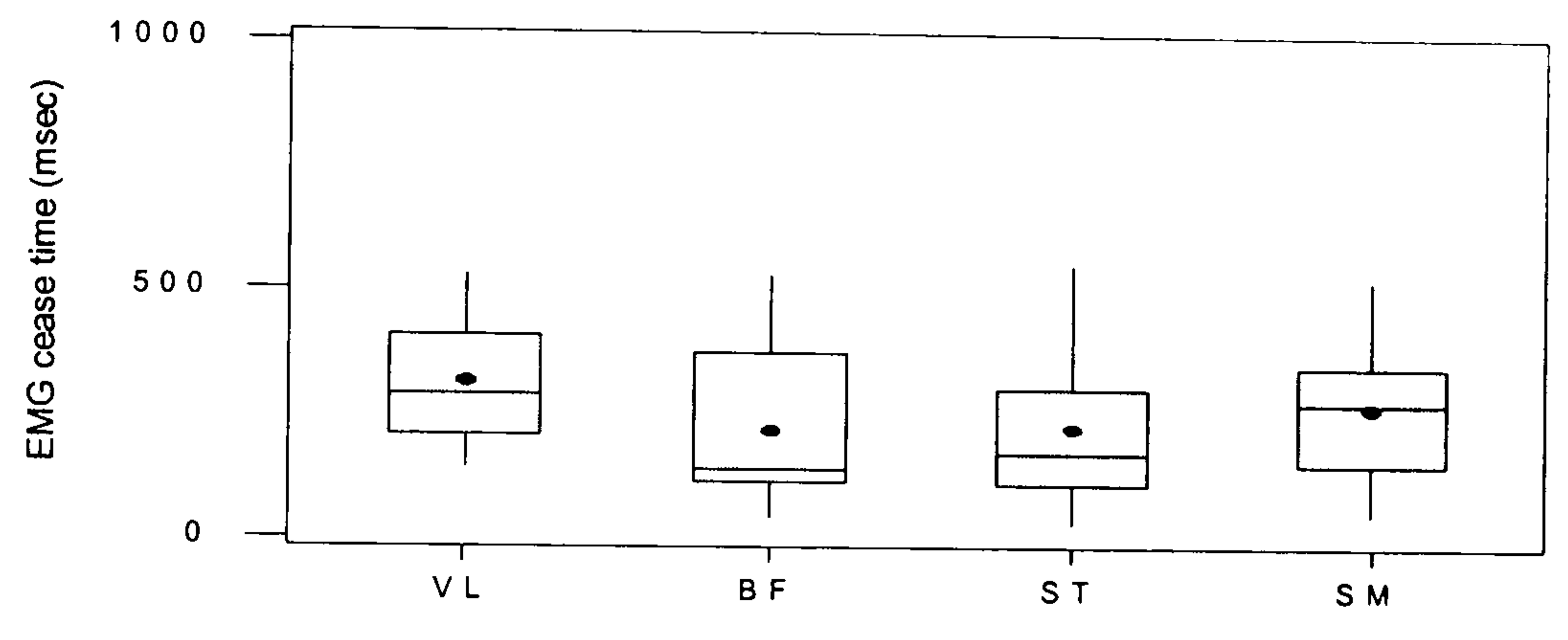

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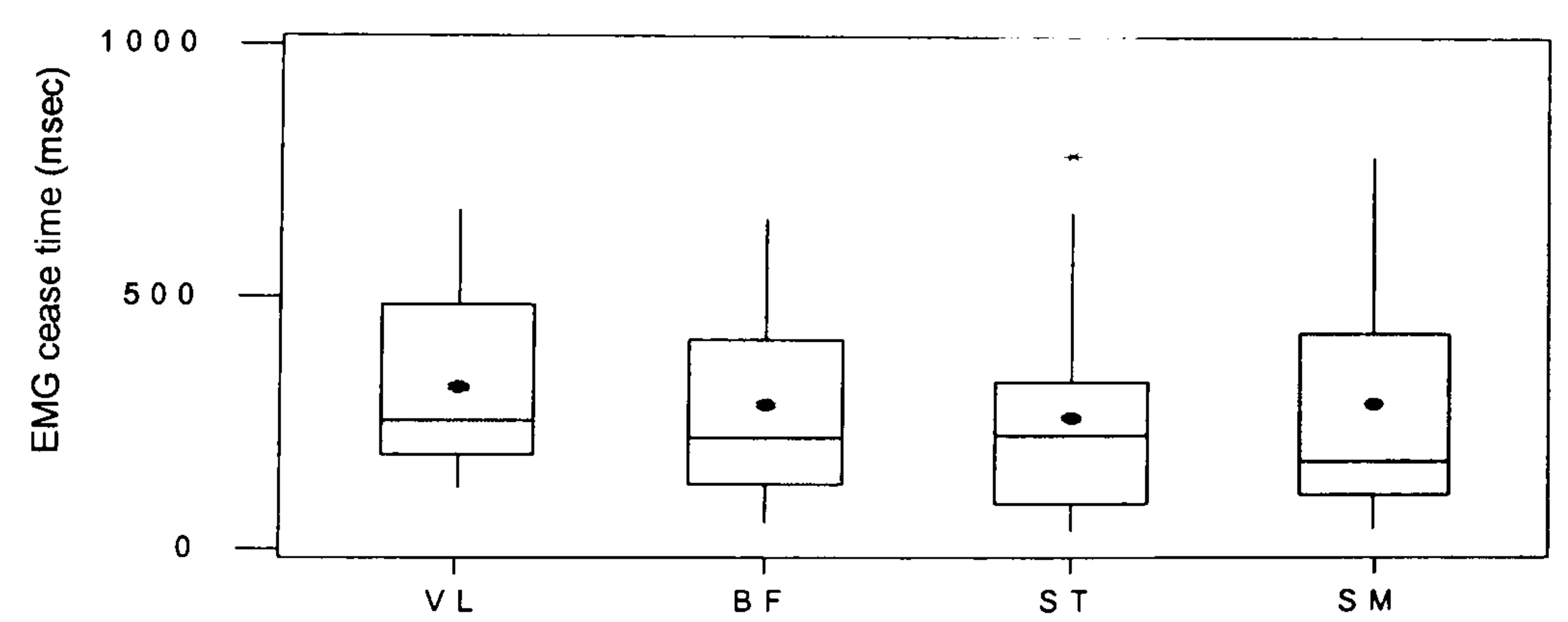


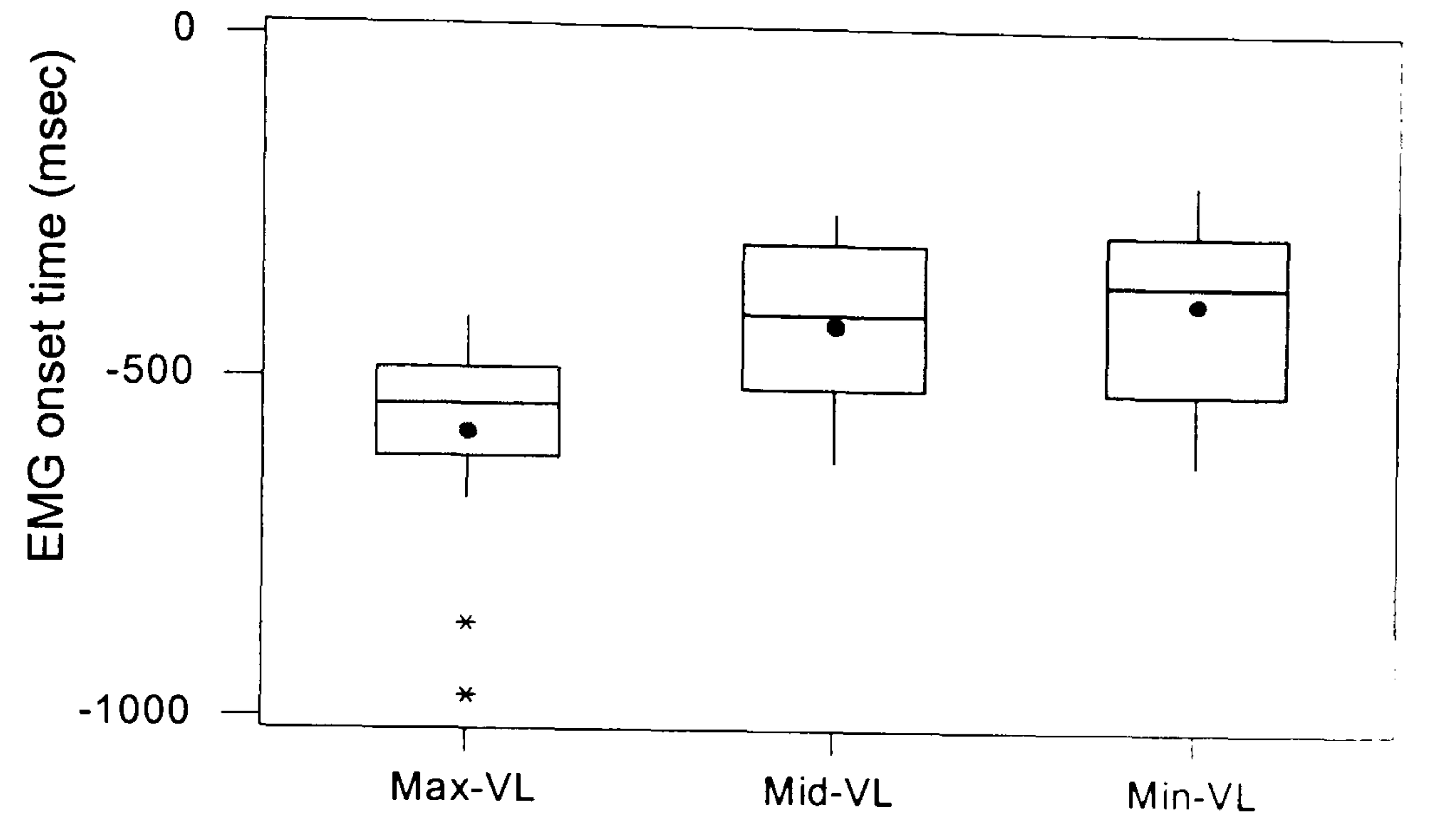
Figure 3.6. The figure shows the range of times at which the EMG stops after landing. The diagram shows data from Vastus Lateralis, Biceps Femoris, Semitendinosus and Semimembranosus A) Maximum jump power. B) Mid range jump power. C) Minimum jump power. The changes in A, B and C are not significant A - ($P < 0.067$). B - ($P = 0.270$). C - ($P = 0.904$).

3.1.3. Timing of VL EMG Activity as Jump Power Increases

Figure 3.7 illustrates the summary data for the times of starting and stopping of activity in the VL electromyogram in all volunteers, organised by vertical jump power. The time of muscle activity of EMG in VL shows begins significantly earlier in maximum power jumps at -582 $\pm$ 160 msec before take-off, than it does in midrange power jump was -418 $\pm$ 123 msec and minimum power jumps was -380 $\pm$ 133 msec, when tested with one-way ANOVA ($P < 0.001$).

When the landings were analysed, it again became clear the electromyogram in VL stopped later after landing from maximum jumps than after smaller jumps. The mean time of stopping after maximum jumps was 478 $\pm$ 207 msec. It stopped 313 $\pm$ 125 msec, after midrange power jumps and 322 $\pm$ 190 msec after minimum power. This was significant when tested with one way ANOVA ($P < 0.017$).

A-



B-

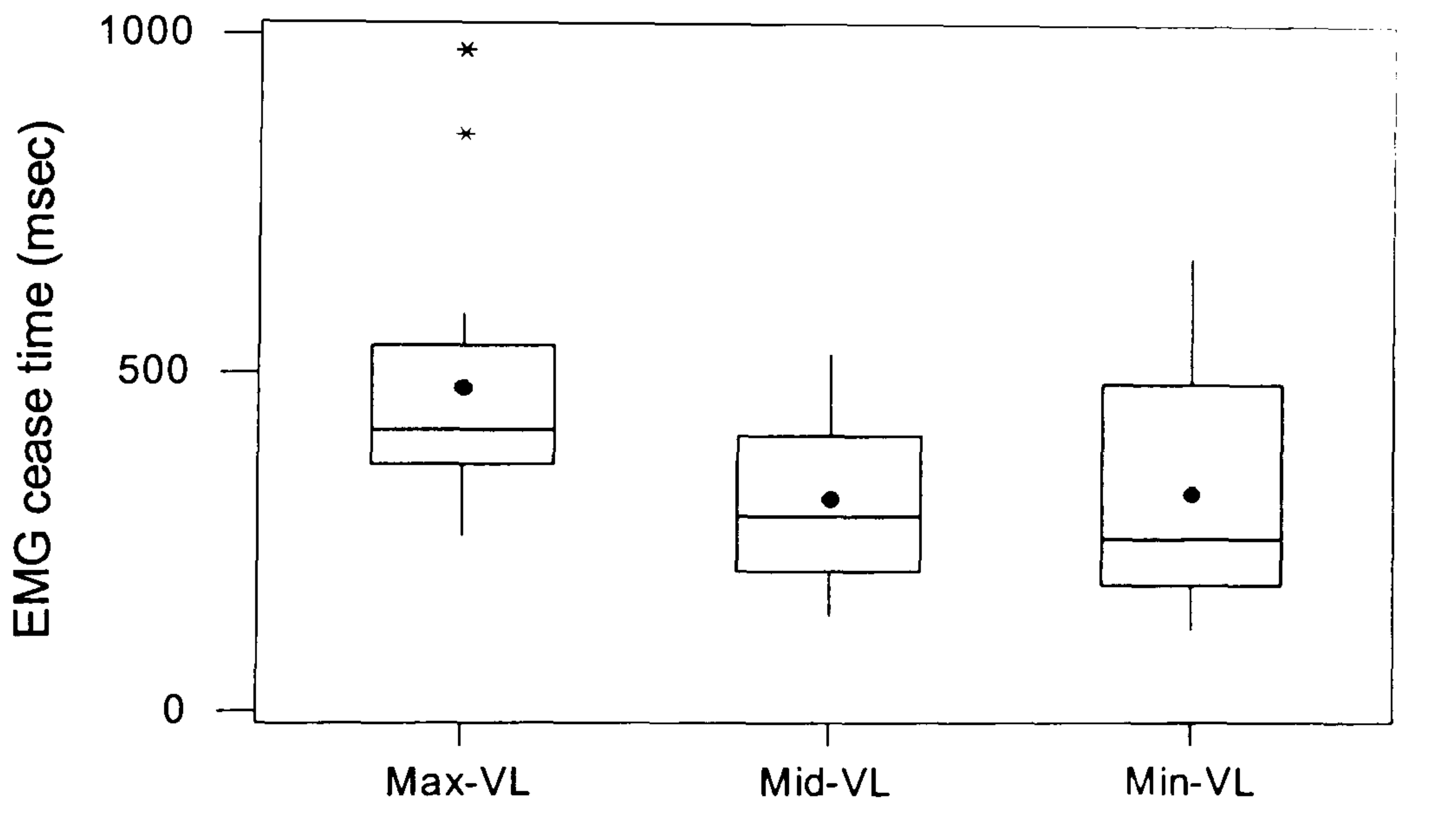


Figure 3.7. The diagram shows the onset and cessation times of EMG activity before take-off and after landing of Vastus Lateralis during maximum, midrange and minimum jump power.

3.2. Co-activation during Fast Knee Extension Movements Controlled by an Isokinetic Dynamometer

3.2.1. Single Movements

A series of experiments were performed to investigate co-activation during knee extension and knee flexion movements at 200°/sec. Details of these experiments are described in the methods section 2.10.2. The volunteers were all male students who were recreationally active. They had no history of injury to their knees. The movements were performed on Kin Com isokinetic dynamometer (Wellness by Design, Chattanooga Group. INC, PN 57682 USA), which regulated magnitude and speed of each movement.

Figure 3.8A illustrates one set of specimen recordings. It shows three extensions and three flexion knee movements. The knee is stationary for approximately 10 seconds before and after each movement. This volunteer does not relax his VL when the knee is extended. During each extension there is an increase in the SM, BF and ST of EMG activity. This can be seen more clearly in Figure 3.8B, where the recording is expanded. Vastus Lateralis and the three hamstring muscles become active at the same moment. As they move into flexion, the hamstrings show a large increase in their electromyogram but there is relatively little change in the VL. This is illustrated in Figure 3.8C. Figure 3.9 shows similar data from another volunteer. The knee is maintained at a fixed position for eight seconds between each movement. For each volunteer the knee was maintained in a similar way during each extension movement. Each person also shows co-activation of VL, BF, SM and ST before and during the extension movement. They also have a strong co-activation during the knee flexion movement. These are illustrated in expanded sections of trace in Figure 3.9 – B, C.

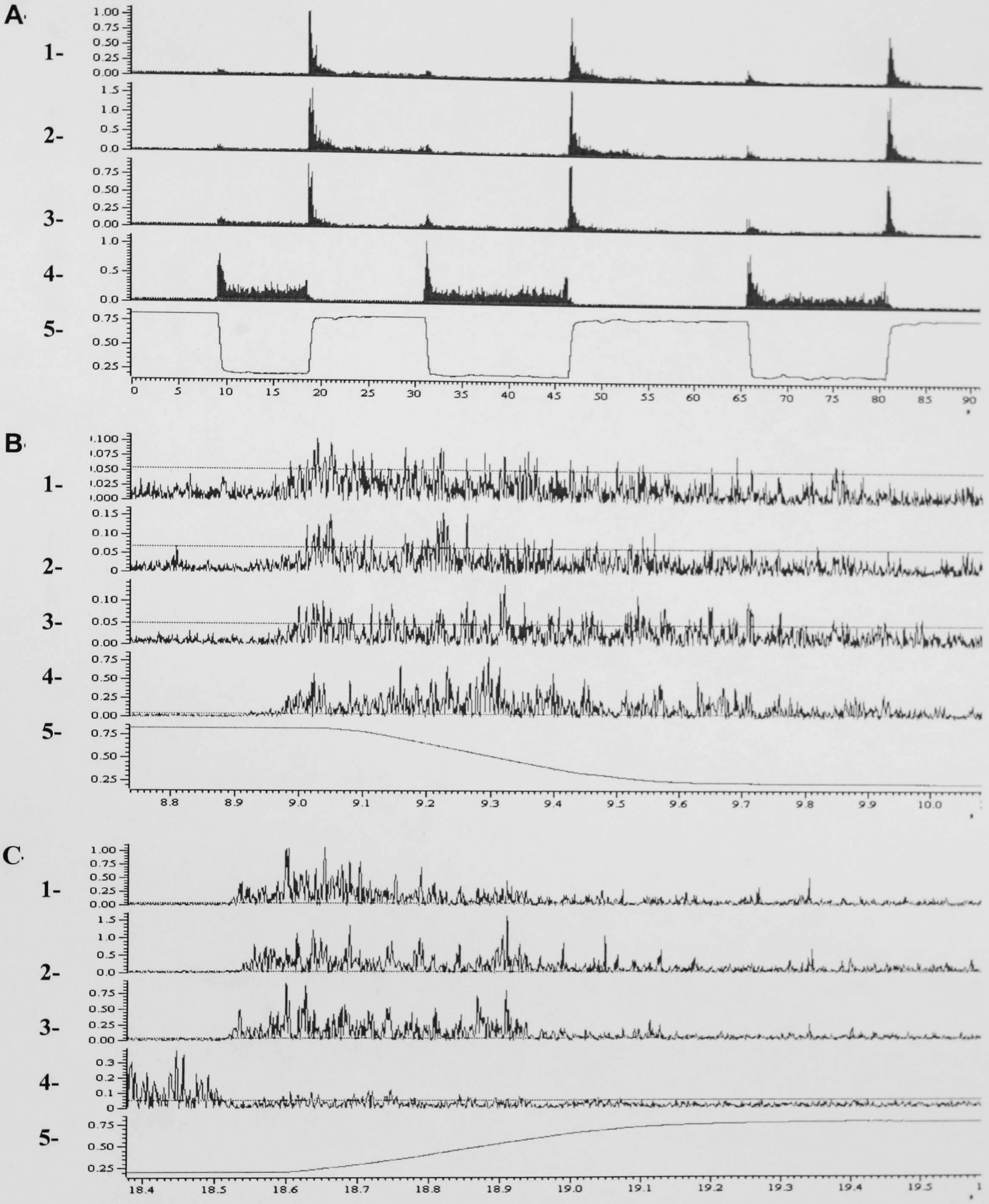


Figure 3.8. The figure shows three single isokinetic movements of knee extension and flexion at 200°/sec. The top 4 channels in each panel shows EMG 1- Semitendinosus. 2- Biceps Femoris. 3- Semimembranosus. 4- Vastus Lateralis. Channel 5 goniometer. Downwards movement signals knee extension. Panels B and C are expanded sections of A.

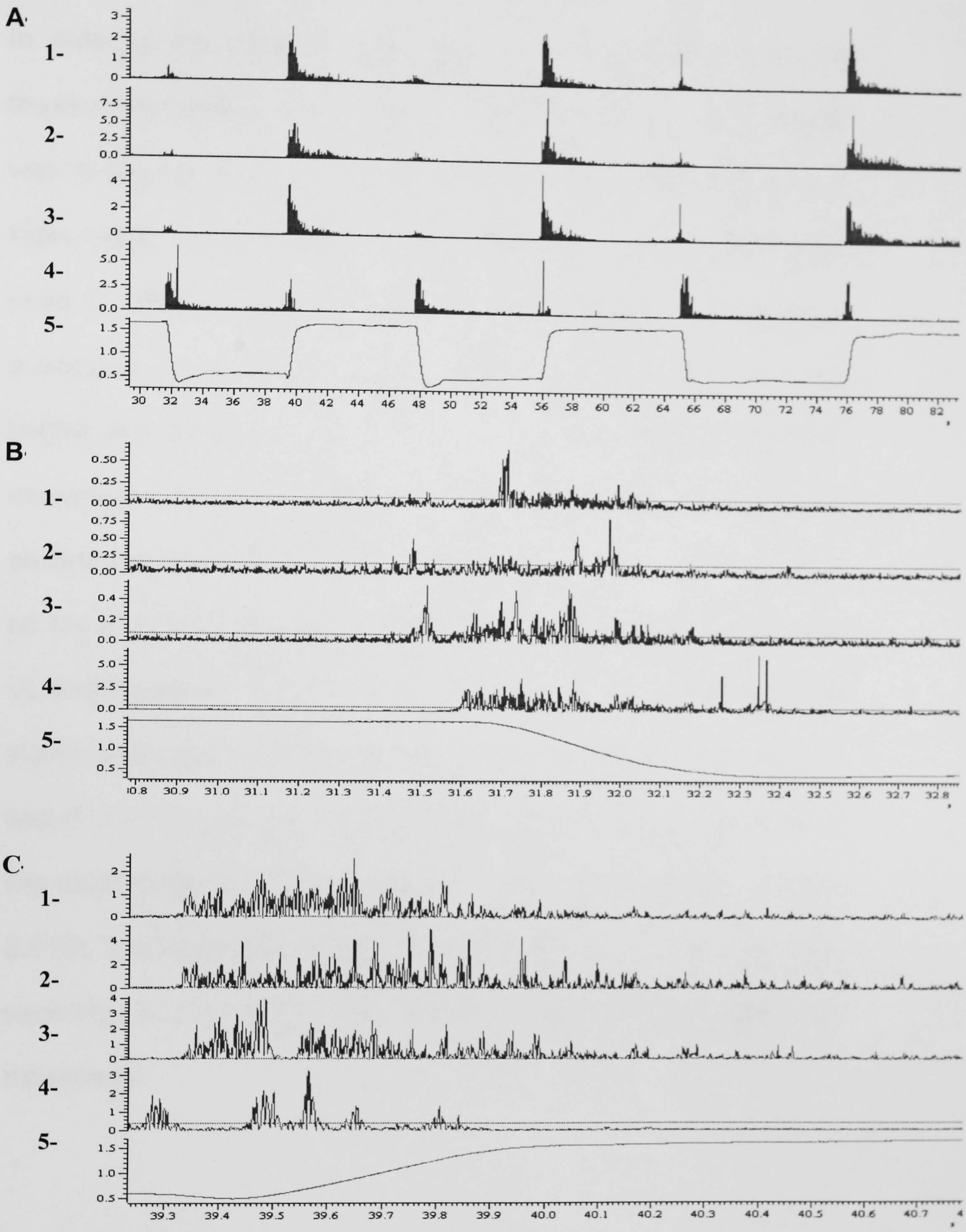


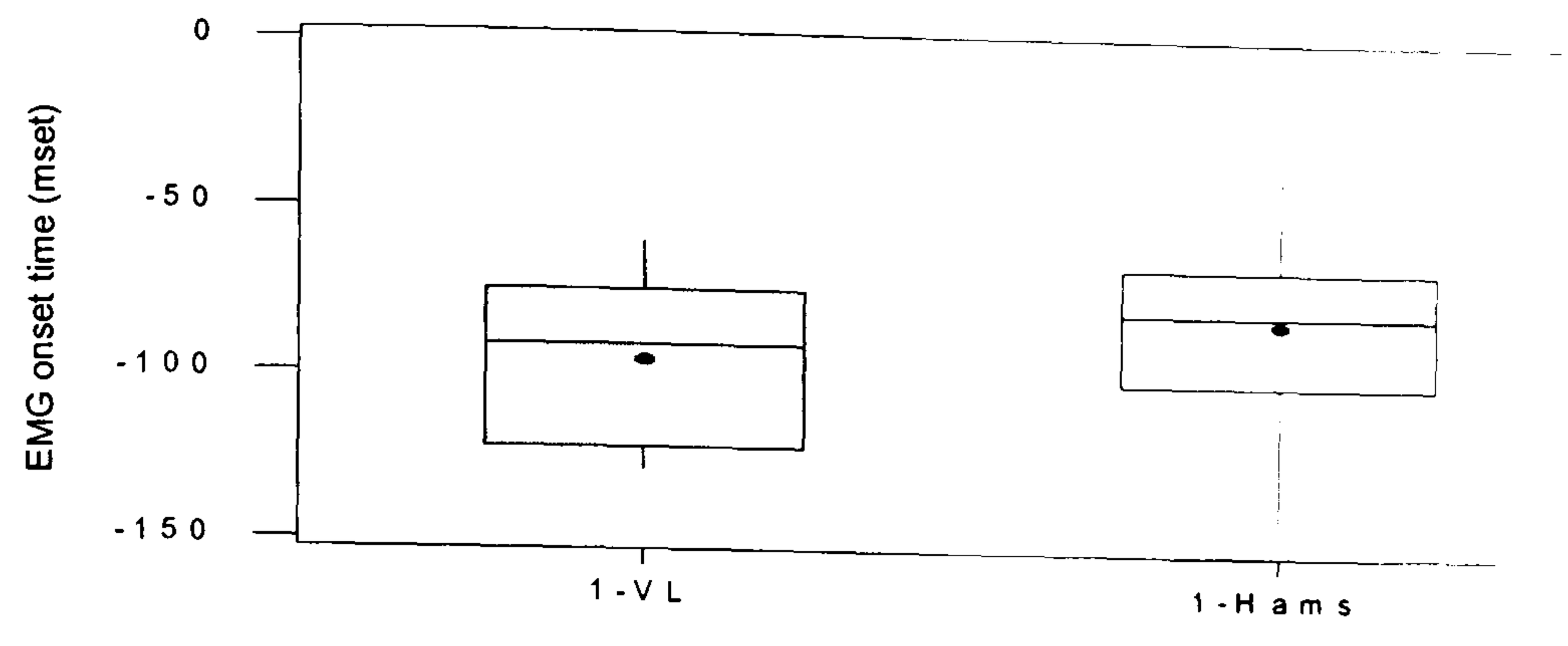
Figure 3.9 The figure shows three single isokinetic movements of knee extension and flexion at 200^{o}/sec. The top 4 channels in each panel shows EMG 1- Semitendinosus. 2- Biceps Femoris. 3- Semimembranosus. 4- Vastus Lateralis. Channel 5 goniometer. Downwards movement signals knee extension. Panels B and C are expanded sections of A.

