THE TIMING AND MAGNITUDE OF MUSCULAR ACTIVITY PATTERNS DURING A FIELD HOCKEY HIT

BY

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Abstract

The field hockey hit is one of the most important skills used in the game. However, due to the paucity of empirical research, little is known about the biomechanics of this movement. Muscular activation patterns have been shown to be major contributing factors to performance variables in similar swinging motions in golf, tennis and baseball but debate remains about which muscles are contributing to and controlling such motions. Moreover, muscle studies have typically neglected the contribution to movement from segmental interactions and have not related muscle activity to the three-dimensional kinematics of the swing.

The aim of this study was to investigate the contributions from muscular activity and from segmental interactions to the hits of ten male, university-level field hockey players. The activity of sixteen upper body and trunk muscles was monitored using surface electromyography alongside synchronized three-dimensional kinematics of the upper body and hockey stick motions.

Surface electromyographic signals were recorded at 2000Hz bilaterally from the biceps brachii, triceps brachii, the anterior and posterior deltoids, the upper trapezius, the latissimus dorsi and the sternal and clavicular pectoralis major muscles. Three-dimensional kinematic data were collected at 240Hz and each hockey hit was broken down into four phases of the backswing, the early forward swing, acceleration and the early follow-through. These kinematic and electromyographic data were then synchronised and temporally normalised before the electromyographic data were normalised to relative maximal reference contractions.

Right anterior deltoid, right pectoralis major and bilateral latissimus dorsi activity initiates the downswing of the hockey hit, causing the early acceleration of the arms. Segmental interactions, due to these accelerations, cause the hockey stick to lag and the wrists to ‘cock’. A combination of left anterior deltoid, left latissimus dorsi and bilateral pectoralis major activity continue to accelerate the shoulders during the downswing whilst elbow musculature appears to control the effects of segmental interactions. These segmental interactions then become involved in wrist ‘uncocking’ as the stick accelerates towards impact with the ball.

The effects of muscular activity and segmental interactions cause the right elbow to flex then extend, whereas the left elbow demonstrates a more constant degree of extension throughout the hit. Both wrists display the same pattern of ‘cocking’ then ‘uncocking’. These combined patterns lead the left arm and stick system to function as a double pendulum whilst the right arm and stick more closely resemble a triple pendulum.

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1. Introduction

The field hockey hit is a two-handed swing motion which, due to the production of a high ball velocity, is generally used for long range passing and for shooting at goal (Murtaugh, 2000; Brétigny *et.al.* 2011; Willmott and Dapena, 2012) and serves to give velocity to the game (Brétigny *et.al.*, 2008). During the performance of the hit, both hands are typically placed at the proximal end of the stick grip and the technique employed resembles that of the golf drive or of the baseball or softball hit.

Numerous coaching manuals exist describing the field hockey hitting technique (for example, Anders and Myers, 1999); however, these accounts are subjective and remain primarily qualitative accounts, relying heavily on the personal experiences of the authors. As a result, discrepancies exist between manuals, which ultimately could lead to poor coaching of the field hockey hitting technique.

There is also a lack of quantitative biomechanical studies in the scientific literature focussing upon the field hockey hit despite it being one of the most fundamental and most commonly used techniques in the game (Mackey, 1964; Chivers and Elliot, 1987). The application of biomechanics to the field hockey hit is of benefit to both coaches and players (Chivers and Elliot, 1987) and studies to date have ascertained the general shape of the hit (Willmott and Dapena, 2012), the utilisation of proximal-to-distal sequencing (Okuda *et.al.*, 2011), coordination profiles (Brétigny *et.al.*, 2011) and the planarity of the hockey stick face (Willmott and Dapena, 2012), yet little is still known about how the hitting motion is generated or controlled.

1.1 The field hockey hit

Hitting the hockey ball, as opposed to sweeping or pushing the ball, can give rise to an increased ball velocity. The 'classic' hit is the most common hitting technique used in field hockey and is preferred to other hitting techniques, such as the short-handle grip, due to the higher ball velocity developed (Brétigny et.al., 2008). The classic hit utilizes a double 'V' grip for the duration of the hit (England Hockey, 2005) (Figure 1.). Field hockey is a 'right-handed' sport, whereby the head of the stick is 'flat on the left hand side only' (FIH, 2012). Consequently, the stick is swung from right to left during the downswing of the 'classic' hit (Murtaugh, 2000; Brétigny *et.al.*, 2011).