In order to investigate further the extent of co-activation during these movements, the time of onset of EMG activity in each muscle was measured. Table 3.10 shows the data for the three extension kicks made by the 10 volunteers. The start of the movement was used to define 0 msec and EMG activity before this is expressed as a negative value. The EMG in VL begins approximately 100 msec before the movement and this was consistent across all three movements. Volunteer 1 did not activate his hamstrings during the second and third kicks. Volunteer 4 did not activate his hamstrings on his third kick. The remaining eight volunteers co-activated their VL and hamstring in every kick. The hamstrings activation occurred significantly later than VL in the second and third kicks ($P < 0.020$) and ($P < 0.0001$). There was no significant difference in the start of the electromyography in VL and hamstrings on the first kick ($P = 0.315$). These data are illustrated in Figure 3.10, where it can be seen that hamstring activation occurs progressively later with each movement.

	First Kick		Second Kick		Third Kick	
Volunteer	VL msec	Hams msec	VL msec	Hams msec	VL msec	Hams msec
1	-73	-75	-97		-107	
4	-60	-42	-81	-76	-75	
3	-88	-142	-88	-71	-110	-58
7	-129	-109	-99	-67	-106	-60
5	-108	-99	-108	-123	-76	-22
9	-122	-92	-89	-63	-66	-40
8	-123	-81	-115	-18	-100	-40
10	-84	-80	-120	-82	-82	-77
2	-75	-75	-97	-72	-101	-71
6	-94	-31	-83	-11	-124	-35
Mean	**-96**	**-83**	**-98**	**-65**	**-95**	**-50**
SD	**24**	**32**	**13**	**34**	**19**	**19**

Table 3.10. The table shows the time of onset of EMG in VL and hamstrings during three single knee extension kicks made by 10 volunteers.

A-



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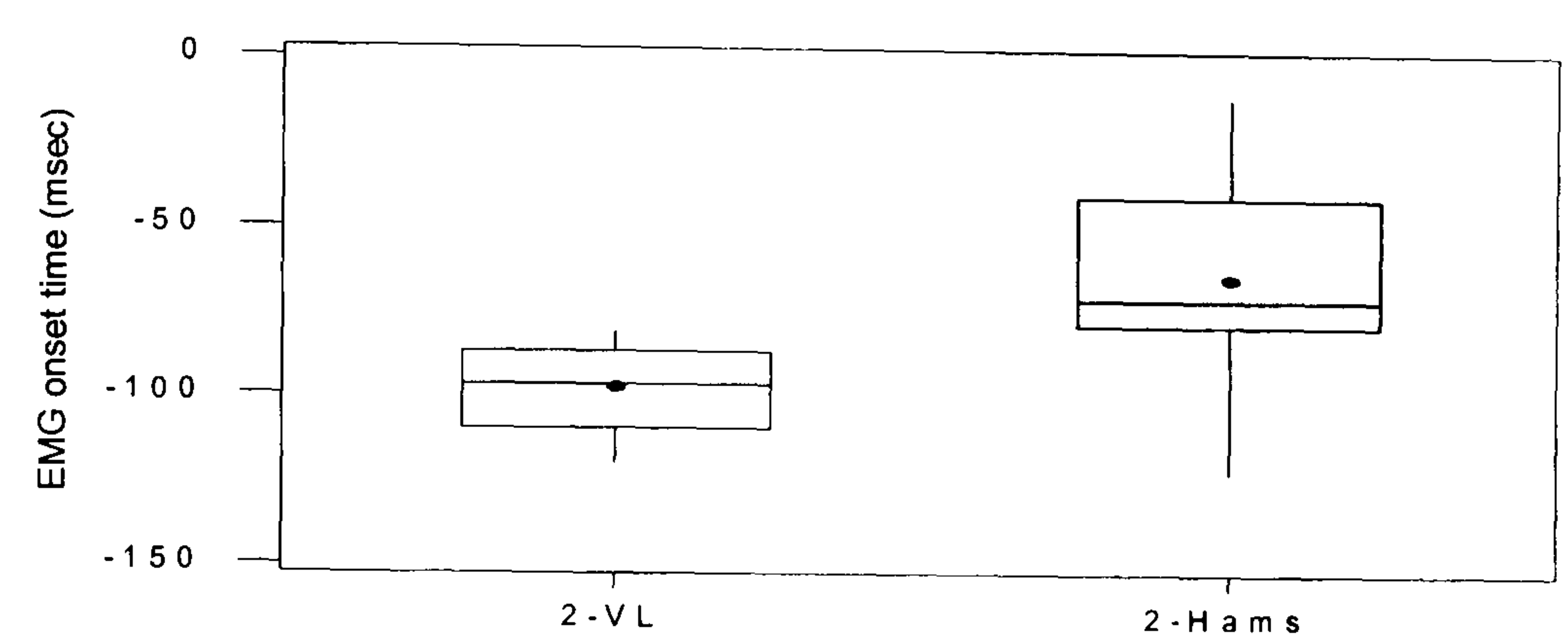

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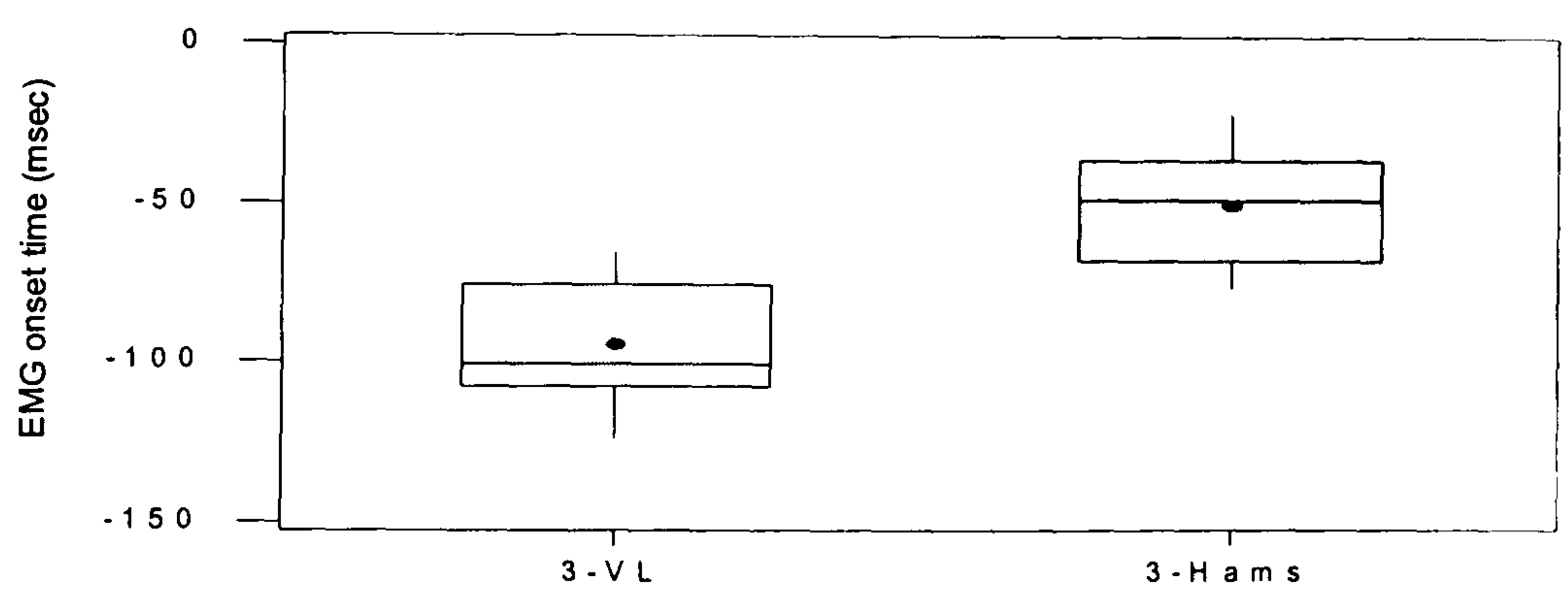


Figure 3.10. The figure shows the range of times at which the EMG starts before knee extension. The diagram shows data from Vastus Lateralis, and the data for BF, SM and ST pooled and described as Hams. (A) First extension: no significant difference between (VL) and (Hams) (P = 0.315). (B) Second extension: hams significantly later (P < 0.020) (C) Third movement hams significantly later (P < 0.0001).

Table 3.11 shows the electromyography activation times during the flexion movements. Co-activation is less common during these movements. Only two volunteers show consistent co-activation; volunteers 6 and 3. Volunteers 2 and 5 were showed occasional co-activation and the remaining six volunteers never co-activated during flexion movements.

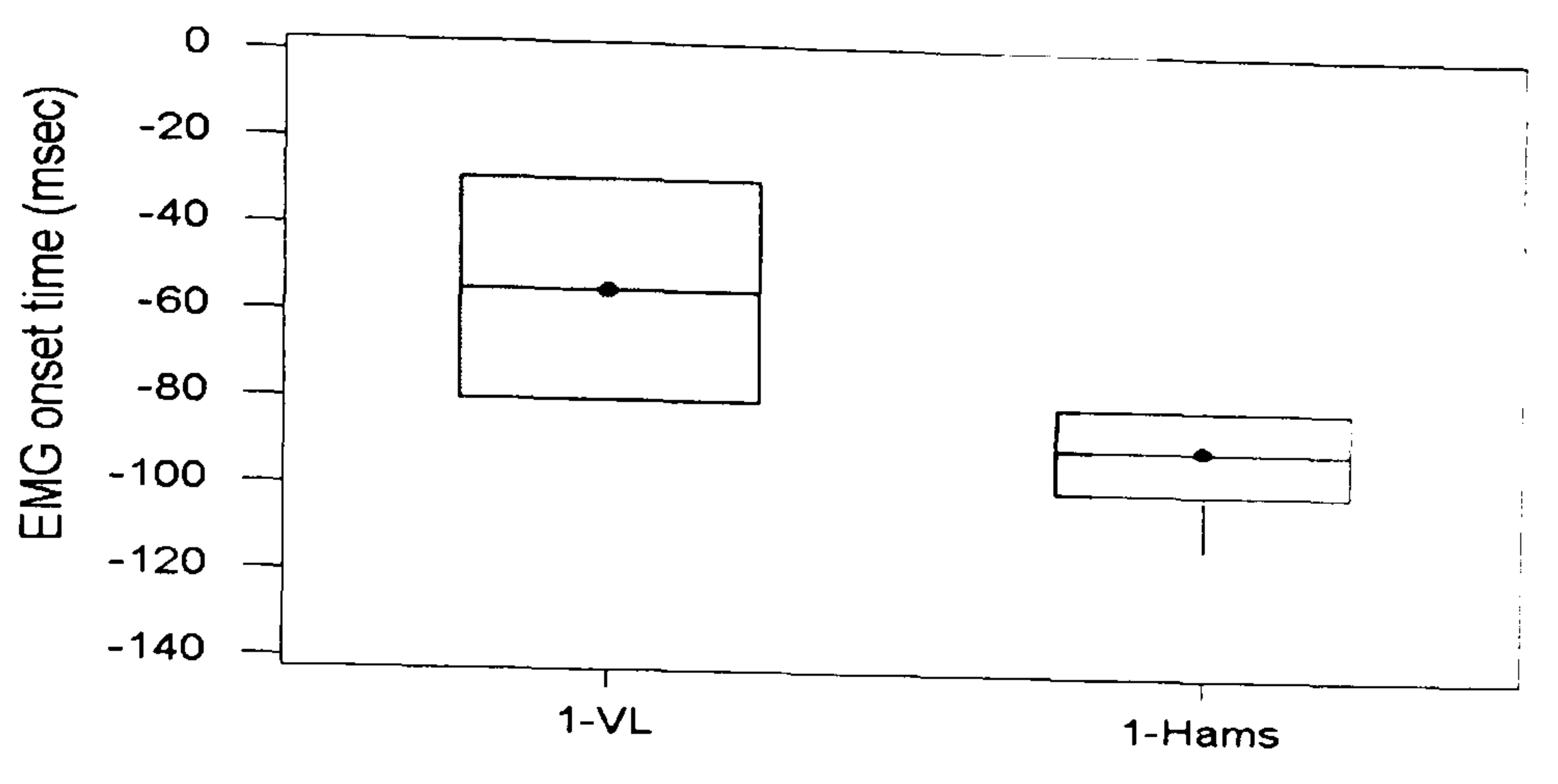
As with the extension movements, hamstrings become active some 90 msec before the flexion begins and the time of activation does not change significantly over the three tests. The small number of VL activations makes statistical analysis difficult, but it is clear that VL activation happens after the hamstrings activation but before movement begins. This is clearly seen in the example shown in Figure 3.8-C.

The data in Table 3.11 are illustrated graphically in Figure 3.11. It is clear from the table that co-activation of VL during hamstrings activation is much less frequent than hamstrings activation during extension movements. Only two volunteers (6 and 3) showed consistent co-activation. Two others (5 and 2) showed co-activation during their second and third kicks. The activation of VL occurred later than hamstrings activation in every case, except in the first flexion movement in volunteer 3, where the activation of VL and hamstrings occurs at the same time. On average the VL activation occurred from 50 to 60 msec after the start of the hamstrings EMG. Thus the VL activation tends to occur in the relatively early period during the flexion movement after the limb has moved through approximately 10 degrees.

	First Kick		Second Kick		Third Kick	
Volunteer	**VL msec**	**Hams msec**	**VL msec**	**Hams msec**	**VL msec**	**Hams msec**
4		-111		-133		-81
10		-96		-101		-70
8		-90		-75		-73
7		-89		-103		-110
1		-85		-61		-76
9		-80		-64		-84
2		-90	-14	-131	-36	-120
5		-59	-41	-81	-56	-77
6	-29	-113	-28	-90	-33	-125
3	-80	-80	-47	-69	-67	-77
Mean	**-55**	**-89**	**-32**	**-91**	**-48**	**-89**
SD		**32**	**13**	**34**	**19**	**19**

Table 3.11. The table shows the time of onset of EMG in VL and hamstrings during three single knee flexion movements.

A-



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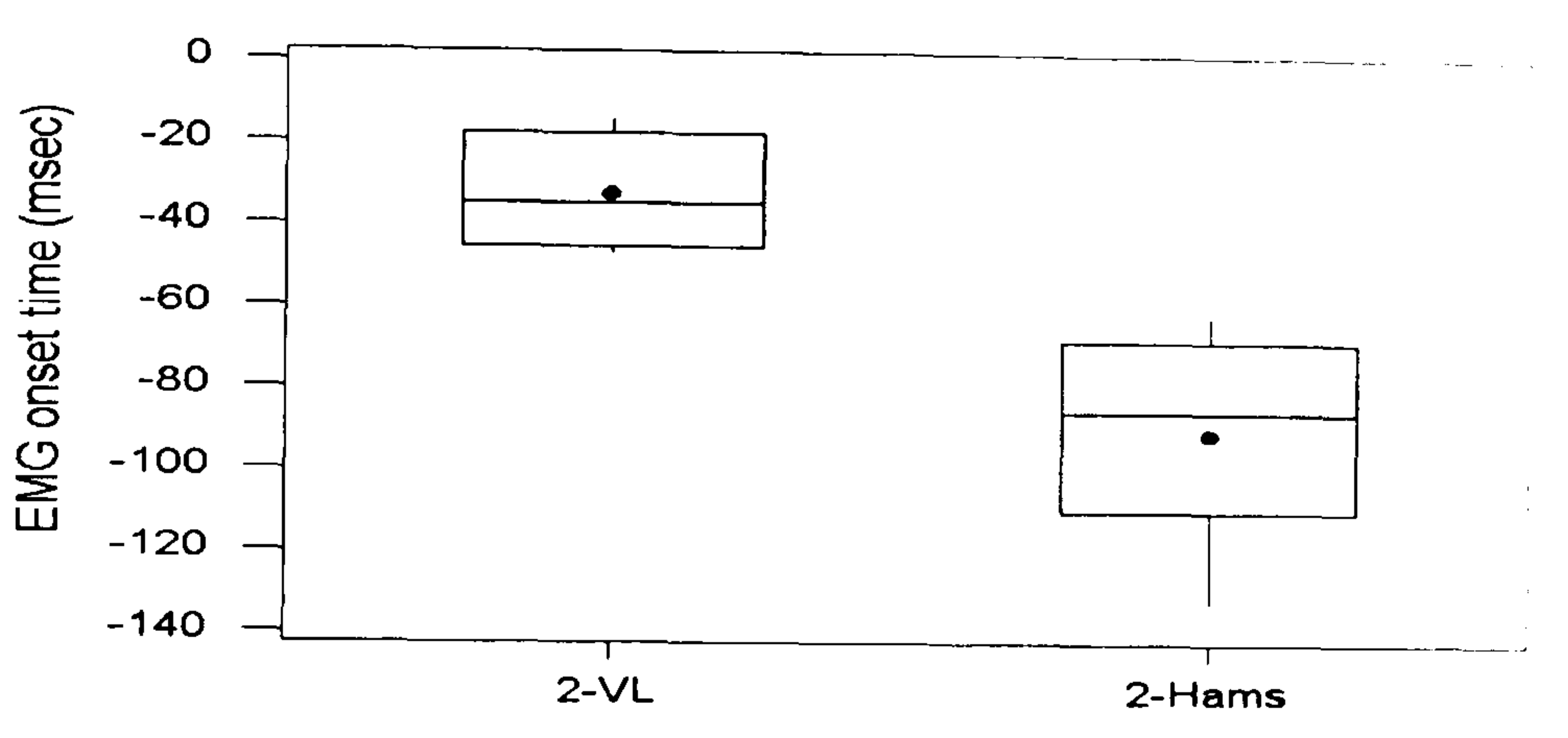

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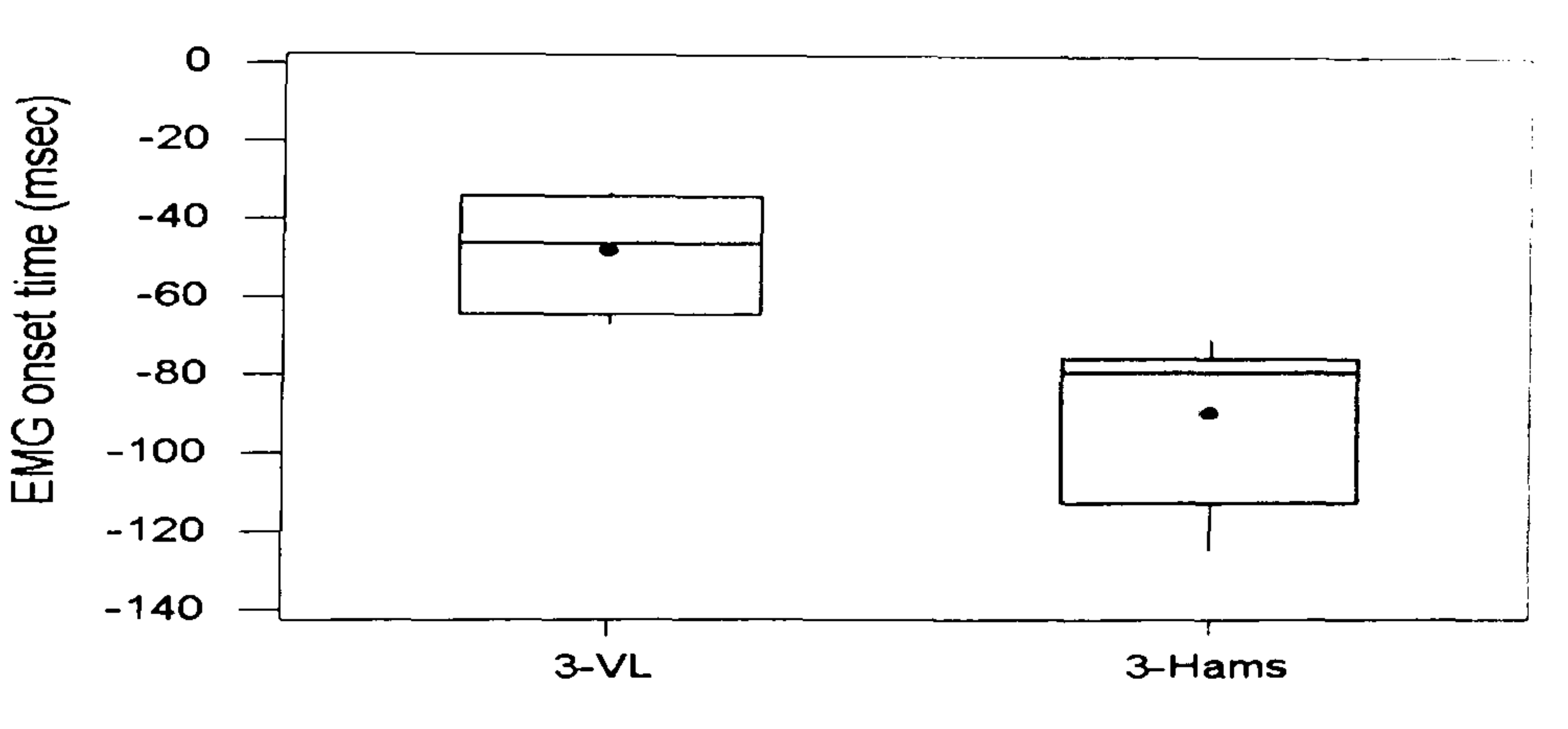

Figure 3.11. The figure shows the range of times at which the EMG starts before knee flexion. The diagram shows data from Vastus Lateralis, and the data for BF, SM and ST pooled and described as Hams. (A) First flexion: no significant difference between (VL) and (Hams) ($P = 0.408$). (B) Second flexion: hams significantly earlier ($P < 0.0001$) (C) Third flexion: hams significantly earlier ($P < 0.005$).

Tables 3.12 and 3.13 show the peak torque delivered during the extension and flexion movements. The data are organised to show the movements during which co-activation occurred, on the left side of table and those, which did not display co-activation, on the right. It is difficult to make any clear statement about the data in Table 3.12. Only two volunteers (1 and 4) who did not show co-activation during knee extension and so statistical comparison has little value. The mean force without co-activation lies within the range of those who did show co-activation without significant differences between them in three movements ($P = 0.224$), ($P = 0.295$) and ($P = 0.170$). However, since co-activation was more frequent during flexion, a better comparison can be made. Analysis of the forces shown in Table 3.13 indicates that there are no significant differences in the forces produced during three knee flexion kicks with and without co-activation. A t-test provided P-values of ($P = 0.378$), ($P = 0.335$) and ($P = 0.299$) for the first, second and third movements.

	Co-activation in Extension			Non Co-activation in Extension		
Volunteers	First Nm	Second Nm	Third Nm	First Nm	Second Nm	Third Nm
1	*	*	*	173	175	167
4	*	*	*	177	185	175
10	117	131	94	*	*	*
8	136	135	134	*	*	*
5	134	135	132	*	*	*
6	137	147	134	*	*	*
7	182	187	178	*	*	*
3	184	191	180	*	*	*
9	170	192	157	*	*	*
2	199	213	177	*	*	*
MN	**157**	**166**	**148**	**175**	**180**	**171**
SD	**30**	**33**	**30**	**3**	**7**	**6**

Table 3.12. The table shows the peak torque (Nm) of knee extension in concentric contraction at 200°/sec of isokinetic test for co-activation and non-co-activation of VL and Hamstring muscles before three single movements. In the first, second and third movements the torque between co-activation and non-co-activation are not significantly changed (P = 0.224), (P = 0.295) and (P = 0.170).

	Co-activation in Flexion			Non Co-activation in Flexion		
Volunteers	First Nm	Second Nm	Third Nm	First Nm	Second Nm	Third Nm
6	100	107	96	*	*	*
5	122	129	116	*	*	*
3	147	172	132	*	*	*
2	176	179	158	*	*	*
10	*	*	*	74	91	55
8	*	*	*	96	103	88
9	*	*	*	124	118	81
7	*	*	*	141	147	130
4	*	*	*	160	172	145
1	*	*	*	177	186	172
MN	**136**	**147**	**126**	**129**	**136**	**112**
SD	**33**	**35**	**26**	**39**	**38**	**44**

Table 3.13. The table shows peak torque (Nm) of concentric contraction in knee flexion at 200°/sec of isokinetic test for co-activation and non-co-activation of extensor and flexors muscle before three single movements. In the first, second and third movements the torque between co-activation and non-co-activation are not significantly changed (P = 0.378), (P = 0.335) and (P = 0.299).

3.2.2. Repetitive Movements of Knee Extension and Flexion

The ten volunteers who took part in the previous experiments also performed a series of rapidly alternating flexion extension movements of the knee. These movements were performed approximately 5 to 10 minutes after the single movements. The EMG recording conditions were unchanged.

There was considerable variation between the pattern of co-activation of Vastus Lateralis and Hamstrings seen in the single movements and during the repeated movements.

Table 3.14 shows the ten volunteers co-activation had during repeated and single movements for VL and hamstring in extension and flexion. There were different patterns of co-activation during repeated and single movements. Volunteers 3, 7 and 9 had shown no co-activation during repeated movements but varied in single movements. Volunteer 3 showed co-activation in extension and flexion movements, whereas volunteers 7 and 9 showed co-activation in extension but not in flexion movements. The second pattern of volunteers 1, 4 and 6 displayed Vastus Lateralis activation during flexion of repeated movements but varied in single movements. Volunteer 1 showed no co-activation, volunteer 4 showed occasional co-activation in extension but never in flexion movements, volunteer 6 always showed co-activation in extension and flexion movements. The last pattern of volunteers 2, 5, 8 and 10 had showed hamstrings activation during extension of repeated movements. Performing in single movements, volunteers 2, 8 and 10 always showed co-activation in extension but this never happened in flexion movements. However, volunteer 5 always showed co-activation in extension and sometimes it happened in flexion.

Co-activation during Repeated Movements	Volunteer	Co-activation during Single Movements
No Co-activation	3	Extension and flexion
	7	Extension but not flexion
	9	Extension but not flexion
V. Lateralis activation during flexion	1	Does not co-activate
	4	Sometimes in extension but never in flexion
	6	Always in extension and in flexion
Hams activation during extension	2	Always in extension but never in flexion
	5	Always in extension sometimes in flexion
	8	Always in extension but never in flexion
	10	Always in extension but never in flexion

Table 3.14. The table shows the number of volunteers showing co-activation during single and repeated movements in knee extension and flexion for Vastus Lateralis and Hamstrings.

Figure 3.12 shows the electromyography recorded from volunteers 3, 7 and 9. These volunteers show no significant co-activation during the repeated movements. This contrasts with their pattern of EMG during single movements when the hamstrings co-activated during knee extension.

Figure 3.13 shows the electromyography from volunteers 2, 5 and 8 during the repeated movements. These volunteers show significant hamstrings activation during knee extension but not VL activation during knee flexion. It is easy to see that the co-activation does not occur during the first movement cycle but emerges later in the sequence.

Figure 3.14 shows the electromyography from volunteers 6, 1 and 4. The volunteers are characterised by VL activation during knee flexion, though number 4 (Figure 3.14C) also shows occasional hamstrings activation during extension. The VL activation is particularly disorganised in volunteer 4 and he shows VL activation during the flexion phase of the first movement cycle.

The magnitude of the co-activation was surprisingly large and the bursts occurred with little warning. Sections of the recordings shown in Figures 3.13B and 3.14A, are shown in expanded form in Figure 3.15. In Figure 3.15-A, repeated bursts of VL activity happen as the limb reaches the end of the extension phase and moves into flexion. This is clear co-activation since the hamstrings burst is well established by repeated movements.

Figure 3.15B, shows a very large EMG burst of Semitendinosus at the end of the knee flexion phase almost at the same time as the start of the VL burst, which will initiate knee extension.

In summary there is no simple relationship between the frequency and magnitude of co-activation during single and repeated movements. During repeated movements co-activation varies from cycle to cycle, though it seems more likely to occur later in the series of movements.

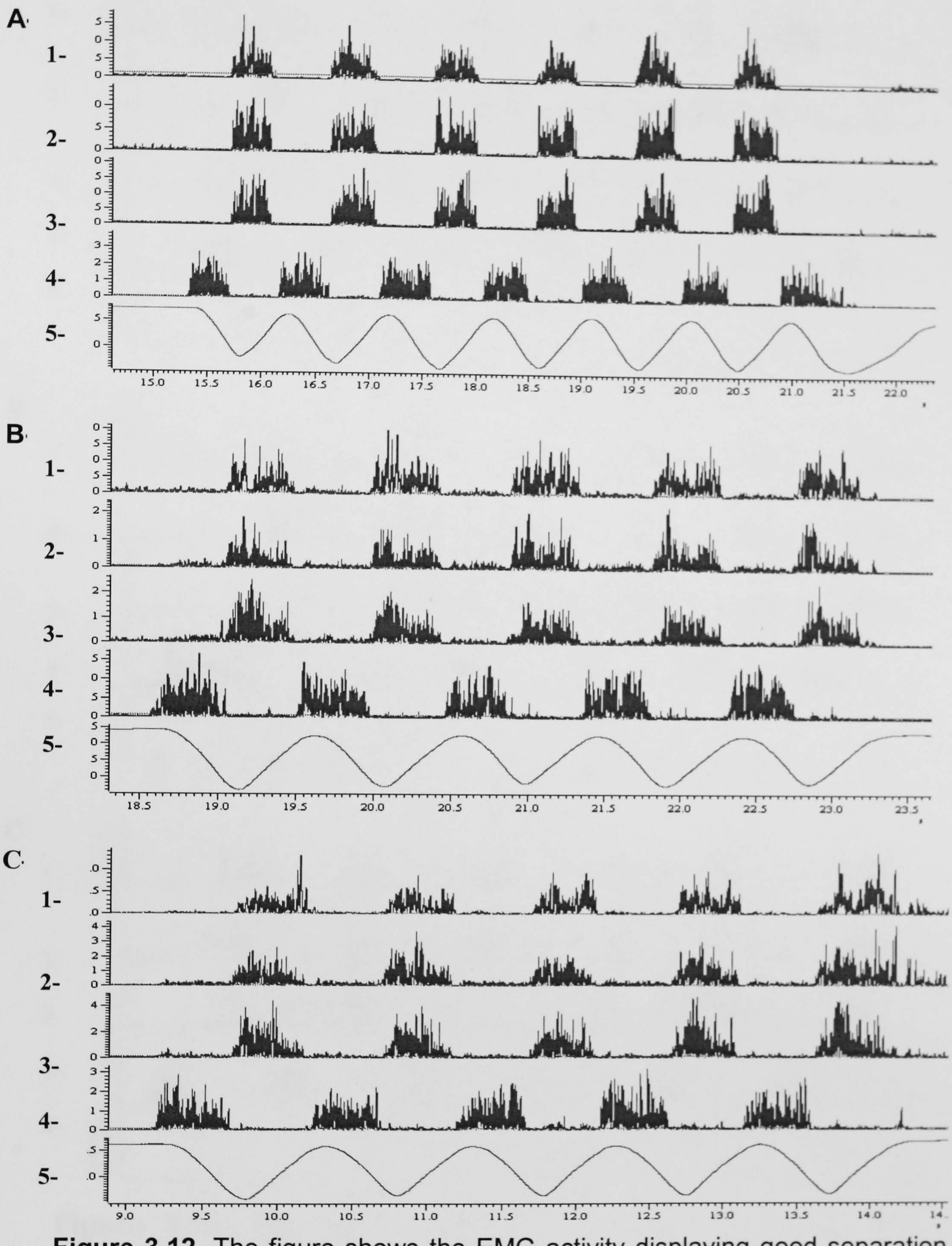

Figure 3.12. The figure shows the EMG activity displaying good separation of flexor and extensor activity during knee extension flexion movements for volunteer 3 in panel A, number 7 in panel B, and number 9 in panel C. 1) Semitendinosus. 2) Biceps Femoris. 3) Semimembranosus. 4) Vastus Lateralis. 5) electrogoniometer signal: movement downward indicates extension.

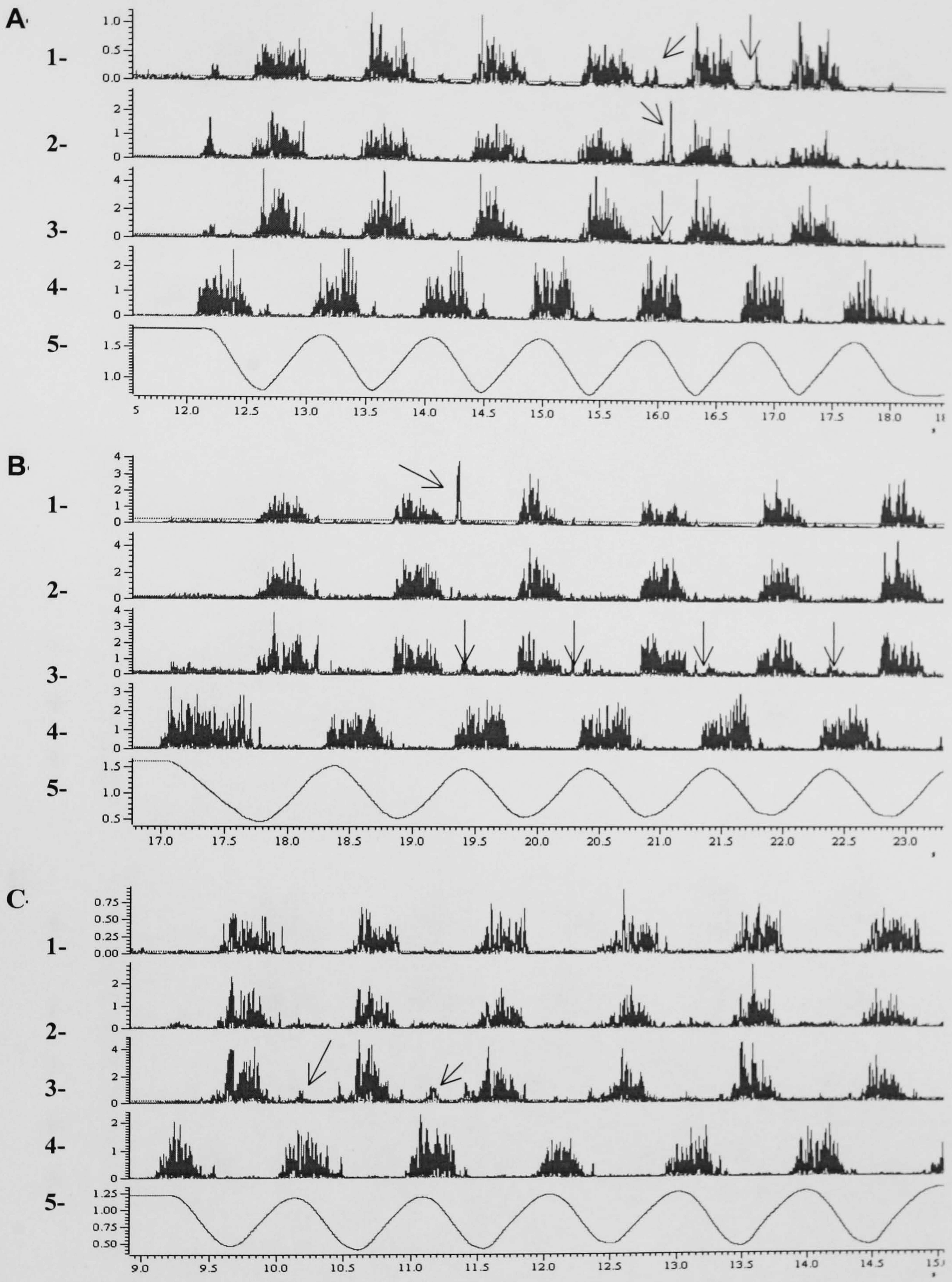

Figure 3.13. The figure shows the EMG activity of VL and Hamstring. In these cases there are bursts of flexor EMG during knee extensions. Channels as in figure 3.12.

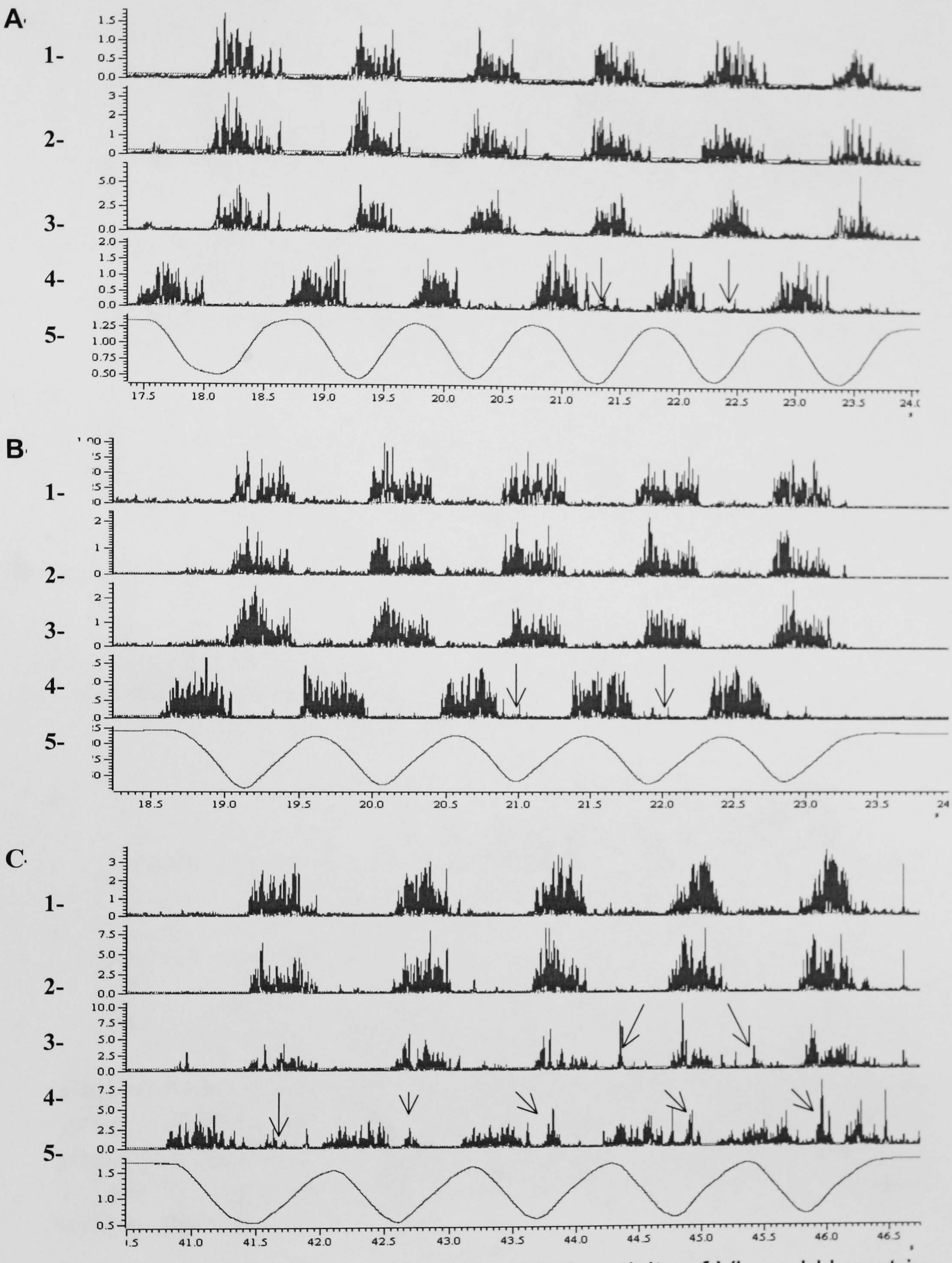

Figure 3.14. The figure shows the EMG activity of VL and Hamstring. In these cases there are bursts of VL EMG during knee flexions. Channels as in figure 3.12

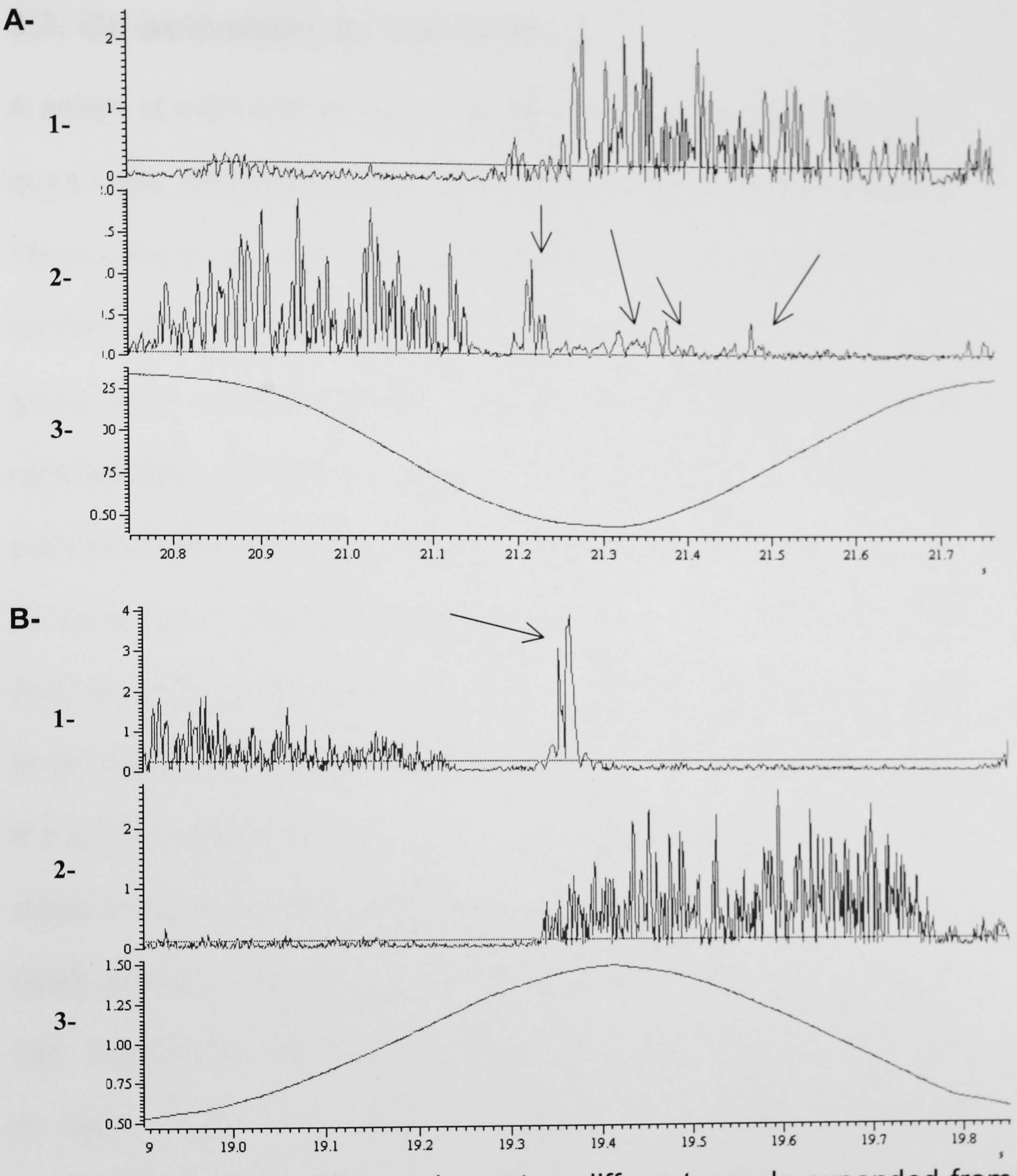

Figure 3.15. The figure shows two different panels expanded from previous figures. (A) From fig 3.14A. It shows co-activation of SM in channel 2 and VL in channel 4 during knee extension (B) From fig 3.13-B. It shows co-activation of ST in channel 1 and VL channel 2 during knee flexion.

3.3. Co-activation during Kicking

A series of experiments was performed to investigate the extent of quadriceps and hamstrings co-activation during kicking a football. Three groups of volunteers participated. Two groups were junior football players in the 11-year-old age group and 15-year-old age group of a Scottish Premier League club. The third group were recreationally active adults aged 18 years and above. It was not possible to get the adult professional players to participate.

In each experiment the volunteer was fitted with a four-channel EMG system. Goniometers measured the hip and knee angles. The shoe of their performing kicking foot had a toe switch fitted to mark the instant of ball contact. These techniques are described in more detail in the Methods section 2.11.2. The volunteers were invited to make a series of progressively more powerful kicks of a tethered ball. This section describes the results of the maximum power kick for each person. The minimum power and a specimen midrange power kick close to 50% of maximum were also analysed.

Figure 3.16 shows maximum power kicks for three volunteers from each group. The top panel (A) shows data from the 11-year-olds, the middle panel (B) shows data from the 15-year-olds and lower panel (C) shows data from the untrained adults. The sequence of data in each panel in Figure 3.16, and all subsequent figures of this sort, is from the top rectified EMG from Biceps Femoris (BF)-(1), Semitendinosus (ST)-(2), Vastus Lateralis (VL)-(3) and Semimembranosus (SM)-(4).

Channel 5 shows the instant of ball contact with the foot. Channel 6 shows the knee position and channel 7 shows the hip position.

Figure 3.16-A, channel 5 shows ball contact by foot just after 260.6 msec. Immediately before ball contact there is a period of knee flexion, shown by the upward deflection in channel 6. This lasts approximately 100 msec. This is preceded by a longer-lasting, slower extension phase. The knee is extended for about 100 msec just after ball contact. Hip flexion ends about 50 msec before ball contact, which occurs during a period of hip extension. This pattern of joint movement can be seen in the 15-year-old and the adult kicks shown in Figure 3.16-B and C. Figures 3.17 and 3.18 showed similar pattern.

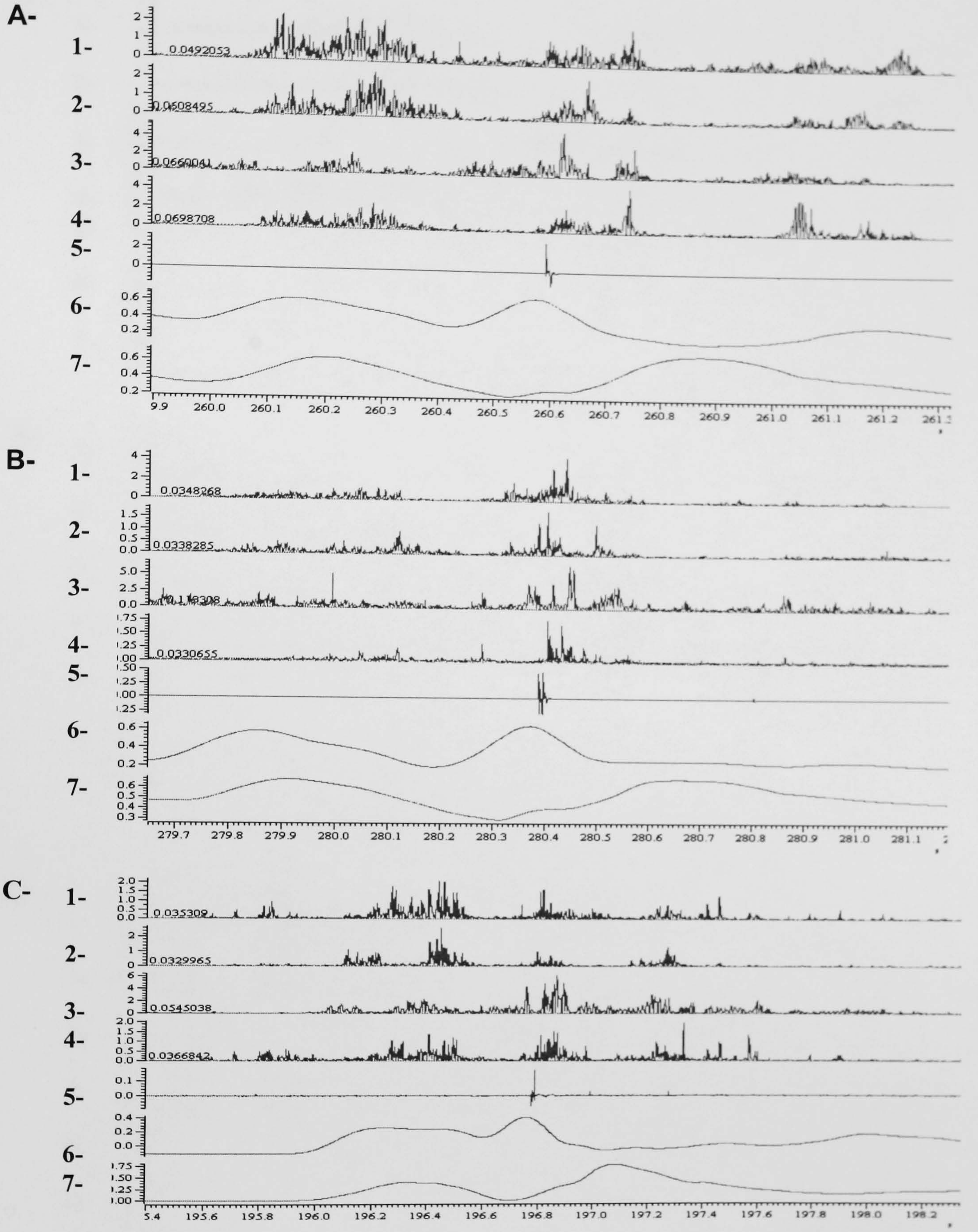

Figure 3.16. The figure shows maximum power kicks of a stationary football by 3 volunteers. A) 11-year-old footballers. B) 15-year-old footballers and C) untrained adults. Channels show: (1) Biceps Femoris. (2) Semi-tendinosus. (3) Vastus Lateralis, (4) Semimembranosus. (5) Ball contact. (6) Knee position, upwards indicates flexion. (7) Hip position upward indicates extension..

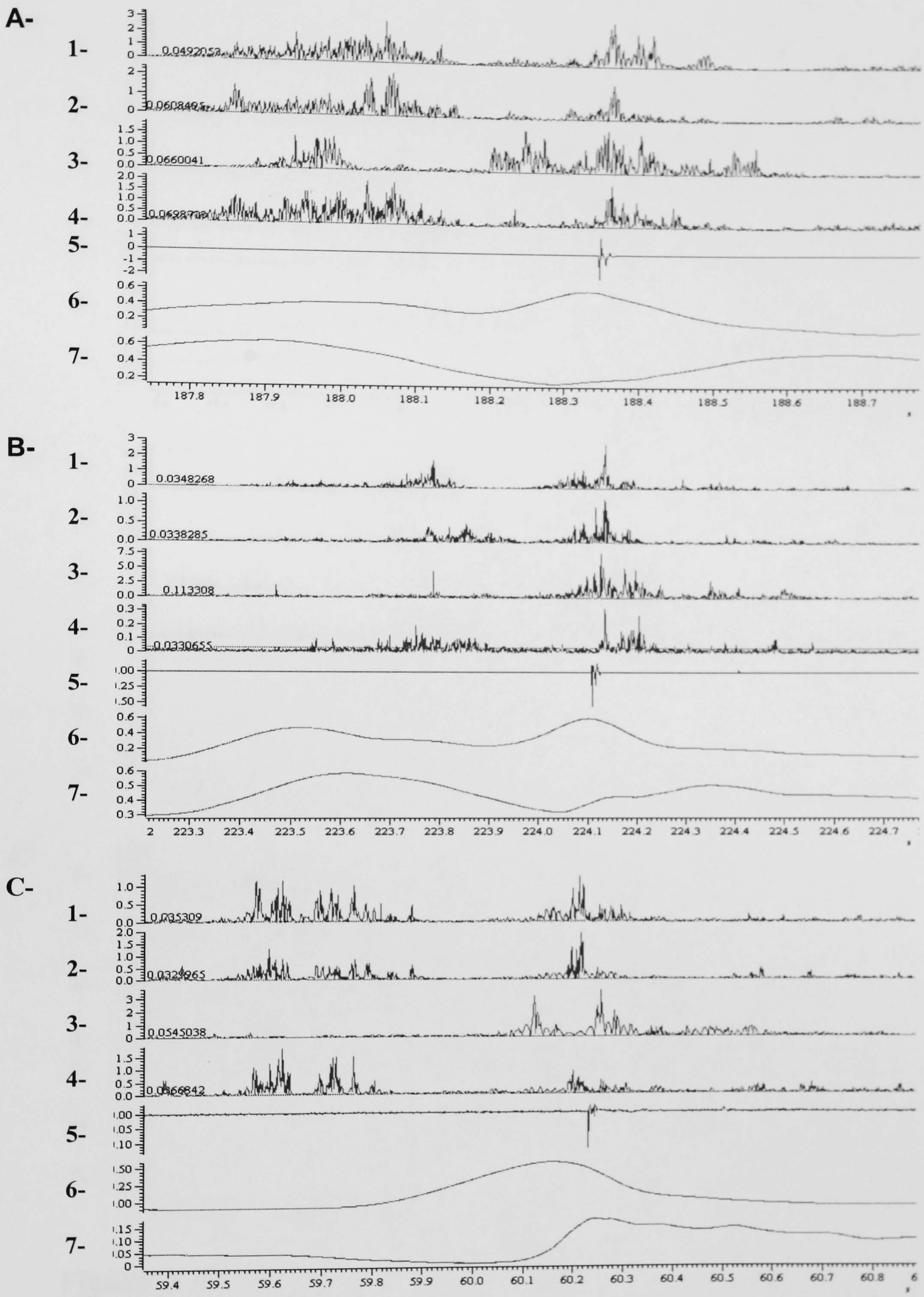

Figure 3.17. The figure shows mid-range power kicks of a stationary football by 3 volunteers. A) 11-year-old footballers. B) 15-year-old footballers and C) untrained adults. Channels show. 1 – BF. 2 – ST. 3 – VL. 4 – SM. 5 – ball contact. 6 – Knee movement. 7 – Hip movement.