Techniques for hitting the hockey ball and mechanisms for increasing stick speed and acceleration have been proposed in the coaching literature. It has been suggested that the player should adopt a side-on stance with the left shoulder facing in the direction of the target to increase weight transfer between the right foot and the left during the hit (Wein, 1979). It has also been proposed that the player should maintain a low body position during the backswing, keeping the left arm straight for the entirety of this phase and that the right arm should flex at the elbow to accommodate the movement of the stick to the right (Anders and Myers, 1999). At the start of the backswing, whilst the stick is being drawn to the right, it is advised that a step towards the ball with the left foot is taken to provide a large base of support for increasing forward momentum by facilitating weight transfer (Gros, 1979). Both Gros (1979) and Wein (1979) proposed that a player could increase their forward momentum prior to the hit if a run-up is adopted before the stride to the ball is taken and that if a run-up is adopted, to account for a greater transfer of weight onto the front foot, it is advised that the ball should be positioned slightly further away from the lead foot than if the player was stationary before the stride (Wein, 1979). Gros (1979) suggested that during the backswing, weight is transferred from the left foot to the right yet weight shifts back to the left foot before the end of this phase, accompanied by rotation of the hips and shoulders back towards the target. The shoulders should turn to facilitate a greater range of motion and the wrists should ‘cock’ while the stick proceeds through the whole backswing.

Barnes and Kentwell (1979) suggested that momentum should be transferred from the lower body, to the upper limbs and the stick during the downswing and that the hands pull the stick towards the ball as weight is shifted back onto the left foot and that this transfer of weight flattens the swing arc of the stick, helping to improve accuracy during the downswing (Barnes and Kentwell, 1979). Chivers and Elliott (1987) proposed that the acceleration of the stick in the late downswing comes from the straightening of the right arm and from ‘uncocking’ of the wrists accompanied by pronation of the right forearm prior to impact, and Read (1976) noted that at ball impact the arm and hands lead the stick with the extension of the left elbow allowing the stick to act as an extension of the left arm (Figure 1.).

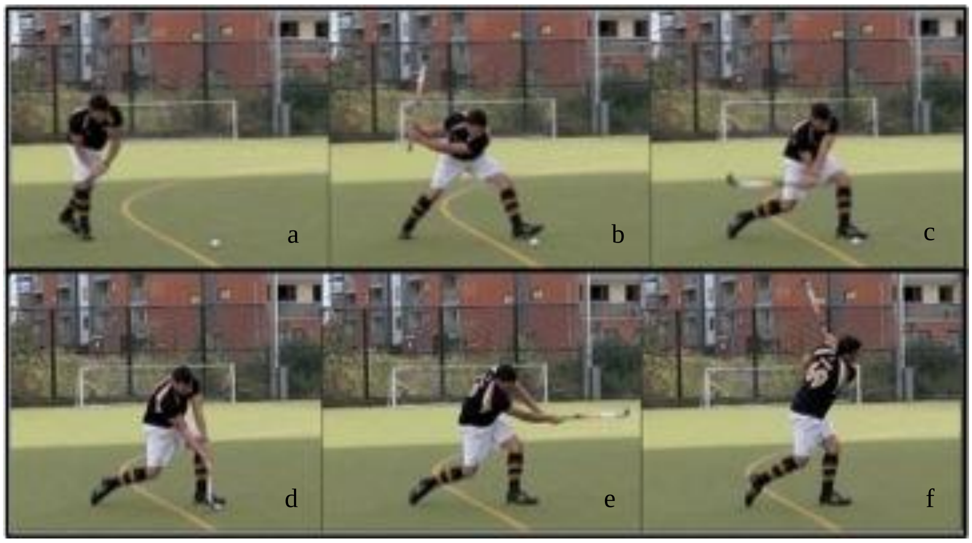


Figure 1. The field hockey hit: a) initiation of the hit and the start of the backswing; b) top of the hit, the end of the backswing and the start of the early forward swing; c) stick horizontal in the downswing, the end of the early forward swing and the start of the acceleration phase; d) ball impact, the end of the acceleration phase and the start of the early follow-through; e) stick horizontal, the end of the early follow-through and the start of the late follow through; f) end of the swing.