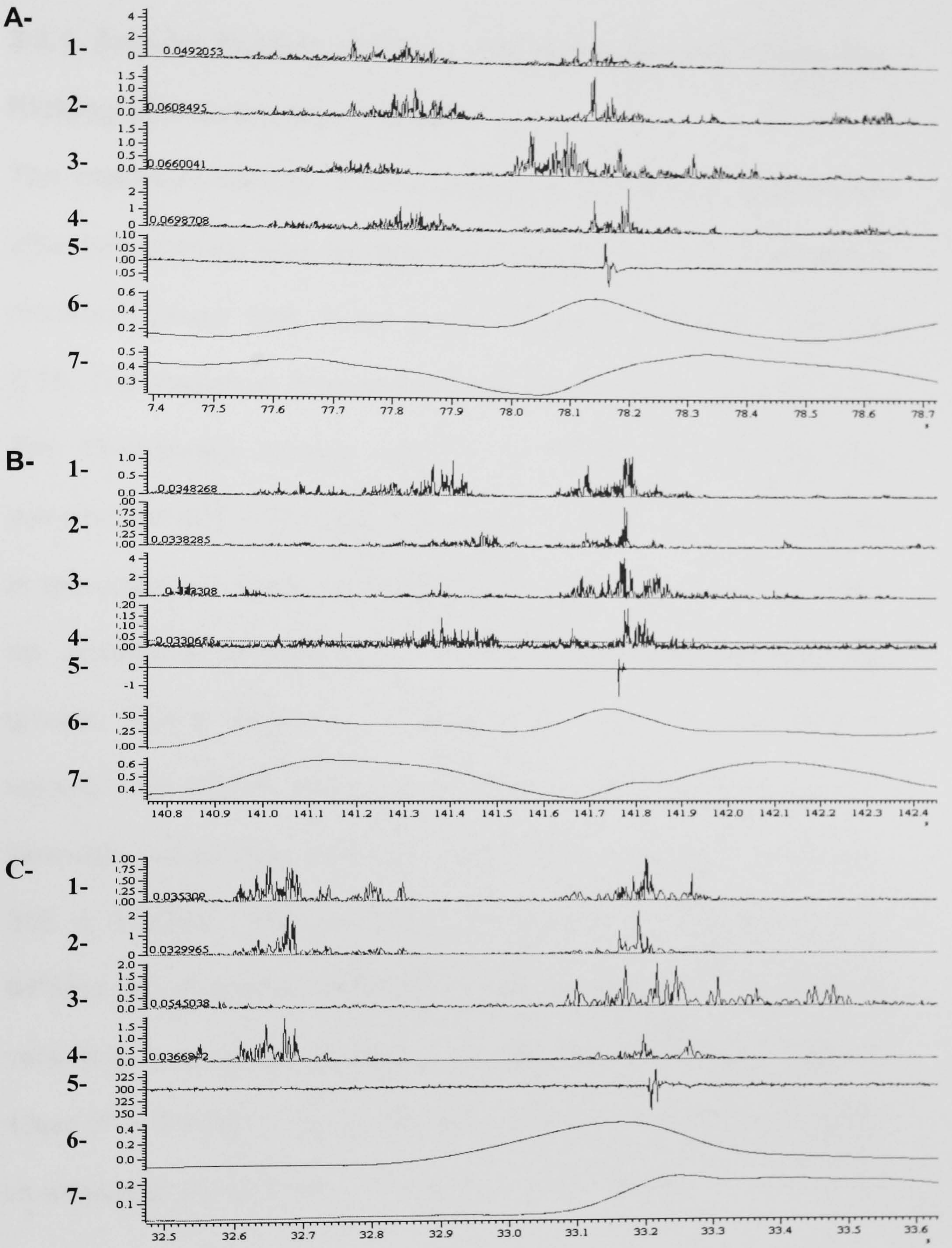

Figure 3.18. The figure shows minimum power kicks of a stationary football by 3 volunteers. A) 11-year-old footballers. B) 15-year-old footballers and C) untrained adults. . 1 – BF. 2 – ST. 3 – VL. 4 – SM. 5 – ball contact. 6 – Knee movement. 7 – Hip movement.

3.3.1. Angular Velocity of Knee and Hip Movements during the Kicking of a Stationary Football.

The maximum velocity of knee extension and flexion, before and after ball contact, was identified with cursors for each volunteer's maximum power kick. These data are shown in Tables 3.15 and 3.16. The maximum extension velocities were more than 400°/sec. The 11-year-olds velocity was 411 ± 81°/sec. The 15-year-olds velocity was 451 ± 107°/sec. The maximum knee extension velocity in the untrained adults group was 401 ± 123°/sec. T-tests showed no significant differences in maximum velocities between the groups. This is illustrated in Figure 3.19. The mean knee flexion velocity was slightly slower than the extension velocity. The 11-year-olds velocity was 388 ± 77°/sec. The 15-year-olds velocity was 365 ± 103°/sec. The untrained adult group velocity was 420 ± 68°/sec. No significant differences were found between the flexion velocities in each age group by statistical analysis t-test 11yrs vs 15yrs ($P = 0.546$), 11yrs vs untrained adults ($P = 0.293$) and 15yrs vs untrained adults ($P = 0.170$) shown in Figure 3.20.

(A) 11-years	
Volunteers	deg/sec
6	308
9	325
5	338
4	341
10	353
8	417
2	434
11	436
12	456
3	463
7	480
1	585
Mean	411
SD	81

(B) 15-years	
Volunteers	deg/sec
2	339
6	345
1	402
4	423
8	423
5	430
3	446
7	602
9	652
Mean	451
SD	107

(C) Adults	
Volunteers	deg/sec
7	244
12	259
2	311
4	332
1	358
9	366
6	377
8	421
10	452
3	471
11	543
5	679
Mean	401
SD	123

Table 3.15. The table shows the maximum knee extension velocities in three groups of volunteers performing maximum knee extension velocities. No significant differences in (A) vs (B) (P = 0.364), (A) vs (C) (P = 0.812) and (B) vs (C) (P = 0.331).

(A) 11-years	
Volunteers	deg/sec
8	271
5	284
4	341
6	345
9	347
10	378
11	389
7	400
12	449
1	461
3	463
2	533
Mean	**388**
SD	**77**

(B) 15-years	
Volunteers	deg/sec
8	185
9	299
6	331
3	334
7	357
1	365
4	366
5	488
2	542
Mean	**363**
SD	**103**

(C) Adults	
Volunteers	deg/sec
3	283
1	351
9	382
4	384
7	390
2	415
8	421
5	453
6	459
12	494
10	497
11	517
Mean	**420**
SD	**68**

Table 3.16. The table shows the maximum knee flexion velocities in three groups of volunteers performing maximum knee flexion velocities. No significant differences in (A) vs (B) (P = 0.546), (A) vs (C) (P = 0.293) and (B) vs (C) (P = 0.170).

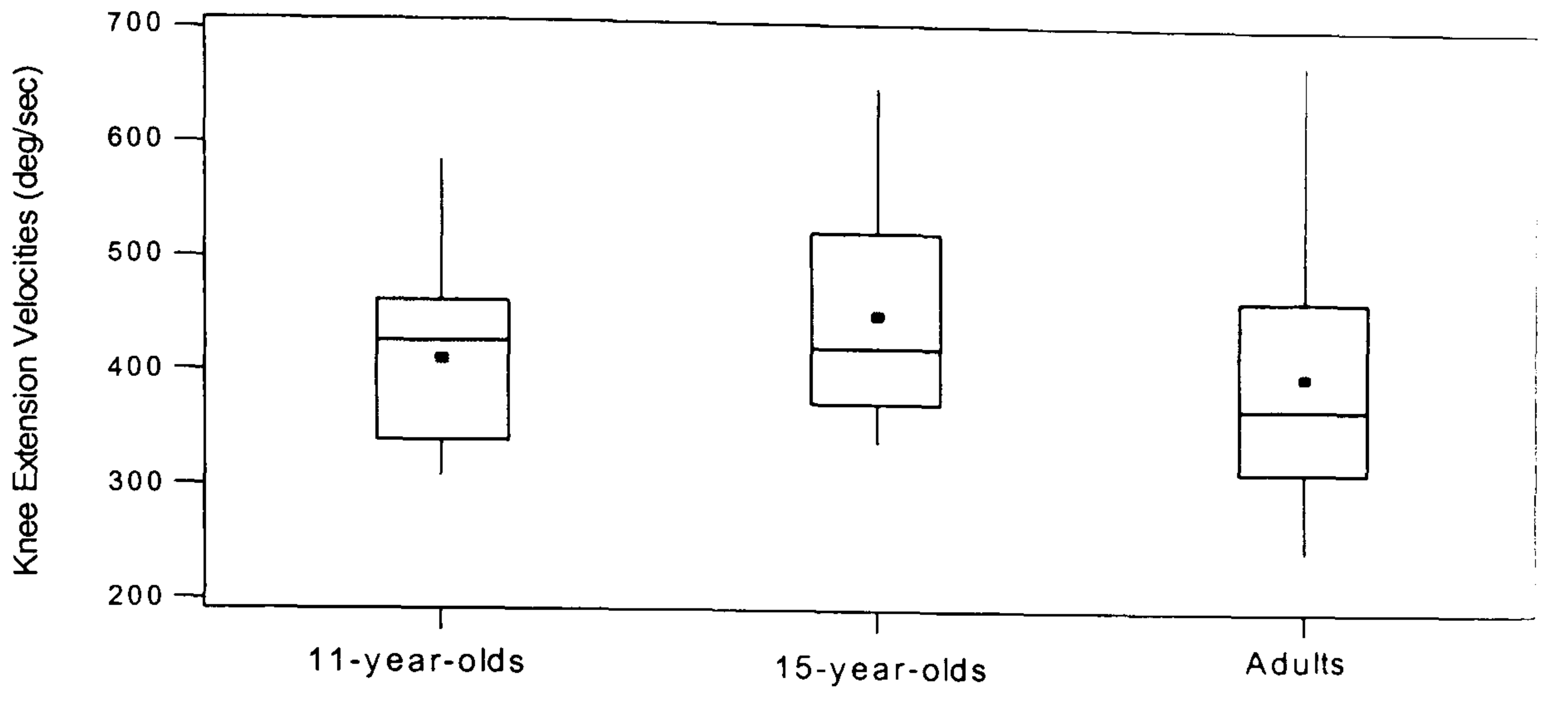

Figure 3.19. The diagram shows the maximum knee extension velocities during kicking. First rectangle on the left shows data from the group of 11-year-old footballers. The middle one shows data from the group of 15-year-old footballers and data from the untrained adults is on the right side.

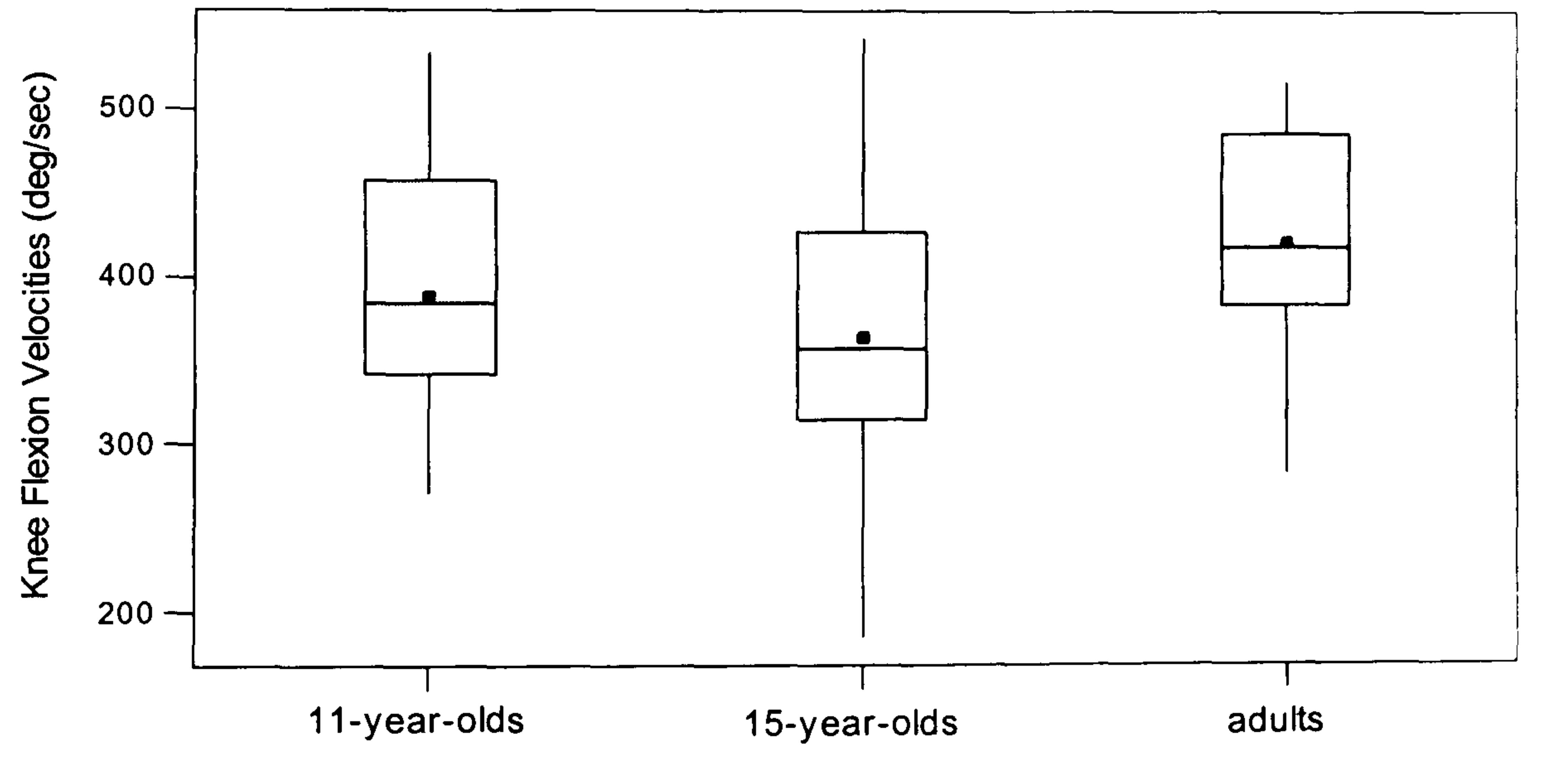

Figure 3.20. The diagram shows the maximum knee flexion velocities during kicking. First rectangle on the left shows data from the group of 11-year-old footballers. The middle one shows data from the group of 15-year-old footballers and data from the untrained adults is on the right side.

A similar analysis was done for hip velocity in extension and flexion during the kick. The maximum velocity of hip extension in the 11-year-olds was 176 $\pm$ 61°/sec. The 15-year-olds' maximum velocity was 159 $\pm$ 44°/sec. The untrained adults had a maximum velocity of 123 $\pm$ 38°/sec. The velocity was not significantly different between 11 and 15 year old groups (t-test, $P = 0.453$). There was no significant difference between the 11 year old group and the adults ($P < 0.069$). However, the 15 year old group was significantly faster than the adults ($P < 0.018$).

The maximum velocity of hip flexion of the 11-year-olds was 209 $\pm$ 75 °/sec. The maximum velocity of the 15-year-olds was 232 $\pm$ 75 °/sec. The maximum velocity of the adults was 199 $\pm$ 83°/sec. There were no significant difference between the three (11yrs vs 15yrs $P = 0.486$, 11yrs vs adults $P = 0.764$ and 15yrs vs untrained adults $P = 0.348$). These data are shown in Tables 3.17 and 3.18 and illustrated in Figures 3.21 and 3.22.

The hip velocities are substantially slower than the knee velocities in all cases. There is a clear tendency for the adult kickers to move their hips more slowly but this is statistically significant only when hip extension is compared in the 11-year-olds and the adults.

(A) 11-years		(B) 15-years		(C) Adults	
Volunteers	**deg/sec**	**Volunteers**	**deg/sec**	**Volunteers**	**deg/sec**
3	54	9	93	5	77
8	114	3	113	6	84
9	147	2	118	9	90
4	151	5	152	11	98
12	156	1	152	2	104
1	170	4	180	4	115
2	177	6	199	3	117
11	197	7	203	12	124
5	201	8	217	7	126
6	209			10	162
10	253			1	186
7	284			8	189
Mean	**176**	**Mean**	**159**	**Mean**	**123**
SD	**61**	**SD**	**44**	**SD**	**38**

Table 3.17. The table shows the maximum hip extension velocities in three groups of volunteers during kicks. No significant differences in (A) vs (B) (P = 0.453) and (B) vs (C) (P = 0.069), but significant differences exist between (A) vs (C) (P < 0.018).

(A) 11-years		(B) 15-years		(C) Adults	
Volunteers	**deg/sec**	**Volunteers**	**deg/sec**	**Volunteers**	**deg/sec**
3	46	6	163	12	83
4	128	9	168	9	101
1	181	7	171	4	140
7	183	8	217	5	143
8	183	3	226	2	166
2	193	1	228	6	181
9	226	5	251	10	189
6	227	2	256	7	206
11	236	4	410	11	246
12	290			8	264
10	300			3	300
5	310			1	366
Mean	**209**	**Mean**	**232**	**Mean**	**199**
SD	**75**	**SD**	**75**	**SD**	**83**

Table 3.18. The table shows the maximum hip flexion velocities in three groups of volunteers during kicks. No significant differences were found. (A) vs (B) (P = 0.486), (A) vs (C) (P = 0.764) and (B) vs (C) (P = 0.348).

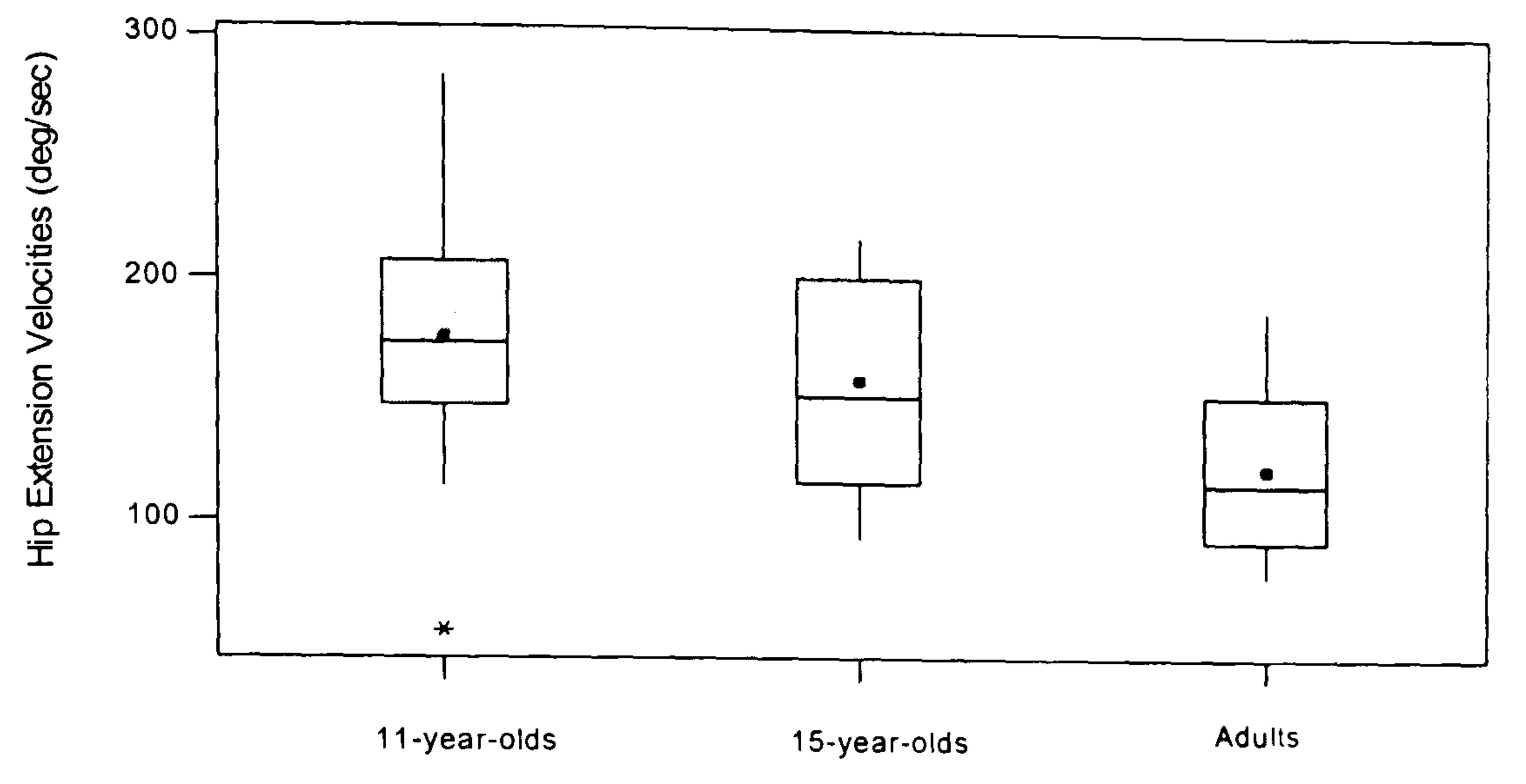

Figure 3.21. The diagram shows the maximum hip extension velocities during kicking.

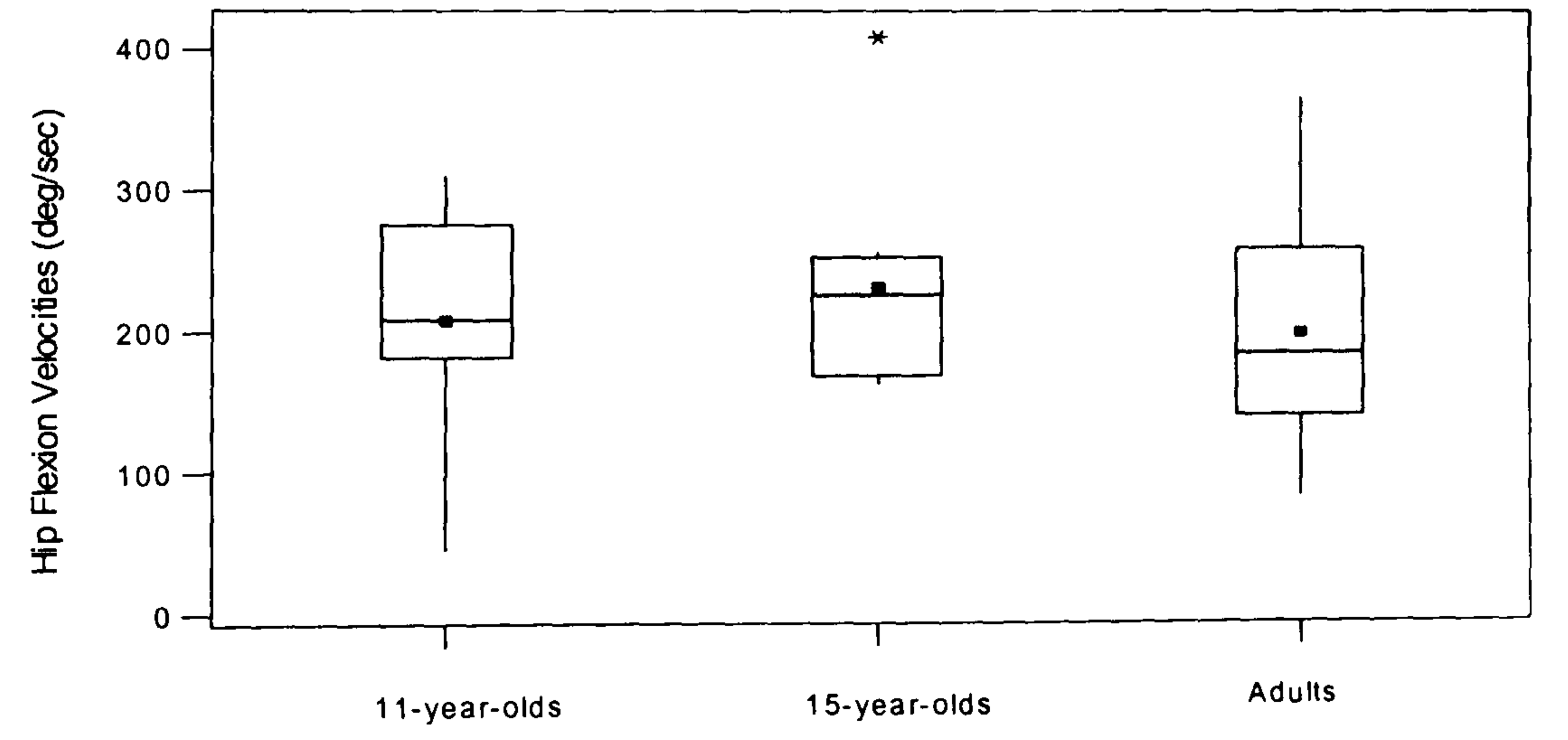

Figure 3.22. The diagram shows the maximum hip flexion velocities during kicking.

3.3.2. Angular Velocity of Knee and Hip at Ball Contact

The angular velocity of the knee and hip were measured at the instant of ball contact. The knee velocity in the 11-year-olds was 111 $\pm$ 27°/sec, in the 15-year-olds 131 $\pm$ 51°/sec and in the untrained adults 75 $\pm$ 33°/sec. These data are shown in Table 3.19. The adults' knee extension velocity at ball contact was significantly slower than younger groups, 11yrs vs 15yrs ($P = 0.316$), 11yrs vs untrained adults ($P < 0.007$), 15yrs vs untrained adults ($P < 0.014$) These data are illustrated in Figure 3.23.

The hip velocity at ball contact in the 11-year-olds was 71 $\pm$ 56°/sec, in the 15-year-olds it was 64 $\pm$ 37°/sec and in the untrained adults it was 83 $\pm$ 41°/sec. There was no significant difference between the three groups, 11yrs vs 15yrs ($P = 0.739$), 11yrs vs untrained adults ($P = 0.525$), 15yrs vs untrained- adults ($P = 0.261$). This is shown in Table 3.20 and illustrated in Figure 3.24.

(A) 11-years	
Volunteer	**deg/sec**
4	65
5	83
2	95
10	95
12	97
6	103
1	114
9	124
8	125
3	129
7	141
11	165
Mean	**111**
SD	**27**

(B) 15-years	
Volunteer	**deg/sec**
8	79
3	89
1	107
2	107
4	128
9	133
5	134
6	149
7	254
Mean	**131**
SD	**51**

(C) Adults	
Volunteer	**deg/sec**
6	33
3	47
8	48
9	55
4	58
5	68
2	68
11	75
7	77
1	99
12	120
10	147
Mean	**75**
SD	**33**

Table 3.19. The table shows the knee velocities at ball contact for the three groups of volunteers. No significant differences in (A) vs (B) ($P = 0.316$), but significant differences in (A) vs (C) ($P < 0.007$), (B) vs (C) ($P < 0.014$).

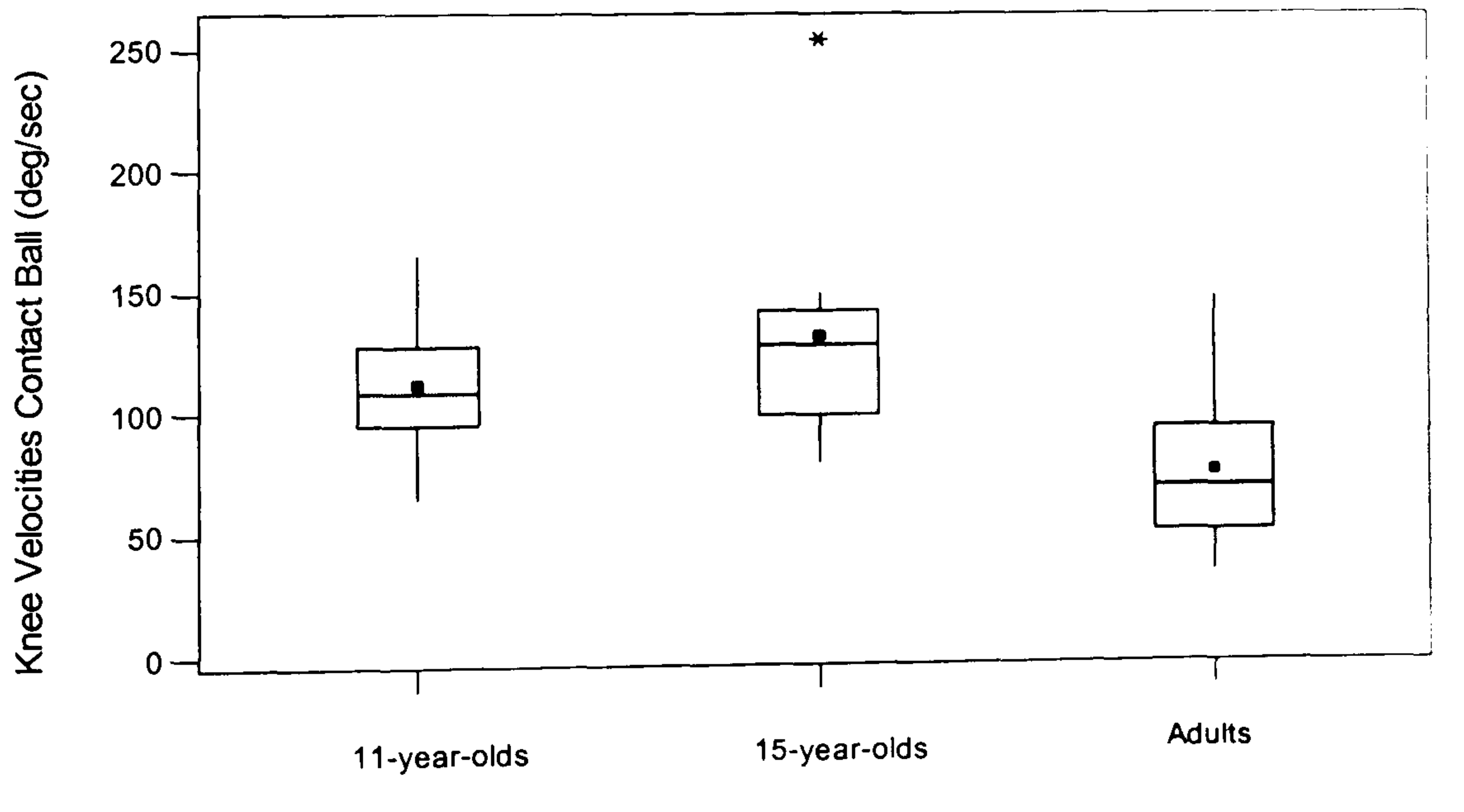

Figure 3.23. The diagram shows the range of knee velocities at ball contact.

(A) 11-years	
Volunteers	deg/sec
2	28
3	30
8	31
4	32
12	39
9	44
10	45
6	53
1	83
7	108
5	153
11	200
Mean	71
SD	56

(B) 15-years	
Volunteers	deg/sec
3	14
7	22
9	23
6	59
5	68
1	86
4	86
2	106
8	109
Mean	64
SD	37

(C) Adults	
Volunteers	deg/sec
12	45
8	57
6	61
3	62
5	64
11	65
4	67
9	72
2	92
7	103
10	116
1	198
Mean	83
SD	41

Table 3.20. The table shows the hip velocities at contact with the ball. No significant differences in (A) vs (B) (P = 0.739), (A) vs (C) (P = 0.525) and (B) vs (C) (P = 0.261).

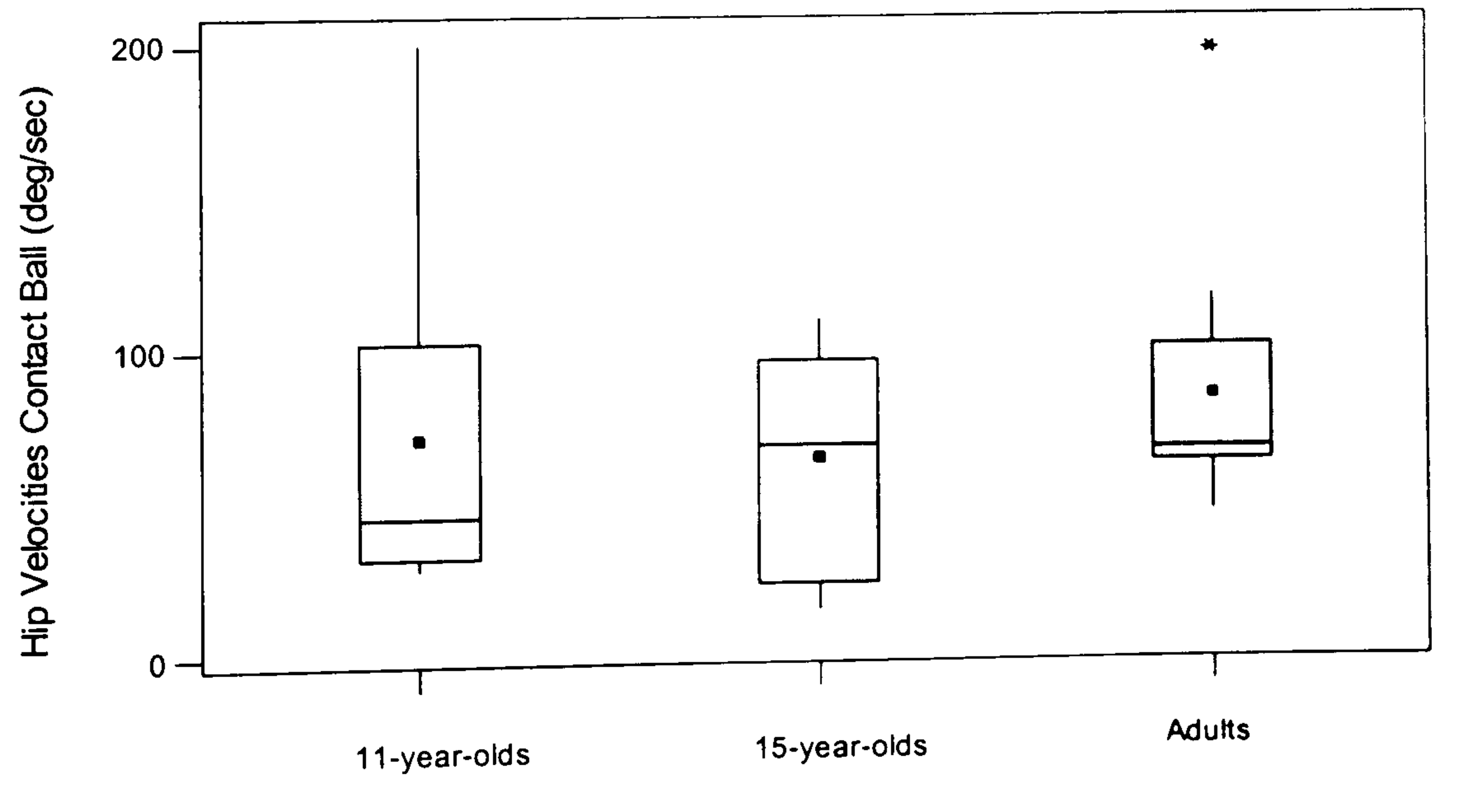

Figure 3.24. The diagram shows the hip velocities at ball contact.

3.3.3. Knee and Hip Positions at Ball Contact

The data captured during the kicks was analysed to identify the position of the kicking limb at ball contact. The knee position is shown in Table 3.21 and illustrated in Figure 3.25. The young footballers showed a consistent knee position of 11-year-olds 76 $\pm$ 8 degrees and 15-year-olds 74 $\pm$ 8 degrees of flexion at ball contact. These positions (11yrs vs 15yrs) were not significantly different ($P = 0.762$). The untrained adults had a greater range of knee angles, some being more flexed and some more extended than the young footballers. The mean untrained adults position of 59 $\pm$ 15 degrees was significantly more extended than the 11-year-olds ($P<0.005$). The difference between the 15-year-olds and the untrained adults was reached statistical significance ($P < 0.011$).

The data on hip angles at ball contact are shown in Table 3.22 and illustrated in Figure 3.26. The range of hip angles at ball contact is much wider, almost 60 degrees, than the range of knee angles, which is approximately 20 degrees (see Table 3.21). It can be seen that there is no significant difference between the 11-year-olds and the adults, but that the 15-year-olds make contact with the ball with their hip significantly less flexed.

(A) 11-years	
Volunteers	**deg/sec**
10	60
5	67
4	67
11	69
9	72
1	77
12	79
2	80
7	83
3	83
6	85
8	85
Mean	**76**
SD	**8**

(B) 15-years	
Volunteers	**deg/sec**
3	64
9	64
2	67
8	73
7	74
1	78
6	78
4	86
5	86
Mean	**74**
SD	**8**

(C) Adults	
Volunteers	**deg/sec**
3	41
10	43
9	46
1	48
4	54
11	55
2	57
12	57
7	71
8	73
5	84
6	85
Mean	**59**
SD	**15**

Table 3.21. The table shows the knee angles at ball contact. No significant differences in (A) vs (B) ($P = 0.762$), but significant in (A) vs (C) ($P < 0.005$) and (B) vs (C) ($P < 0.011$).

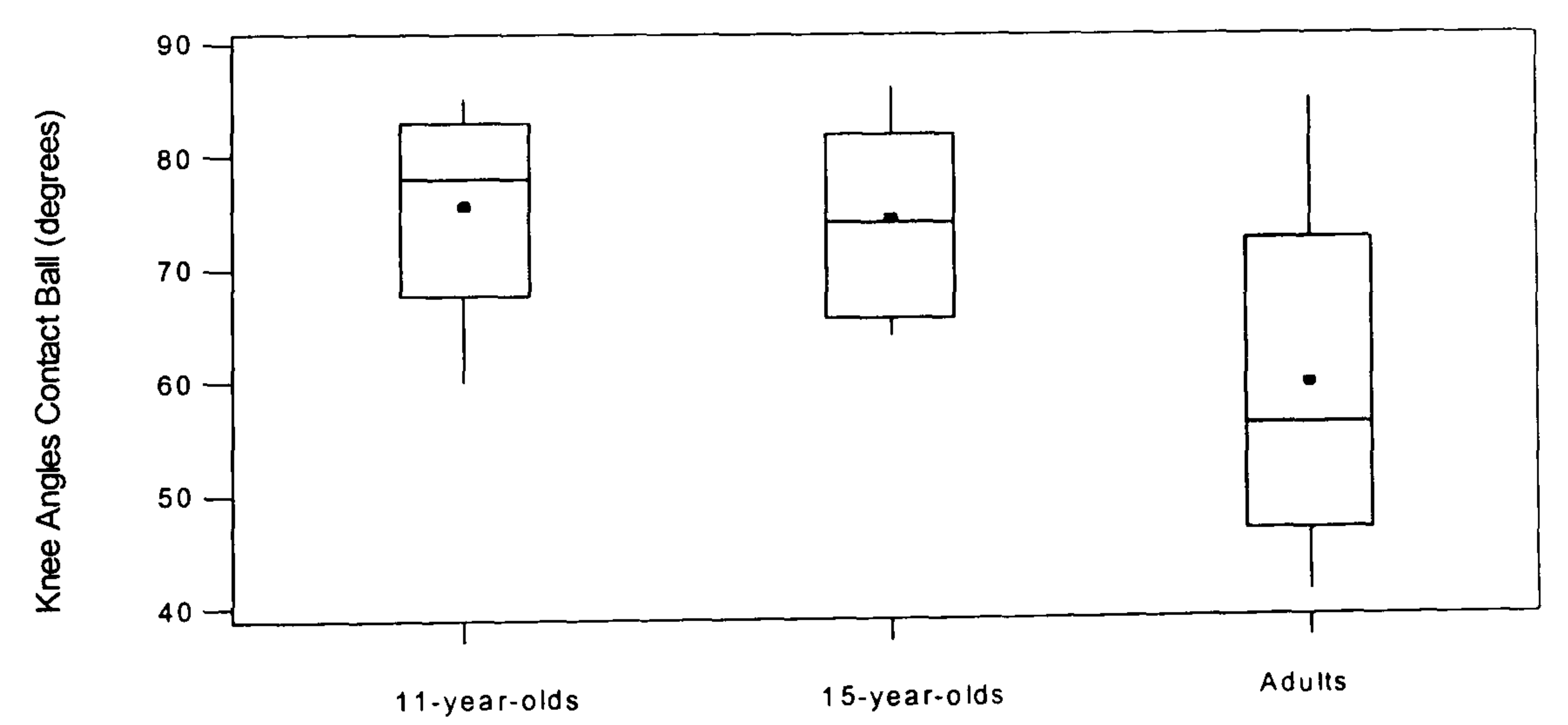

Figure 3.25. The diagram shows the knee angles at ball contact.

(A) 11-years	
Volunteers	deg/sec
12	7
5	13
11	14
9	18
6	23
2	24
8	25
7	27
3	28
1	36
10	56
4	60
Mean	**28**
SD	**16**

(B) 15-years	
Volunteers	deg/sec
3	24
9	35
1	39
6	40
5	41
2	44
4	60
8	70
7	81
Mean	**48**
SD	**18**

(C) Adults	
Volunteers	deg/sec
11	-9
4	-8
12	-2
8	5
1	8
2	13
10	18
6	25
3	35
5	39
7	54
9	66
Mean	**20**
SD	**24**

Table 3.22. The table shows the hip angles at ball contact. Significant differences were found between (A) vs (B) ($P < 0.016$) and (B) vs (C) ($P < 0.007$), but no significant difference was found between (A) vs (C) ($P = 0.398$).

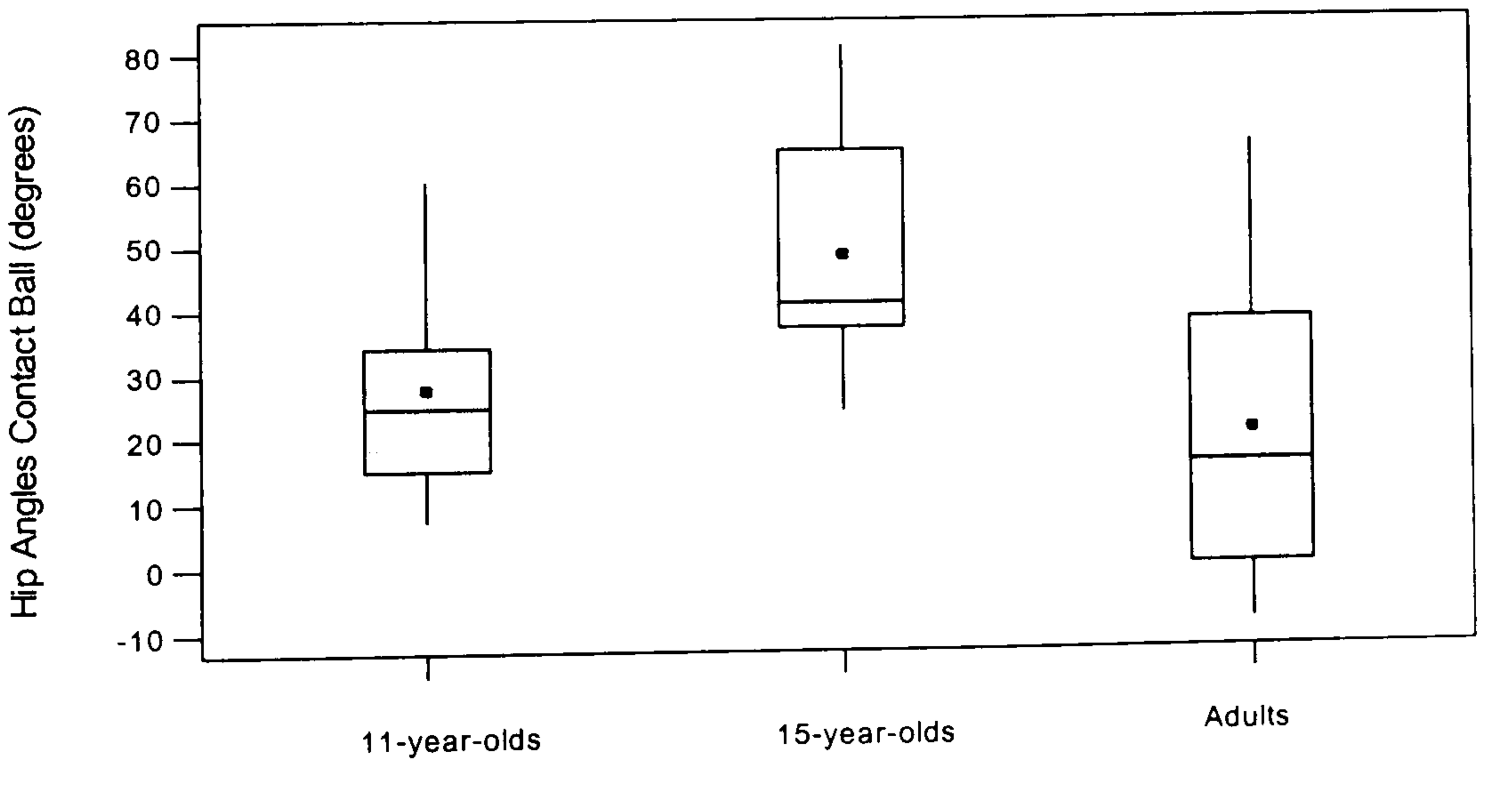

Figure 3.26. The diagram shows the hip angles at ball contact.

3.3.4. Power Developed during Kicks.

An attempt was made to measure the power transferred to the ball using the Kickmaster device, see methods section 2.9.3. The data from the Kickmaster is shown in Table 3.23. These show a very broad range of power in each group. For example, in the adults the largest power is ten times greater than the lowest power and illustrated in Figure 3.27. The lowest power kick is recorded from adult volunteer numbered 1, who has the third fastest knee extension at ball contact (see Table 3.19) and the fastest hip velocity at ball contact (see Table 3.20). There is a poor relationship between speed of movement and the power recorded by the Kickmaster and no significant differences ($P = 0.065$) in power were found.

(A) 11-years	
Volunteers	**watt**
1	756
2	1149
3	1198
4	1244
5	1389
6	1512
7	1818
8	1903
9	2168
10	2168
11	2233
12	3920
Mean	**1788**
SD	**820**

(B) 15-years	
Volunteers	**Watt**
1	2080
2	2940
3	4790
4	4900
5	4900
6	5352
7	5634
8	5971
9	6372
Mean	**4771**
SD	**1402**

(C) Adults	
Volunteers	**watt**
1	838
2	917
3	1154
4	1270
5	1579
6	2262
7	2480
8	2592
9	3744
10	5040
11	5971
12	8496
Mean	**3029**
SD	**2377**

Table 3.23. The table shows the maximum kick power of three groups of volunteers. Significant differences were found in (A) vs (B) ($P < 0.0001$), but no significant differences in (A) vs (C) ($P < 0.060$) and (B) vs (C) ($P < 0.065$).

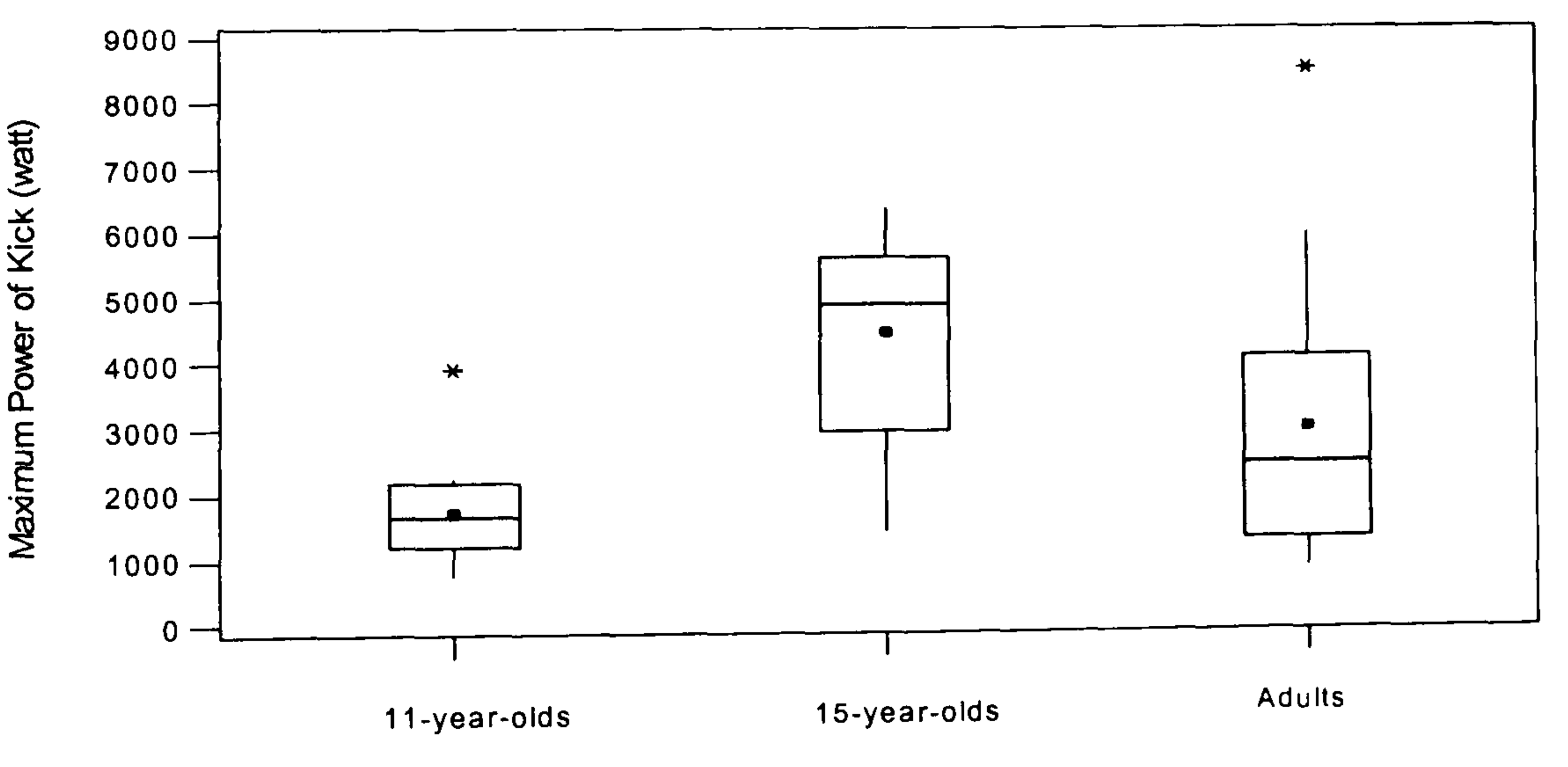

Figure 3.27. The diagram shows the range of maximum kick powering each group.

3.4 Co-activation during Kick Phases

The volunteers wore skin mounted EMG electrodes over VL, BF, SM and ST whilst they made the series of kicks. Specimen EMG recordings are shown in Figure 3.16.

It is possible to see three distinct phases of EMG activity. For example in Figure 3.16-A, the VL shows a period of EMG activity lasting from about 600msec before ball contact to about 300 msec before ball contact. This activity occurs whilst the leg is on the ground and is a "push phase" towards the ball. A second burst of VL EMG activity occurs about 150 msec before contact with the ball and finishes about 100 msec after ball contact. This represents the swing forward phase during which contact with the ball occurs. A third EMG phase happens about 300 msec after contact with the ball as the body weight is supported again and posture is restored. Similar patterns can be seen in Figure 3.16-B and C.

During each of the phases of VL activity, there is substantial EMG activity in the hamstring muscles. Co-activation is a very common feature is observed over a range of kicks in all three groups and also in lower force kicks. Figure 3.17 shows clear co-activation of these four muscles during kicks at about half maximum power and Figure 3.18 shows co-activation still present even in the lowest power kicks. The timings of start and stop of the EMG bursts are different from those seen in the maximum kicks in Figure 3.18, but clear synchronous activation is present especially at the phases just before and after ball contact.

3.4.1 Co-activation during the Push Phase

In an attempt to quantify the extent of co-activation, the times of onset EMG activity in each muscle were measured. Table 3.24 and Figure 3.28 shows the times when muscles become active in the push phase during maximal kicks in the 11-year-old group. VL activity started at -553 ± 323 msec. The negative number signifies times before ball contact. The time of onset of BF, SM and ST was not significantly different from the VL onset, when tested by ANOVA (P = 0.780). Table 3.25 and Figure 3.29 show the same data of the 15-year-old group. There is no significant difference between the EMG onset, VL starts at -592 ± 117 msec and when tested with an ANOVA (P = 0.427).

The push phase was different in the untrained adult group. Their data is shown in Table 3.26 and Figure 3.30. In this case the three hamstring muscles start together, BF -595 ± 42 msec, but they are 120 msec earlier than the onset of VL at -475 ± 107 msec. The difference between VL and BF times of onset was significant when tested with ANOVA (P< 0.0001).

Thus, in the push phase in 11 and 15 year old footballers, the four muscles all begin their EMG burst at the same time. However, in the adults, the hamstrings are active significantly earlier than the VL. However, both sets of muscles are active at ball contact.

Volunteers	VL msec	BF msec	ST msec	SM msec
5	-011	-647	-645	-555
4	-180	-540	-536	-554
2	-369	-552	-465	-423
1	-419	-507	-523	-507
7	-464	-508	-509	-495
6	-476	-537	-553	-554
3	-538	-519	-519	-508
8	-562	-453	-456	-565
11	-680	-525	-556	-632
12	-815	-959	-944	-974
10	-915	-951	-938	-419
9	-1212	-1005	-1005	-1005
Mean	**-553**	**-642**	**-637**	**-599**
SD	**323**	**204**	**202**	**192**

Table 3.24. The table shows the time onset of EMG activity during the initial push phase of maximum kicks in the 12 volunteers aged 11-years-old. The time shown is relative to the instant of ball contact.