Studies into other two-handed swing motions could provide biomechanical insights into the hockey hit. Due to the unique nature of the field hockey hit though, the differences that exist between the hit and other two-handed swinging motions should therefore be appreciated. In field hockey the ball being struck is of a greater mass than the golf ball and is usually moving, resulting in little time for a pre-rehearsed address phase to a stationary ball, of the type seen in golf, unless the performer is taking a hit out or a free hit. Even in situations where the hockey ball is not moving, the step towards the ball is still utilised in an attempt to increase ball velocity. Usually though, the field hockey hit is performed when both the player and the ball are moving. Baseball players also aim to hit a moving ball that is travelling towards them, yet the contact point between the bat and the ball is off the ground.

Changing environmental task conditions, for example the speed and direction in which the hockey ball is travelling, affect temporal aspects of the hit (Franks *et.al.*, 1985) and this consequent variability in the kinematics of the hit would have a relative influence on muscular activation patterns of the upper limbs and the trunk to possibly produce, for each hit, a slightly different movement pattern. These differences therefore make extrapolation of EMG data from other sports to the hockey hit difficult.

Electromyographic (EMG) activity patterns have been studied in sports that utilise similar movement patterns to those displayed when performing a field hockey hit; for example, in baseball, softball and most extensively in golf (Jobe *et.al.*, 1989; Abernethy *et.al.*, 1990; Ellenbecker *et.al.*, 2006; Escamilla and Andrews, 2009). However, contrasting findings with regard to the timing and magnitude of muscle activity during other swing motions, and also the inherent differences in performance between other two-handed swings and the field hockey hit, makes extrapolation to the hockey hitting motion difficult. Knowledge of muscular activation patterns in relation to the field hockey hit could begin to detail their contribution not only to the production and control of the hit, but also to skilled performance and ball velocity. Moreover, changes in technique, strength training programs and injury prevention and rehabilitation strategies could be developed and initiated.

Underlying muscular activation patterns during the performance of the field hockey hit have only briefly been presented in the scientific literature, despite their influence on the production and control of such motions. To date, there has only been one study focussing upon the collection of EMG data during the field hockey hit. Murtaugh (2000) published an un-normalised linear envelope of EMG recorded from four selected trunk muscles during a field hockey hit. This data though, provided little quantitative information as to the contribution or the role of each muscle to the hit. Therefore a description of muscular activity of the trunk and upper body during the hit does not exist. Putnam (1993) however, provided evidence to show that movement can be a consequence of the interactions between moving segments and that muscular activity is not necessarily required to produce motion. Consequently, the causes of the motions seen during the field hockey hit might not necessarily be attributable to the muscles crossing the joint where the motion is seen.

Alongside ambiguity as to the timing and magnitude of muscular activity, the kinematics of the hit also remain unclear with the role that each arm plays during the field hockey hit being particularly uncertain. Chivers and Elliott (1987), in one of only two studies - the other being Elliott and Chivers (1988) - proposed that the left arm can be represented by a double pendulum model consisting of the left arm system and the hockey stick and that the right arm can be represented by a three-segment model consisting of the right upper arm, the right forearm and the hockey stick during the field hockey hit.

The aim of this investigation was to establish muscular activity patterns during the field hockey hit. This is the first study to detail the timing and magnitude of muscular activation during the field hockey hit and in particular aimed to question the contribution of the deltoids and the timing of pectoralis major and latissimus dorsi to the hit. Moreover, this study aimed to synchronise EMG data with kinematic data from the hockey hit to make meaningful kinetic assumptions as to the temporal contributions of EMG activity to the performance of the hit and, where EMG activity is not prevalent, to provide meaningful assumptions as to the possible cause of the kinematic patterns observed. Furthermore, this will provide the basis for investigation of the role of the trunk and arm musculature to the production and control of the field hockey hit and allow investigation into the differing roles of the arms based on previous speculations made by both Chivers and Elliott (1987) and Elliott and Chivers (1988).