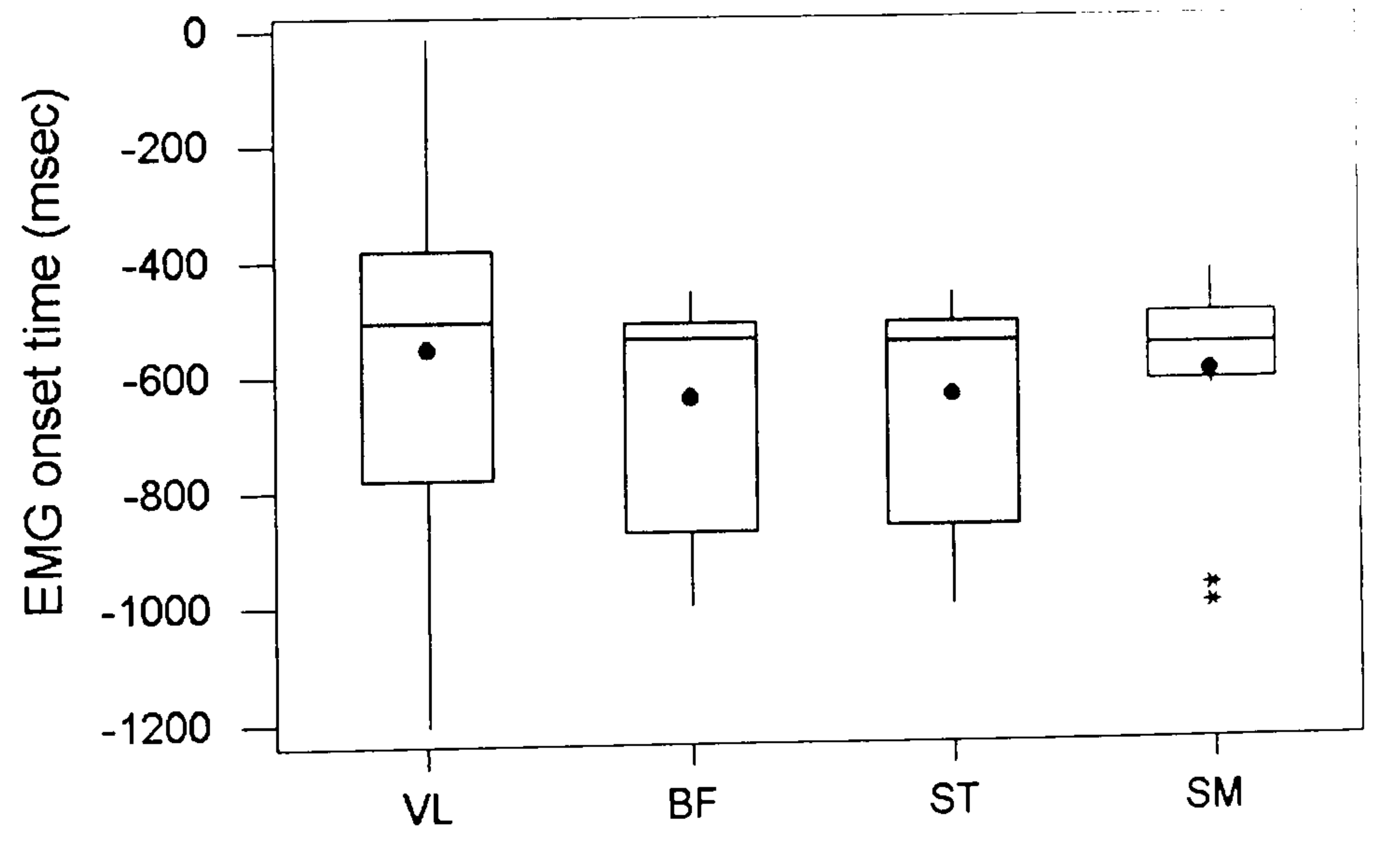

Figure 3.28. The diagram illustrates the time of EMG onset in VL, BF, ST and SM muscles relative to ball contact during the push phase of kicking in the 11 yrs group. The VL activity shows no significant difference vs hamstrings (P= 0.780).

Volunteers	VL msec	BF msec	ST msec	SM msec
2	-479	-569	-533	-576
8	-481	-565	-542	-458
5	-500	-536	-577	-568
7	-554	-587	-575	-489
4	-562	-615	-565	-539
9	-591	-480	-498	-689
6	-613	-583	-577	-536
1	-714	-536	-565	-339
3	-834	-589	-621	-560
Mean	**-592**	**-562**	**-561**	**-528**
SD	**117**	**40**	**34**	**96**

Table 3.25. The table shows the time onset of EMG activity during the initial push phase of maximum kicks in the 9 volunteers aged 15-years-old. The time shown is relative to the instant of ball contact.

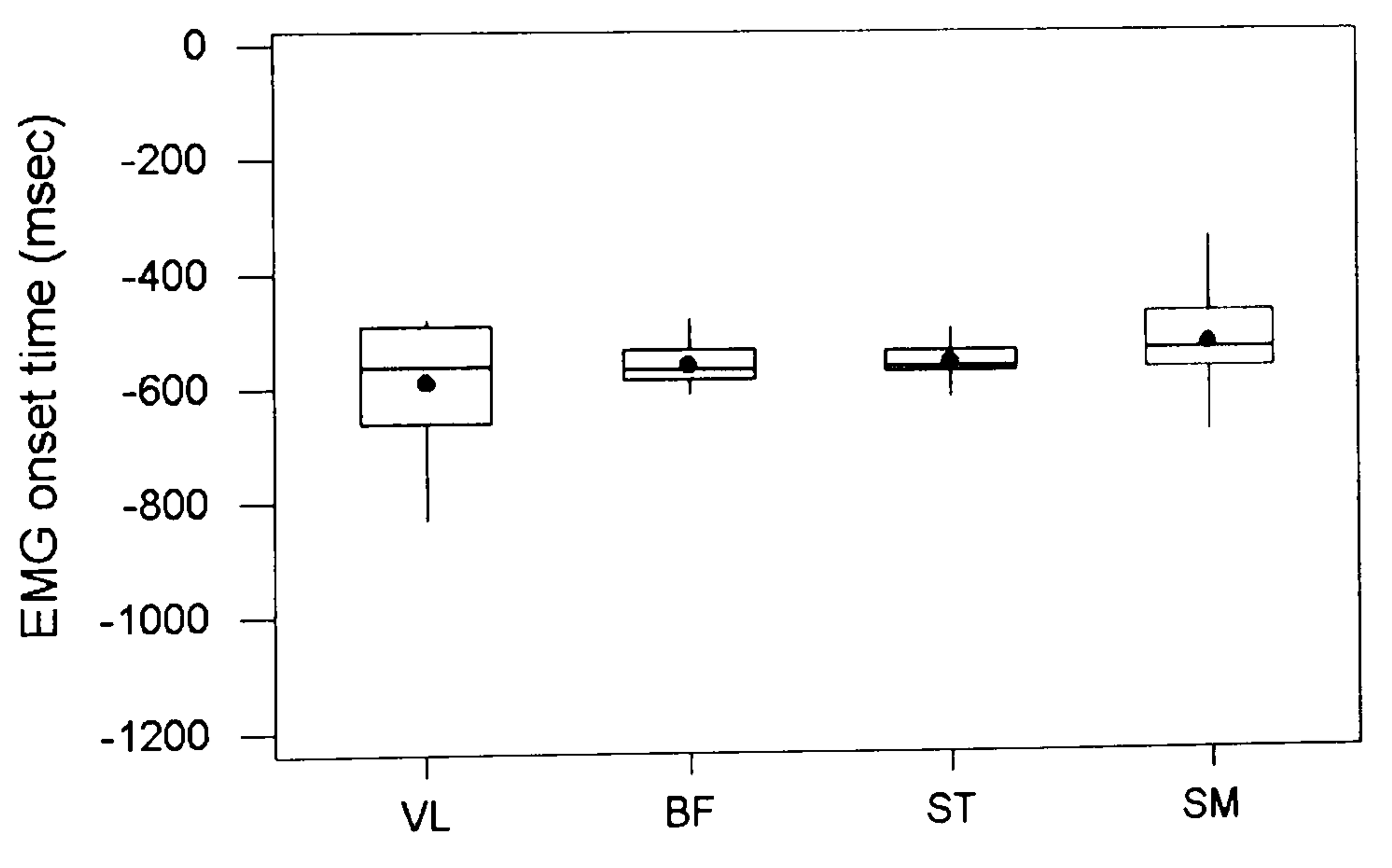

Figure 3.29. The diagram illustrates the time of EMG onset in VL, BF, ST and SM muscles relative to ball contact during the push phase of kicking in the 15 yrs group. The VL activity shows no significant difference vs hamstrings (P= 0.427).

Volunteers	VL msec	BF msec	ST msec	SM msec
9	-160	-602	-716	-520
3	-436	-542	-546	-550
1	-450	-584	-455	-510
12	-481	-531	-534	-534
10	-485	-588	-611	-581
7	-501	-580	-593	-630
2	-503	-611	-613	-598
4	-505	-679	-664	-667
8	-509	-582	-587	-584
6	-529	-569	-607	-607
11	-550	-630	-632	-613
5	-589	-646	-627	-623
Mean	**-475**	**-0.595**	**-599**	**-585**
SD	**107**	**0.042**	**66**	**48**

Table 3.26. The table shows the time onset of EMG activity during the initial push phase of maximum kicks in the 12 adult volunteers. The time shown is relative to the instant of ball contact.

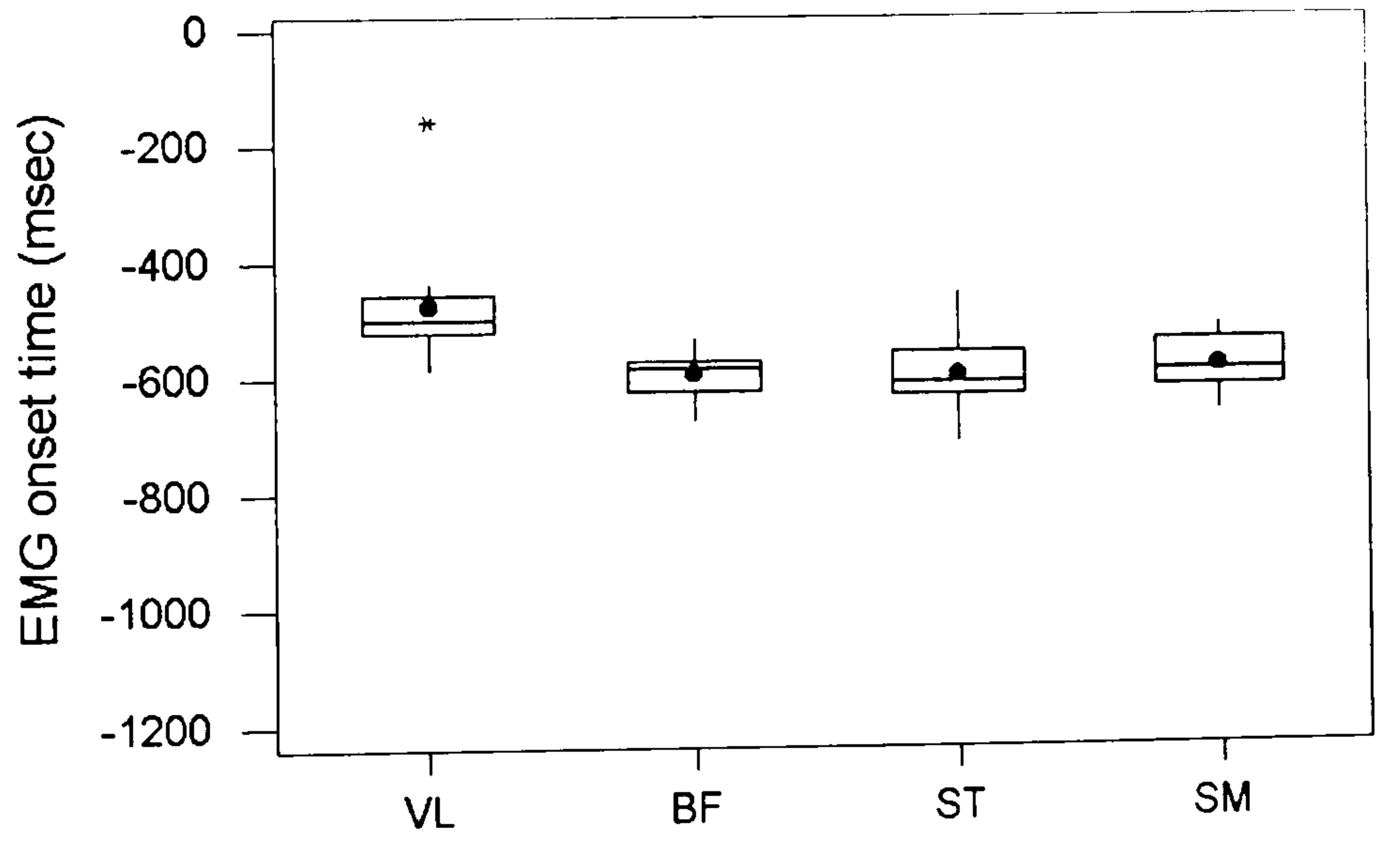

Figure 3.30. The diagram illustrates the time of EMG onset in VL, BF, ST and SM muscles relative to ball contact during the push phase of kicking in the adult group. VL activity starts significant later than hamstrings (P < 0.0001). All hamstrings muscles become active together.

3.4.2. Co-activation at Ball Contact

Figures 3.16, 3.17 and 3.18 all show co-activation of VL, BF, SM and ST as the leg swings through to strike the ball. This second phase of EMG co-activation is separated from the earlier push phase by a period of EMG silence. The times of beginning and end of these bursts were analysed using the technique described earlier.

Table 3.27 and Figure 3.31 show the activation times for the muscles of the 11-year-olds group before ball contact. VL becomes active at -129 $\pm$ 62 msec before contact. The three hamstring muscles are all activated synchronously about 60 msec later than VL. The difference in activation times between VL and the hamstrings is significant ($P < 0.001$).

Volunteers	VL msec	BF msec	ST msec	SM msec
10	-47	-20	-58	-99
2	-61	-101	-74	-142
5	-80	-43	-22	-15
1	-111	-51	-73	-67
6	-116	-84	-68	-77
3	-133	-89	-8	-18
12	-148	-80	-55	-50
9	-175	-110	-118	-127
4	-177	-104	-30	-93
8	-179	-46	-57	-147
11	-193	-47	-33	-18
7	-197	-28	-10	-23
Mean	**-129**	**-67**	**-50**	-73
SD	**62**	**31**	**33**	**49**

Table 3.27. The table shows the time of EMG onset before contact with the ball during maximum force kicking in the group of 11-year-olds trained footballers.

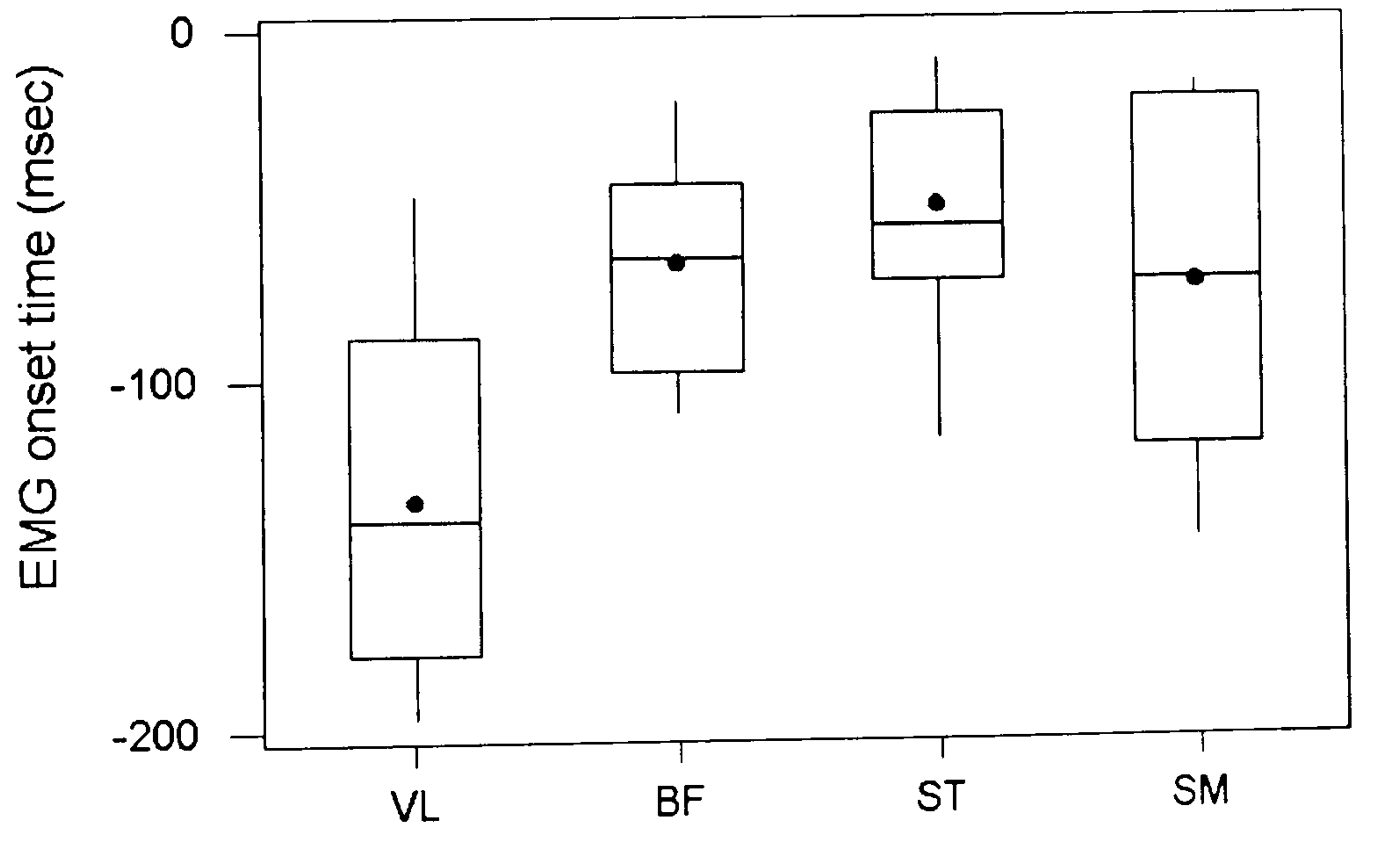

Figure 3.31. The diagram shows the EMG onset times for 11-year-olds before contact with the ball. When subjected to ANOVA tests, no significant difference was found between the times of EMG onset in BF, ST and SM (P = 0.321). VL starts significantly earlier than the hamstrings (P < 0.001).

A similar analysis for the 15-year-olds again shows no significant difference between the activation times of the hamstrings (P = 0.376). In addition, there is no significant difference between VL and hamstrings (P = 0.568). The mean activation time of these muscles (VL, BF, ST and SM) is much closer to the instant of ball contact than for the younger group. These data are seen in Table 3.28 and Figure 3.32.

Volunteers	VL msec	BF msec	ST msec	SM msec
8	-7	-9	-4	-76
9	-11	-18	-23	-35
7	-19	-25	-44	-2
1	-20	-50	-55	-3
3	-22	-18	-24	-15
4	-28	-4	-4	-82
6	-29	-5	-15	-20
2	-39	-32	-21	-18
5	-79	-46	-16	-49
Mean	**-28**	**-23**	**-25**	**-37**
SD	**21**	**17**	**16**	**29**

Table 3.28. The table shows the time of EMG onset before contact with the ball during maximum force kicking in the 9 volunteers of the 15-year-olds trained footballers group.

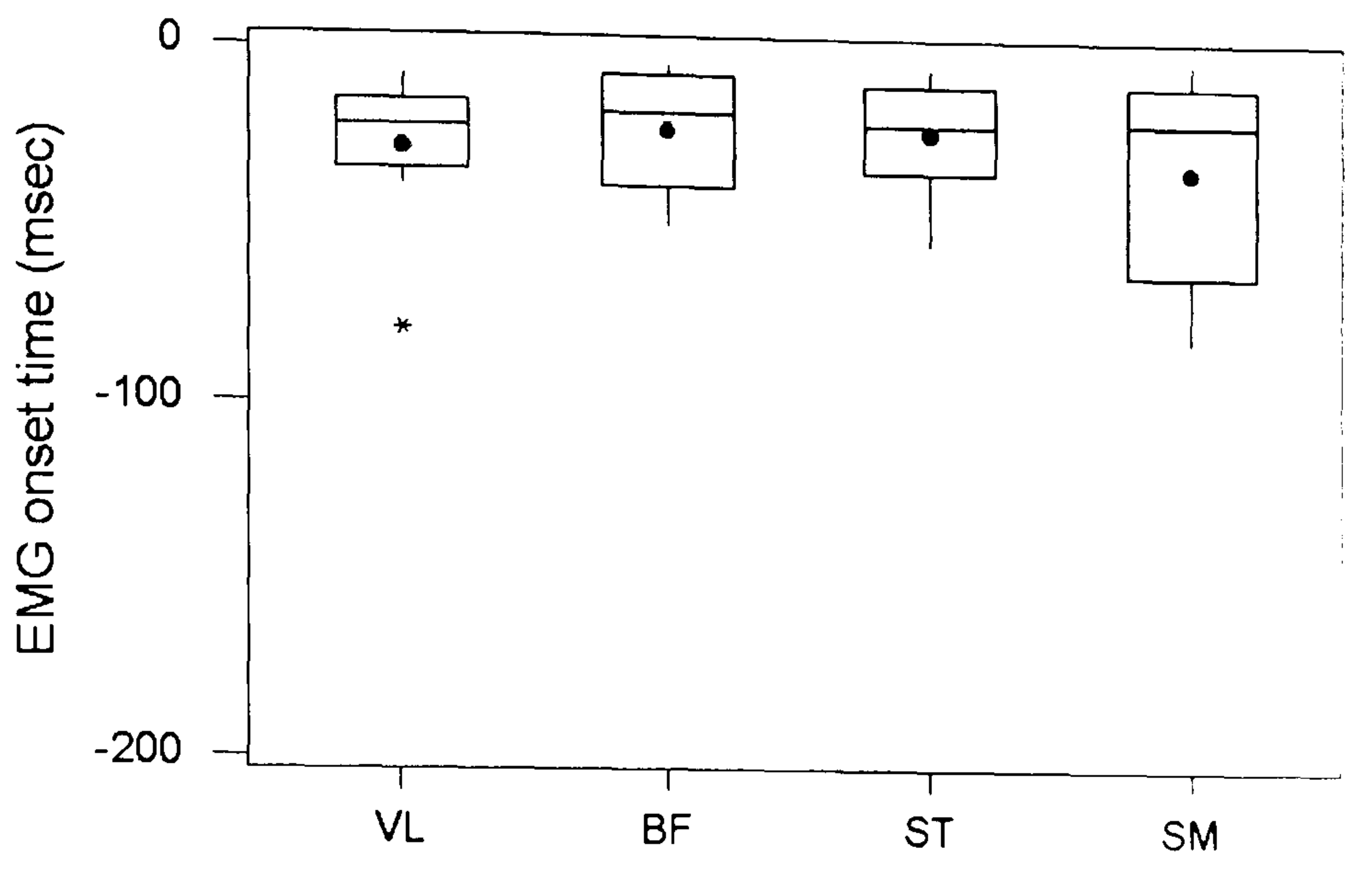

Figure 3.32. The diagram shows the EMG onset time for 15-year-olds before contact with the ball. When subjected to ANOVA tests, no significant difference was found between the times of EMG onset in BF, ST and SM (P = 0.376). There is no significant difference between the time of onset of EMG in VL and hamstrings (P = 0.568).

The adult values are given in Table 3.29 and Figure 3.33. As with the younger trained groups, all three heads of hamstrings become active synchronously. The VL becomes active significantly earlier than the hamstrings (P < 0.001). The times of activation are closer to ball contact than was seen in the youngest kickers but later than the time for the 15-year-olds.

This burst of EMG activity stopped shortly after ball contact in all groups. The 11-year-olds showed an end of EMG activity in VL 128 $\pm$ 50 msec after ball contact. The times of EMG silence were not significantly different (P = 0.936) in BF, SM and ST. These data are to be found in Table 3.30 and Figure 3.34.

The same pattern of all four muscles falling silent together was seen in the 15-year-olds (Table 3.31 and Figure 3.35) and in the adults, (Table 3.32 and Figure 3.36). The VL EMG showed persisted longest after contact with the ball in the 11-year-olds (128 $\pm$ 50 msec) and in-between in the adults (73 $\pm$ 32 msec).

Overall, the longest VL EMG activation time was seen in the 11-year-old footballers -129 to 128 msec. The untrained adults have an intermediate duration of -82 to 73 msec. The shortest times were seen in the 15-year-old footballers, -28 to 42 msec. This was a surprise since the 15-year-olds had the highest knee extension velocity at ball contact (see Table 3.19) and the highest recorded kick power (see Table 3.23).

Volunteers	VL msec	BF msec	ST msec	SM msec
1	-19	-41	-25	-32
8	-19	-61	-107	-11
6	-63	-32	-11	-6
12	-68	-25	-15	-9
4	-82	-44	-78	-24
10	-85	-29	-4	-3
9	-94	-54	-28	-40
11	-100	-63	-42	-35
3	-104	-35	-28	-48
5	-113	-70	-15	-27
7	-119	-28	-69	-99
2	-124	-29	-3	-19
Mean	**-82**	**-43**	**-38**	**-37**
SD	**35**	**16**	**33**	**26**

Table 3.29. The table shows the time of EMG onset before contact with the ball during maximum force kicking in the 12 volunteers of untrained adults group.

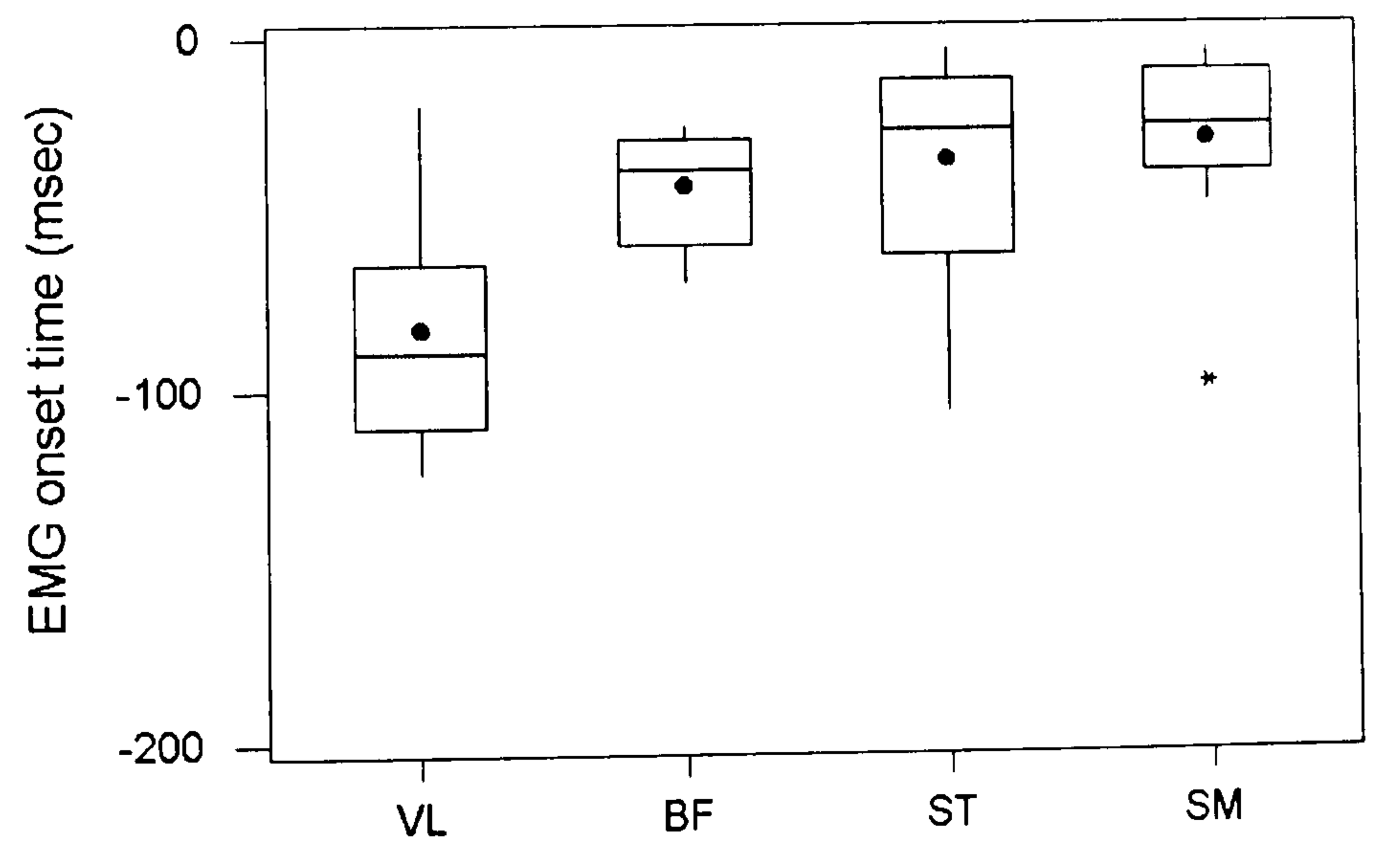

Figure 3.33. The diagram shows the EMG onset time before contact for the untrained adults group. When subjected to ANOVA tests, no significant difference was found between the times of EMG onset in BF, ST and SM ($P = 0.866$). VL hamstrings start significantly earlier than hamstrings ($P < 0.001$).

Volunteers	VL msec	BF msec	ST msec	SM msec
9	62	119	104	112
12	69	52	63	108
8	81	123	136	48
7	85	52	33	45
5	110	164	154	135
4	125	110	141	93
11	129	138	153	116
2	145	123	86	253
3	157	168	146	151
6	171	167	155	205
10	182	246	136	145
1	223	132	195	124
Mean	**128**	**133**	**125**	**128**
SD	**50**	**52**	**45**	**59**

Table 3.30. The table shows the time when the EMG goes silent after contact with the ball during maximum force kicking in the 12 volunteers of 11-year-olds trained footballers group.

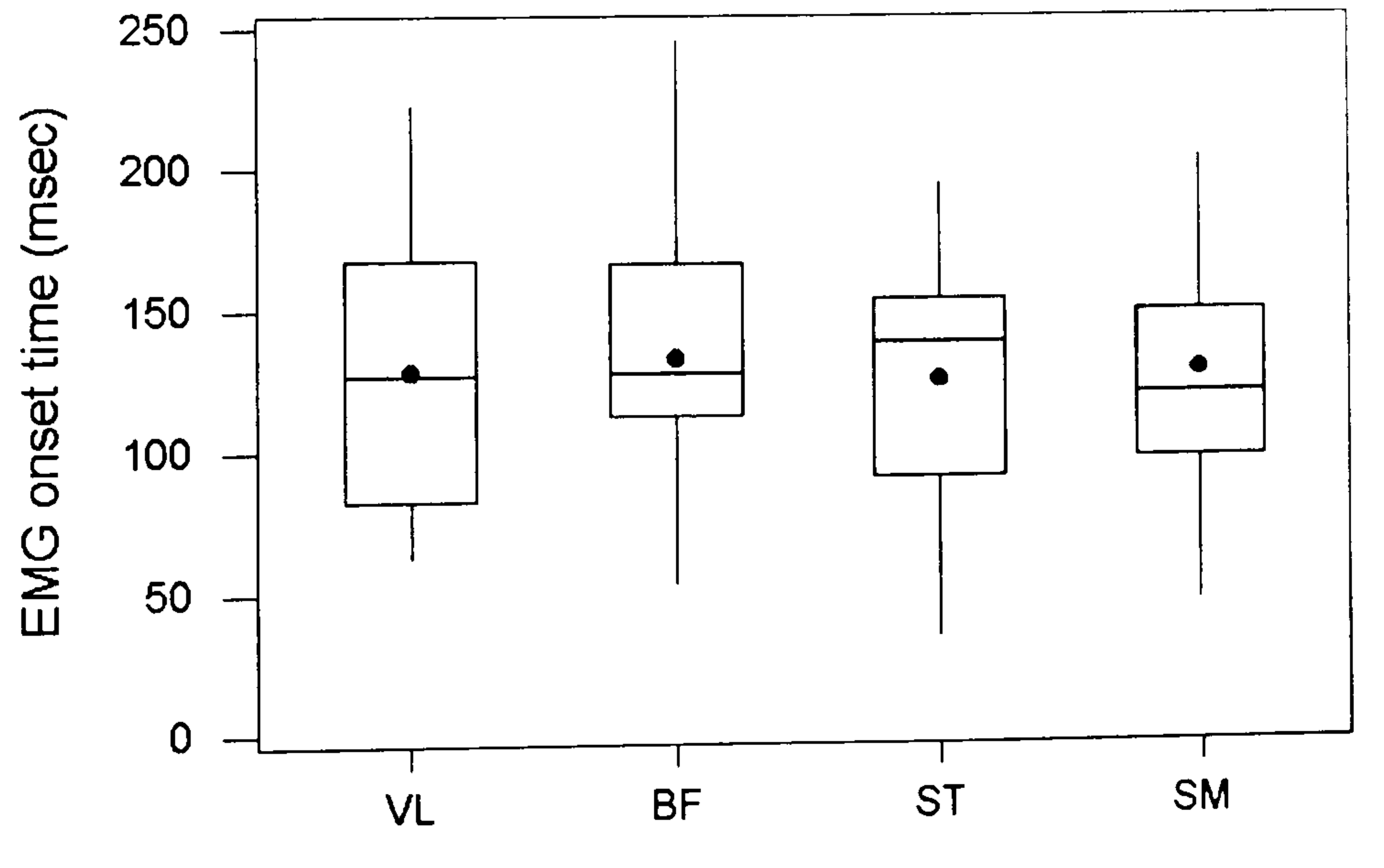

Figure 3.34. The diagram shows the time when the EMG goes silent after contact with the ball during maximum force kicking by 11-year-olds. When subjected to ANOVA tests, no significant difference was found between the times of EMG onset in BF, ST and SM (P = 0.936). There is no significant difference between the time of onset of EMG in VL and hamstrings (P = 0.987).

Volunteers	VL msec	BF msec	ST msec	SM msec
6	21	26	4	32
2	23	32	48	42
7	32	21	24	37
9	33	44	54	52
4	36	71	71	28
3	57	27	45	51
5	57	29	24	34
8	57	48	115	52
1	59	52	36	47
Mean	**42**	**39**	**47**	**42**
SD	**16**	**16**	**32**	**9**

Table 3.31. The table shows the time when the EMG goes silent after contact with the ball during maximum force kicking in the 15-year-olds trained footballers.

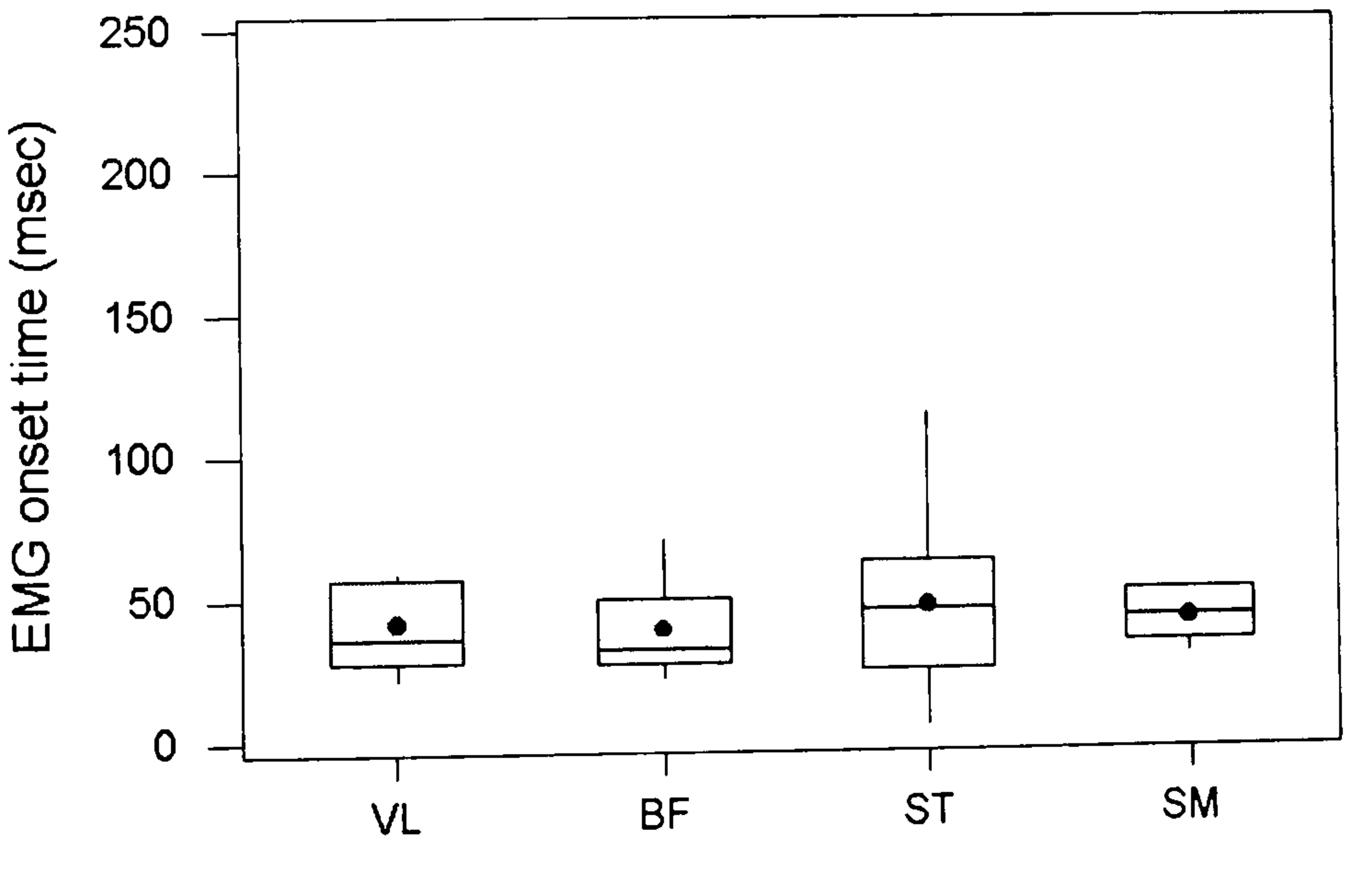

Figure 3.35. The diagram shows the EMG when the EMG goes silent after contact with the ball during maximum force kicking by 15-year-olds. When subjected to ANOVA tests, no significant difference was found between the times of EMG onset in BF, ST and SM (P = 0.734). There is no significant difference between the time of onset of EMG in VL and hamstrings (P = 0.868).

Volunteers	VL msec	BF msec	ST msec	SM msec
4	30	21	40	22
5	30	80	85	87
12	30	13	8	12
6	49	68	77	70
2	52	69	31	88
11	61	64	63	58
7	70	32	71	55
8	90	139	85	88
10	91	69	25	74
3	96	45	37	52
9	115	91	107	76
1	123	143	106	131
Mean	**73**	**70**	**61**	**68**
SD	**32**	**41**	**33**	**32**

Table 3.32. The table shows the time when the EMG goes silent after contact with the ball during maximum force kicking in the 12 volunteers of untrained adults group.

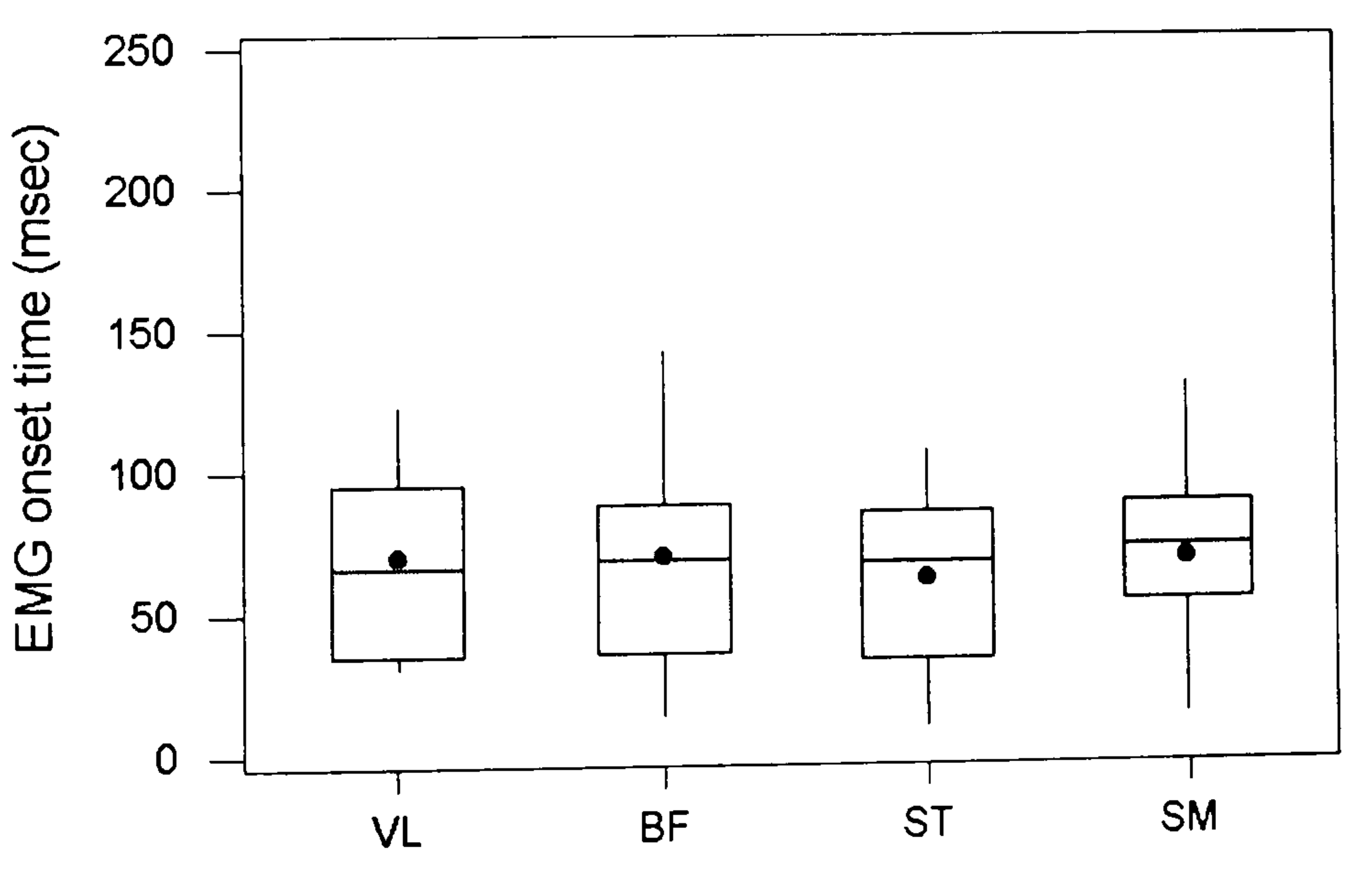

Figure 3.36. The diagram shows the when the EMG goes silent after contact with the ball during maximum force kicking for untrained adults. When subjected to ANOVA tests, no significant difference was found between the times of EMG onset in BF, ST and SM (P = 0.834). There is no significant difference between the time of onset of EMG in VL and hamstrings (P = 0.862).

3.4.3 Co-activation during the Follow through Phase

Table 3.33 and Figure 3.37 show the activation times for the muscles of the 11-year-olds group. BF, ST and SM cease at a similar time but VL activity goes on longer. VL activation stops at 447 ± 272 msec. The three hamstrings muscles all cease activation synchronously at 383 ± 254 msec for BF; 363 ± 239 msec, for ST and 368 ± 199 msec for SM, earlier than VL. The difference in the times at which EMG activity ceases in VL and hamstrings is not significant (P = 0.822).

Volunteers	VL msec	BF msec	ST msec	SM msec
5	112	156	162	154
7	156	144	71	178
3	161	171	149	170
1	207	113	196	136
10	218	439	571	535
9	390	109	124	109
6	545	409	375	398
8	581	379	385	583
11	629	520	416	469
12	720	785	461	579
2	770	832	894	555
4	870	541	553	544
Mean	**447**	**383**	**363**	**368**
SD	**272**	**254**	**239**	**199**

Table 3.33. The table shows the time when the EMG goes silent at the end of follow through for the 11-years-old. The time shown is relative to the instant of ball contact.

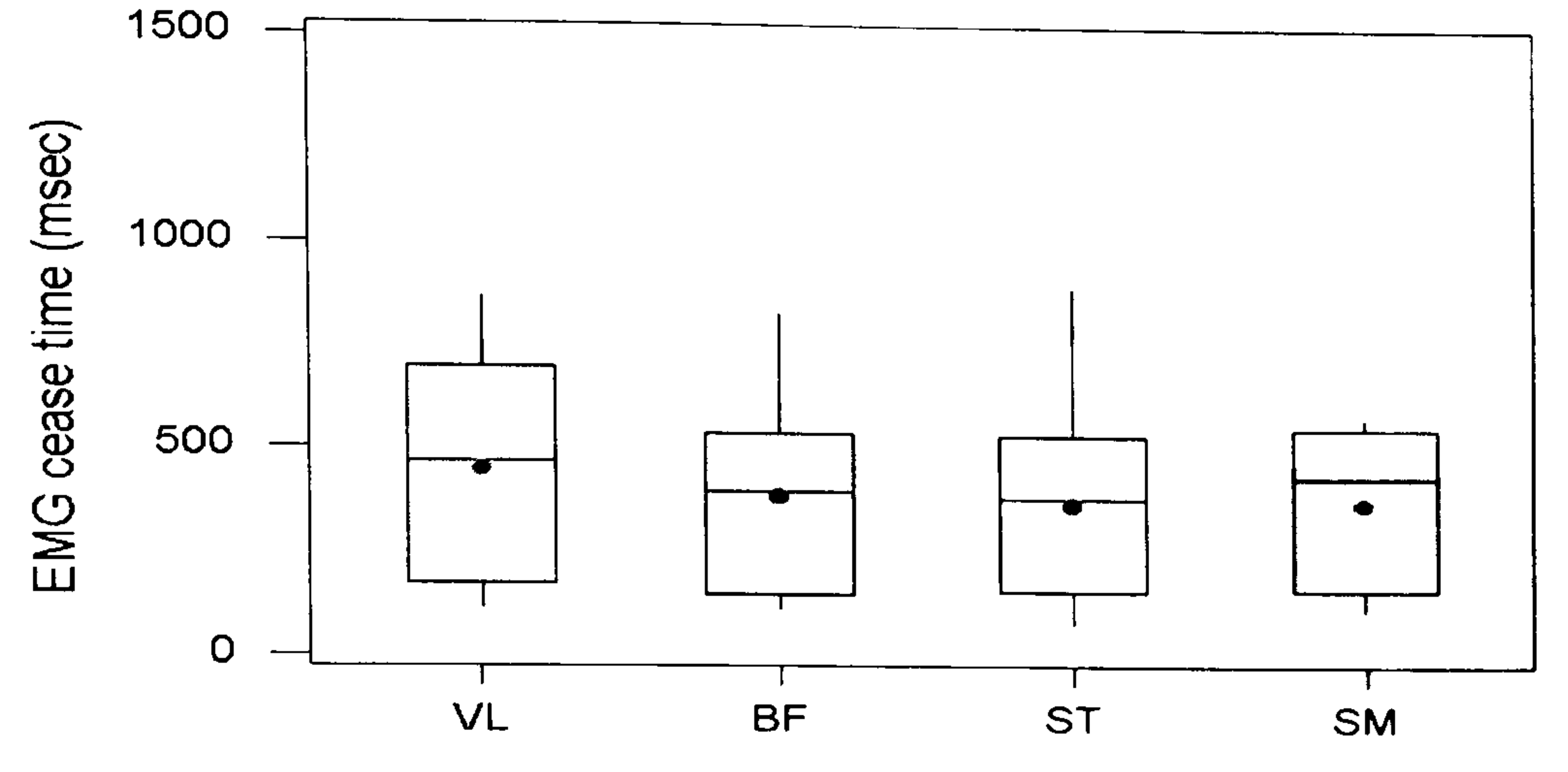

Figure 3.37. The diagram shows the time when the EMG goes silent at the end of follow through the 11-years-old. There is no significant difference between VL activities starts vs hamstrings (P = 0.822). VL – Vastus Lateralis, BF – Biceps Femoris, ST – Semitendinosus and SM – Semimembranosus.

A similar analysis for the 15-year-olds shows no significant difference between the cease activation times of the VL and hamstrings (P = 0.648). The VL behaviour shows the same as the 11yrs, which is that VL ceases later than hamstrings. The VL ceases activation at 513 ± 201 msec. The three hamstrings muscles all cease at a similar time 418 ± 159 msec for BF; 430 ± 201 msec for ST and 415 ± 183 msec for SM. These data can see in Table 3.34 and Figure 3.38.

The adult values are specified in Table 3.35 and Figure 3.39. As previously, all three heads of hamstrings cease the activation synchronously. The VL cessation of activation was no more significant than the hamstrings (P = 0.963). The time of EMG to cease activity of VL was 407 ± 222 msec. The hamstrings (BF, ST and SM) cease muscle activity synchronous at 356 ± 369 msec for BF; 350 ± 321 msec for ST and 352 ± 349 msec for SM.

Volunteers	VL msec	BF msec	ST msec	SM msec
4	142	191	107	138
9	333	296	261	265
5	467	534	511	545
2	493	403	638	427
8	501	524	507	454
7	503	531	501	545
1	641	199	179	172
6	733	444	483	530
3	805	644	684	658
Mean	**513**	**418**	**430**	**415**
SD	**201**	**159**	**201**	**183**

Table 3.34. The table shows the time when the EMG goes silent at the end of follow through for the 15-years-old. The time shown is relative to the instant of ball contact.

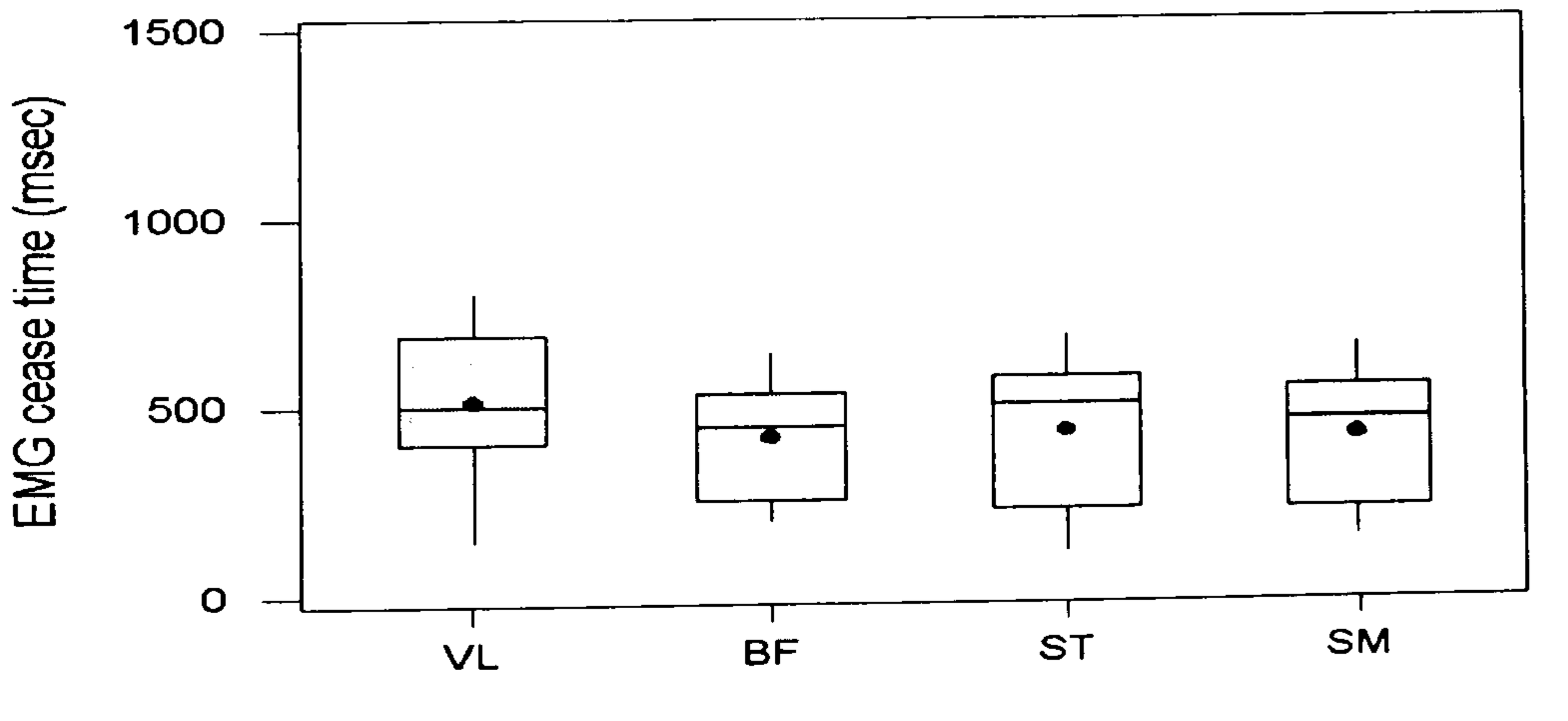

Figure 3.38. The diagram shows the time of EMG cease during maximum power kick of following through for 15-years-old. There is no significant difference between VL activity starts vs hamstrings (P = 0.648). VL – Vastus Lateralis, BF – Biceps Femoris, ST – Semitendinosus and SM – Semimembranosus.

Volunteers	VL msec	BF msec	ST msec	SM msec
8	181	134	211	131
6	188	296	301	168
5	190	242	170	197
11	236	142	257	257
2	294	109	101	107
4	308	99	93	96
7	330	210	153	124
12	409	267	515	511
3	612	468	448	458
9	615	216	187	151
10	697	1401	1252	1234
1	819	686	513	793
Mean	**407**	**356**	**350**	**352**
SD	**222**	**369**	**321**	**349**

Table 3.35. The table shows the time when the EMG goes silent at the end of follow through for the untrained adults. The time shown is relative to the instant of ball contact.

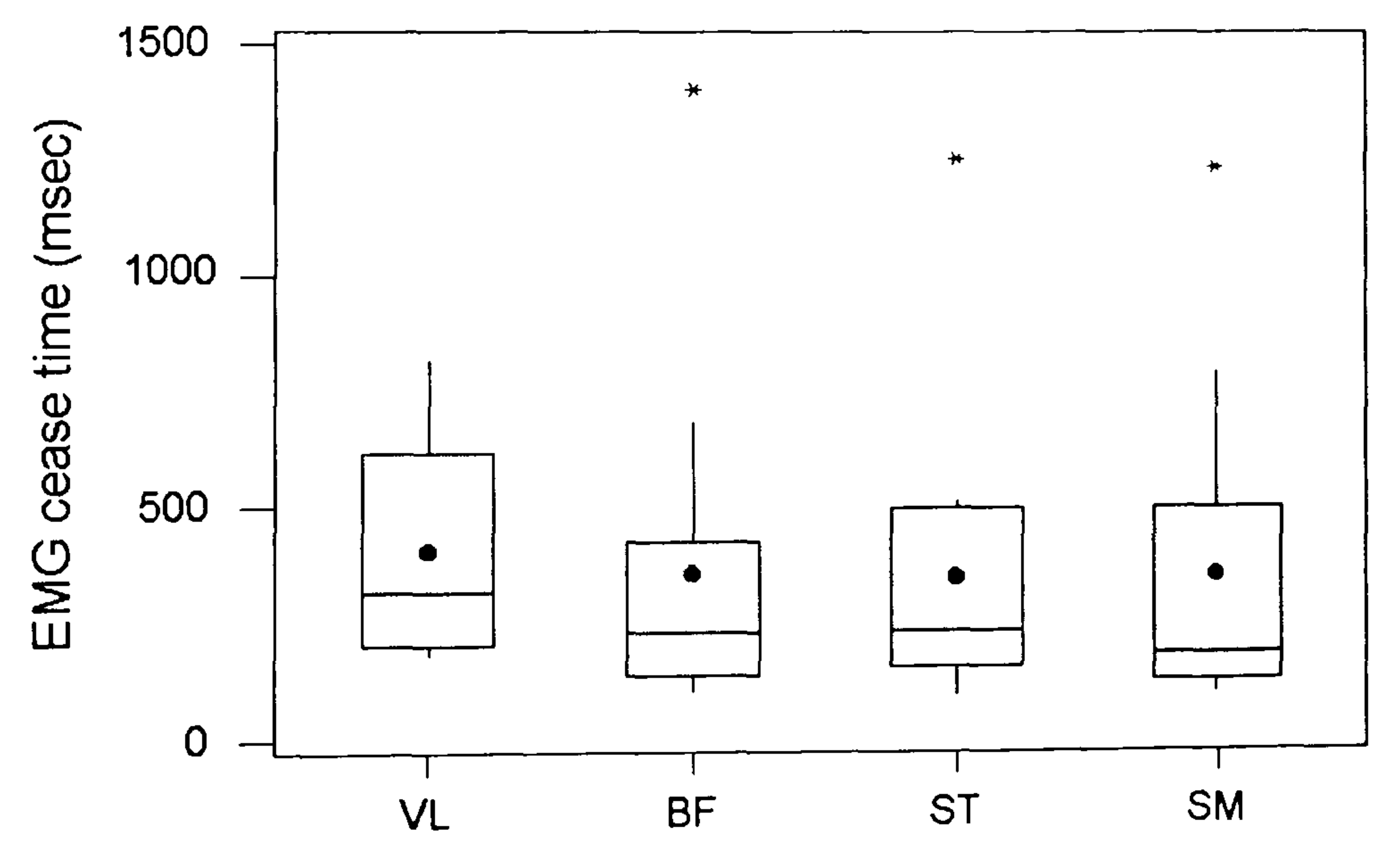

Figure 3.39. The diagram shows the time when the EMG goes silent at the end of follow through the adults. There is no significant difference between VL activities starts vs hamstrings (P = 0.963). VL – Vastus Lateralis, BF – Biceps Femoris, ST – Semitendinosus and SM – Semimembranosus

4. Discussion Section

The main hypothesis tested in this project was that co-activation of the hamstrings might occur during high velocity limb movements. This could lead to high force development during eccentric activity of the muscle.

4.1 Investigation of the Hamstring Activity during High-Speed Knee Extension Movements.

The first aim of the project was to investigate hamstrings EMG during high velocity movements. Three types of movement were studied. Volunteers made knee extension movements at 200°/sec whilst sitting in an isokinetic dynamometer. This velocity is faster than the majority of the Kin Com studies on footballers, (see Table 1.1 page 6). It is also faster than the majority of individuals in pervious studies and those with a training history in sports other than football (see Table 1.2 page 8) and (Table 1.3 page 10).
Volunteers also made unrestrained vertical jumps and kicked a tethered football. During jumping the mean maximum knee extension velocity was 384°/sec, (see Table 3.1 page 56). This is very similar to the values from previous studies (Viitasalo et al, 1993 and Bobbert et al, 1996).

The mean maximum knee extension velocity during kicks was between 401°/sec and 451°/sec. These velocities are similar to those reported by Day (1987) and Putnam (1993). They are much slower than those calculated from video images by Anderson and Sidaway (1994).

The maximum hip flexion velocity during kicks was between 199°/sec and 232°/sec (see Table 3.18, page 107). The maximum velocities of hip movements were always slower than the maximum velocities of knee movements. This was seen easily by comparing Tables 3.17, (page 107) and Table 3.15, (page 104) for extension movements and Table 3.18 (page 107) and Table 3.16, (page 104) for flexion movements.

These data show that during all three types of movements investigated the hamstrings are subjected to rapid stretch as the knee extends. The stretches during kicking will be greater still because knee extension is accompanied by fast hip flexion.

There is an interesting observation that the highest speeds of knee extension were recorded in the 15-year-old group of professional footballers (see Table 3.15, page 104). This age group is reported to be the most vulnerable to hamstring injuries.

The second aim of the project was to investigate co-activation of quadriceps and hamstrings during a range of knee extension velocities. In practice, this was done by asking the volunteers to make a series of progressively faster and more powerful jumps or kicks.

A series of kicks is illustrated in Figures 3.16, 3.17 and 3.18. These show the kicks from three volunteers. The maximum power kicks are shown in Figure 3.16. It is clear in all three cases that there is substantial co-activation at about the time the foot makes contact with the ball. This is shown as the event on channel 5. All three volunteers also show substantial muscle co-activation about 400 msec earlier as the kicker pushes forward. A third phase of co-activation is clearly seen in Figure 3.16 A and C about 500 msec after ball contact as the kicker recovers their posture.

An essentially similar pattern is seen in the 3 mid-power kicks shown in Figure 3.17. There is clear co-activation at about ball contact in each case. There is strong co-activation in the push forward phase in Figure 3.17a. The quadriceps activation is weaker but still present in Figure 3.17b. There is no sign of co-activation in Figure 3.17c.

The mid power kicks cause less disturbance of body position than the maximum kicks and so the recovery of posture after ball contact is minimal.

Even the most minimal kicks of about 10 – 20% of maximum power (Figure 3.18), have clear co-activation at about ball contact. They also show co-activation in the push off phase. Again there is minimum EMG activity 500 msec after ball contact. The postural disturbance in these low force kicks was very minor and the kick was essentially made whilst in a standing position rather than a dynamic whole body movement associated with the maximum kick. These body movements are clearly seen appreciated in the photographs shown in Figures 2.19, 2.20 and 2.21 on page 49.

The EMG patterns of a series of jumps are illustrated in Figures 3.3 and 3.4. In these cases there is clear co-activation before take off and after landing in both jumpers.

The volunteer in Figure 3.3 shows the same pattern in his mid power jump. However, in the minimum power jump there is co-activation of quadriceps and biceps femoris, but not SM and ST, before take off but not at landing. The volunteer whose data is shown in Figure 3.4 does not co-activate before take off in the lower power jumps but does show co-activation on landing.

No systematic investigation of lower power knee extension movements were made during the experiments with the Kin Com. However, during the high power kicks it can be easily seen in Figures 3.8 and 3.9 that strong co-activation occurs. This might be a surprise given the constrained nature of the movement but it is in agreement with other published observations (Baratta et al 1988; Kellis and Baltzopoulos, 1996c, d; Amiridis et al, 1996; Kellis and Baltzopoulos 1997, 1998 and 1999; Miller et al 2000 and Aagaard et al, 2000).

It seems clear that co-activation of quadriceps and hamstrings is a frequent observation during kicking and jumping. It is more frequent and more evident during higher power kicks and jumps. The earlier studies of kicking in footballers and vertical jumping have not reported significant co-activation of quadriceps and hamstrings (Viitasalo et al, 1993; Bobbert et al, 1996; Goodwin et al, 1999; Nagano 2000; Rodacki et al, 2002; Kellis et al, 2003 and Toumi et al, 2004).

The third aim of the project was to investigate the timing of EMG co-activation during high-speed extension of the knee. This was done in three groups of experiments, which studied kicking, jumping and used the isokinetic dynamometer.

Three groups of volunteers were studied as they made high-speed kicks. Each kick could be divided into three phases of EMG activity: push off, ball strike and recovery. This is shown in Figure 3.16A.

During the push off phase VL, BF, SM and ST became active at the same time in the 11 and 15 years-old groups. These data are shown in Tables 3.24 and 3.25. In the adult group, whose data is shown in table 3.26, the EMG begins significantly earlier in hamstrings than it does in VL. This again can be seen in a single case in Figure 316A. Even though the VL and hamstrings begin at slightly different moments in time, they are show co-activation for a significant period.

The second phase of EMG activity occurs just before ball contact. Again in the two groups, the trained 15-years-old and untrained adults, show all four muscles become active at the same time (see Table 3.28 and 3.29). In the youngest volunteers, the muscle activity in VL begins significantly earlier than hamstrings (see Table 3.27) and this period of VL EMG is followed by a period of co-activation.

The third EMG burst associated with recovery of balance after ball contact begins with co-activation of VL and hamstrings. There are no significant differences in the activation times of these muscles in any of the groups (see Tables 3.30, 3.31 and 3.32).

The final set of measurements made was of the time when EMG finished after completion of the kick. These data show no significant differences in the time when EMG stops in any of the muscles in any of groups of volunteers (see Tables 3.33, 3.34 and 3.35).

In summary, during the maximum power kicks the predominant pattern is that VL and hamstrings begin and end their EMG bursts at essentially the same time. There are some exceptions, where activity in one muscle precedes and follows another, but overwhelmingly the activation is present in hamstrings and quadriceps at the same time.

During vertical jumps an essentially similar pattern of co-activation is seen. The time of activation of each muscle is shown in Figure 3.5. It is clear that in maximum jumps, midrange power jumps and in jumps of low power where the volunteer barely leaves the ground, there is no significant difference in the time before take off when each muscle begins to become active.

The muscles tended to become silent whilst the volunteer was in the air before becoming active before ground contact. Figure 3.6 shows a similar analysis for the second EMG burst. Again all four muscles of volunteers became active at the same time. Thus, as in kicking, there is substantial synchronization of VL and hamstrings during vertical jumping.

Figure 3.8A shows co-activation of VL BF ST and SM during extension movements at 200°/sec. The co-activation is strong even though the movement is simpler and slower than the free kicks which are described earlier. Data from 10 volunteers is listed in

Table 3.10. This confirms that during these extension movements there is no significant difference in the time of activation of quadriceps and hamstrings. This pattern is very stable and does not change over three extension movements. Interestingly, this pattern of co-activation is less evident during knee flexion. Figure 3.8B shows strong activation of the three knee flexors before the knee moves but no significant activity in VL. Thus this person shows co-activation during extension but not during knee flexion. This is clearly seen in Table 3.11. Only two of ten volunteers showed co-activation consistently during knee flexion. It can be concluded that the aims of the project have all been achieved.

4.2. Comments an Experimental Methods

The number of participants in the experiments was 57 volunteers. This is broadly in line with size of studies in the previous literature. For example, Barratta et al (1988) used 24 subjects and Amiridis et al (1996) studied 20 subjects, ten of them athletes who trained over five years. The project was significantly smaller than the study by Kellis et al (2000) who investigated one hundred and thirteen male athletes. It is difficult to recruit large numbers of sportsmen or women at a consistent level of performance or ability.

The equipment used was generally of a high standard. The Kin Com isokinetic dynamometer was able to match the range of knee velocities in the majority of previous studies (see Tables 1.1, 1.2 and 1.3 in the Introduction section). The dynamometer provides accurate information about the angle and velocity of knee movement but it does not allow natural movements to be replicated. Its use constrains the movement of the limb and so the movements made in these tests must be considered to be less natural.

The EMG system used in these experiments is illustrated in Figures 2.1– 2.7. It used surface electrodes and there was no noticeable "cross talk" between the channels. This is probably because the muscles studied were large and the distances between the electrodes were relatively large, at least 2 centimetres between the closest pairs. The pre amplifier boxes were light and attached to the waistband. This combination kept movement artefacts small and the cables offered no significant obstruction to natural high-speed movements. The EMG signals were sampled and converted to digital form at rate of 1000 Hz 16 bit analogue to digital converter by A-D. The digital EMG signal was filtered high pass then rectified.

The measurement of the times of EMG onset and end could be difficult. In practice a threshold was set five times above the background rectified EMG signal. The time was measured when this level was crossed. This might have rejected any small amplitude EMG activity. In almost all experiments the volunteers made high force contractions with large EMG signals and it is unlikely much data was lost. It will have delayed the start time and shortened the time to EMG silence. However, a consistent technique was used in all experiments and so the results are all comparable.

The mechanical measurements of ground clearance by the jump mat (see Figures 2.9, 2.10 and 2.11) and by the electro-goniometers (see Results section 2.2 pages 29) across the joints were also consistently reliable and imposed no restrictions on movements.

However, problems were found with two items of equipment. The use of footswitches caused many problems. They were frequently replaced due to their failure. Presumably, they were exposed to high accelerations, and large shear force. The least reliable part of the kicking experiments was the Kickmaster device (see Section 2.9.2 Results Section page 45). It measured the speed and force applied of the cord securing a tethered football. It was programmed to calculate the force delivered to the ball. In practice, even when used with experienced kickers, the data displayed was very variable. The range of kick power from the youngest kickers making maximal kicks was from 756 Watts to 3920 Watts. Similarly large ranges were seen for the other groups. The author places little faith in these values. This is probably not surprising given that the Kickmaster is sold as a training device rather than as a scientific instrument.

4.3 Characteristics of Co-activation

The papers cited in Tables 1.3 and 1.5 of the literature review shows that co-activation of antagonist muscle pairs are a widespread and frequent phenomenon. This observation is supported by the results in this thesis summarised in section 4.1. It raises the question of what purpose is served by co-activation? Is it a problem during movements, which may cause muscle injury or is it an essential feature, which protects joints from injury?

4.4 Purpose of Co-activation

There are two main views about this. Barratta et al (1988) argued that co-activation reduces the risk of knee injuries in high performance athletes. He proposed that co-activation reduces the net torque on the joint and slowing the movement. This assists the ligaments to maintain joint stability and equalises the distribution of forces on the articular surfaces.

Enoka (1997) takes a slightly different view. His observations are that co-activation is particularly strong when people make novel movements. Thus co-activation is seen as a way of protecting the limb by slowing movements and reducing the forces on the joints. However, Enoka and others who have studied training and co-activation see that limb velocity increases and co-activation decreases with training. (Baratta et al, 1988; Osternig & Robertson, 1990; Carrolan & Cafarelli, 1992; Amiridis et al, 1996; Bernardi et al, 1996; Kellis & Baltzopoulos, 1996a; Kellis & Baltzopoulos, 1996b; Hakkinen et al, 1998; Colson et al, 1999; Hakkinen et al, 2000; Hortobagyi & DeVito, 2003 and Pinniger et al, 2003) They view the co-activation seen in high performance athletes as a residual effect rather than as an essential protective feature.

4.5 Co-activation Changes with Age and Experience

The data presented in Table 4.1 is an extract from the data in Tables 3.27 – 3.32. It shows the mean times at which the EMG in VL and BF started and stopped at time with ball contact. It shows that the period of co-activation is significantly shorter in the 15-years-old group than the 11-years-old.

	Start before ball contact (msec)		Stop after ball contact (msec)	
	VL	BF	VL	BF
A	-129	-67	128	133
B	-28	-25	42	39
C	-82	-43	73	7

Table. 4.1. This table shows the time between start and end of the EMG in VL and BF during unrestrained kicks. A - 11-year-olds footballers. B - 15-year-olds footballers. C - Untrained adults. There are significant differences between (A) vs (B) in both times starting and stopping ($P < 0.001$).

This is consistent with the extra experience gained by the older players. The untrained adults lie between these two groups of football players. Thus these data can be used to support Enoka's view. There are however two major qualifications to this. Firstly, the 11-year-olds are not novice kickers. They are good 11-year-old football players. Secondly, whilst the 15-year-olds have more kicking experience, they are also larger and more mature in their motor skills. Consequently, it is hard to be certain that Enoka is correct.

Discussions with J. Wylie, (Youth Coach to a professional football club), revealed anecdotally that injuries are much more common in the 15-year-olds. There is no organised data collection for the injury rate amongst young players. The predisposition to injury could also be related to the reduction in co-activation leading to higher velocity movements and the increased risk of tissue damage. This provides an element of support for the views of Barrata, 1988 and Enoka, 1997.

The question of how much injury risk is acceptable in the pursuit of increased power or speed of movement is still open.

4.6 Muscle Co-activation and Injury

The previous section discussed the possible role of muscle co-activation in the stabilization of joints during movement (Barratta, 1988), particularly during novel movements (Enoka, 1997). It is clear that co-activation is present even in highly skilled sportsmen and after prolonged training and many thousands of repetitions of the movement (see 3.2 in results section and 1.5 Introduction section). This may mean that the co-activation has preserved the joint function in these skilled performers. It is also possible that co-activation exposed the muscles of less skilled performers to injury and prevented them gaining the long training history. It would take a longitudinal study, much larger than this project, to answer that question.

At any rate it is clear that eccentric muscle activity leads to muscle damage. This can appear two or three days after the activity when it is known as delayed onset muscle soreness (Newham et al, 1987; Clarkson and Tremblay, 1988; Whitehead et al, 1998; Proske and

Morgan, 2001). Eccentric activity can also cause acute injury in the form of muscle strains or tears (Nosaka, Newton and Sacco, 2002; Armstrong, 1984).

There have been extensive studies of the frequency of injuries and how frequent they are in particular sports. Backx et al. (1991) studied 1881 secondary schools in the Netherlands and reported sprains in 21% of participants in a range of sports. They also found muscle and soft tissue injuries in 9% of participants. In an analysis of which sports in Switzerland were associated with injuries of all types, de Loes (1995) found handball, football and basketball players to be the most likely injured.

There are no data available about the damage caused in human muscles by fast stretches. It is almost certainly too difficult to perform these experiments. There have been studies in laboratory animals. Lieber, Woodburn and Friden (1991) studied rabbit tibialis anterior after eccentric contractions had damaged the muscles. They found force decrements of 69% and subsequent histological examination showed stretch induced damage at the myotendinous junction. Patel, Cuizon, Costello, Friden and Lieber (1998) also found eccentric exercise damaged rabbit muscle and they attributed this to oxidative capacity stress. The most recent study was by Rathbone, Wenke, Gordon and Armstrong (2003) who found sarcomere and Z line damage after eccentric stretches of mouse muscle. They were able to use extreme velocities of up to 2000 °/sec. Whatever the cellular / molecular mechanism is, the pain of acute muscle injuries is familiar to most sportsmen and sportswomen.

4.7 Injury Prevention

The coaching of athletes requires a balance to be maintained between the need for high speed-high force movements and the need to minimise the frequency of injury to muscles and joints. One of the main aims of coaching is to achieve this through the development of "good technique". There is at present a large separation between coaching, say of young footballers, and laboratory based analysis of biomechanics. This separation is reducing and this can be seen in the requirement next year for Scottish Premier League clubs to provide sports science support for their squads of players (The Scottish Football Association 2004).

The best recommendation which can be made to coaches, is that novice sportsmen need the opportunity to rehearse movements to allow time for the acquisition of skilled movements. This almost certainly requires a slow progression of sportsmen and women to increasingly higher power movements. The roots of this may be evident in the use of lightweight equipment, such as lower weight footballs for younger players and smaller sized pitches. Both of these modifications to the game reduce the power requirements in kicking. This must give the chance for movements to be learned with a reduced risk of injury.

The anecdotal evidence of the increased injury frequency in young footballers at about 15 years also fits this idea. At this age there is an increase in limb length and muscle mass at about the time of puberty. The changes in limb mechanics and muscle power may make higher power movements more difficult to control and so predispose to injury. These mid teenage players have the additional problem of having to show promise to secure professional contracts. The problem of balancing performance and injury risks is a very important one for them.

4.8 Future Plans

Two mains ideas emerge from this thesis. Firstly, it would be very beneficial to perform a longitudinal study, over say five years, to follow the development of kicking power and EMG activity as a group of players progress from the younger team at 11 years to the intermediate team of 15 year olds. This would be even more useful if the changes could be related to injury frequencies.

Secondly, it would be useful to compare the biomechanics and EMG activity in development players as they use lightweight and full size balls to confirm that the suspected advantages are indeed there.

5. Conclusions and Suggestions for Future Work

The main conclusion of this project is that co-activation of the hamstrings and vastus lateralis is very common during high-speed knee extension movements such as kicking and jumping. The co-activation starts in early movement, often before extension begins. It is also frequently observed late in the movement after extension has been completed. Co-activation is not confined to high power jumps and kicks. It is frequently observed even in the lowest power movements.

Analysis of kicking movements in young footballers suggests that as they age from 11 to 15 year there is a reduction in the duration of the periods of co-activation. This is associated with or leads to higher speeds of movement and kicks of greater power. These are signs of increasing skill in performing the task and possibly are the result of skill acquisition through experience. One can only speculate if the higher speed and power of movement exposes the athlete to more risk of injury.

It may be important to control the movements during this learning phase. This probably explains the current emphasis on using smaller pitches and lighter weight footballs for younger players. These rule changes probably allow the player to get the experience of movement and to develop their skills without demanding the higher power movements needed to kick a full-size ball longer distances on a full-sized pitch.

5.1 Suggestions for further work

In the longer term, there should be a longitudinal study of young footballers say starting with novice players aged 9-10 years and following their progress till ages 15- 16 years old.

This will also demand a better way of measuring the power of kicks. The 'Kickmaster' used here was a commercial product rather than a scientific instrument. It needs to be modified to withstand full power kicks and to improve its reliability. This would make a good project for some future mechanical engineering student.

In addition, there were persistent problems with the footswitches. This is a common problem and there is a clear need for a lightweight, robust switching system.

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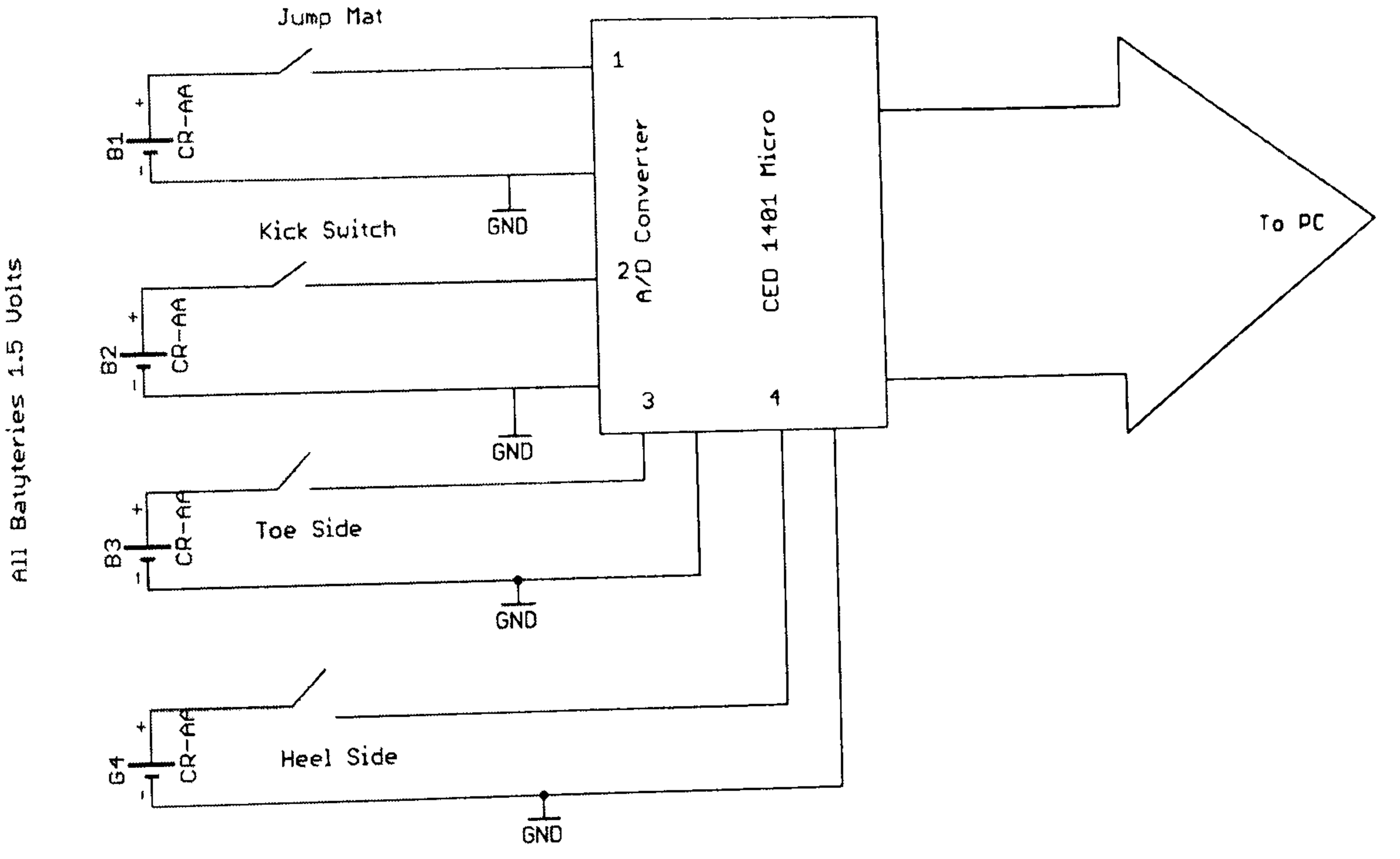
Appendix

Details of switches used to signal foot contact.

A series of switches were used to indicate events during body movements. These all consisted of metal foil elements separated by spacers of plastic foam. The foils were connected to a small battery by fine wire. When the foot made contact with the ground or with the ball the switch closed and a 1.5 volt signal was detected at the appropriate input of the CED 1401 A/D converter.



FootSwitches