2. Review of Literature

2.1 Phases of the field hockey hit

Field hockey based studies have typically divided the hit into three phases: the Backswing, the Downswing and the Follow-through (Franks *et.al.*, 1985). The backswing of the hockey hit has been defined as a hockey stick motion away from the ground (Brétigny *et.al.*, 2011) and involves lifting of the arms, initiated by a rotation of the shoulders and of the trunk (Chivers and Elliott, 1987). However, at the commencement of the field hockey hit, Franks *et.al.* (1985) found that prior to the backswing itself, an initial preparatory phase is seen, termed the 'initiation phase'. This was characterised not by a movement of the stick head away from the ground, but towards it. Despite this, Franks *et.al.* (1985) still showed the backswing as beginning at the stick's lowest point in relation to the ground, encompassing motion of the stick head in the opposite direction to the motion seen during the initiation phase (i.e. away from the ground). The backswing begins with backwards rotation of the trunk and shoulders, ending with both the right shoulder and hip higher than the left shoulder and hip (Chivers and Elliott, 1987). The downswing of the stick face begins at its transition from the backswing (Brétigny *et.al.*, 2008), and corresponds to stick motion in an opposite direction to that of the backswing, back towards the ball (Brétigny *et.al.*, 2011). Chivers and Elliott (1987, pp. 7) noted that this motion was not confined to the same plane as the backswing, rather, it 'curved backwards then downwards and forwards in an oblique plane'. The follow-through was defined as stick motion from impact with the hockey ball to the end of the hit (Brétigny *et.al.*, 2011), with the body moving in an extended position during this phase (Chivers and Elliott, 1987) (Figure 1.). These accounts though, provide little explanation as to the definitions of the phases, stick or body movements during the phases, or the events that define the transitions between them.

2.2 Phases of the golf swing

The golf swing is the swing motion that demonstrates the most similar movement patterns to those of the hockey hit which has been analysed using EMG. Studies that utilise EMG and motion analysis techniques within golf-orientated research have categorised the golf swing as consisting of five phases: the Backswing (BSw), the Early Forward Swing (EFSw), Acceleration (Acc), the Early Follow-through (EFTh) and the Late Follow-through (LFTh). Each of these swing phases have been described as beginning and ending with clearly definable temporal events, thus providing more robust definitions of each phase. Alongside this, descriptions of the movements made during each phase are more prevalent and more extensive in the golfing literature.

The BSw of the golf swing has been defined as being from the first motion of the club away from the ball at address to the top of the swing (Jobe *et.al.*, 1986; Mitchell, *et.al.*, 2003; McHardy and Pollard, 2005, Okuda *et.al.*, 2010). The BSw is characterised by rotation of the shoulder complex to the right, with subsequent right arm abduction, flexion and external rotation and simultaneous corresponding adduction, flexion and internal rotation of the left arm to take the golf club backwards (McHardy and Pollard, 2005). The purpose of the BSw is to align the golfer’s hub centre and club head and to stretch the muscles and joints that are responsible for power generation during the forward swing and acceleration (Hume *et.al.*, 2005). Throughout the BSw phase of the golf swing, muscle activity was observed as being low to moderate. This therefore suggests that the lifting of the arms and the golf club during the BSw is not a strenuous activity (Escamilla and Andrews, 2009).

The next phase of the golf swing, the start of the downswing, has also been termed the early forward swing (Jobe *et.al.*, 1986; Escamilla and Andrews, 2009; Farber, *et.al.*, 2009). This phase begins at the transition from the BSw and finishes when the club and the ground are again horizontal to each other (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; McHardy and Pollard, 2005). The purpose of this phase is to initiate downward motion of the club (Hume *et.al.*, 2005) and is characterised by starting to return the body back to the ball in preparation for contact, initiated by hip and pelvic rotation to the left, producing a combined movement of left shoulder girdle rotation and anti-clockwise scapular rotation (McHardy and Pollard, 2005).

The Acc phase of the downswing, sometimes termed the 'late forward swing' or the 'late downswing' (McHardy and Pollard, 2005) commences when the golf club is horizontal with the ground, continuing through to ball contact (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; McHardy and Pollard, 2005). In golf, it has been proposed that the purpose of the Acc phase is to continue to return the club head to the ball in the correct plane with maximum velocity, accelerating the club with the left arm dictating the plane of the club and the right arm providing power in the latter part of the downswing (Hume *et.al.*, 2005), however, this is only an assumption and remains untested. This phase has been termed the 'most active' of the entire golf swing (McHardy and Pollard, 2005; Escamilla and Andrews, 2009) and is characterised by a continuation of the movements seen during the EFSw. The left arm demonstrates adduction and external rotation, whilst on the right side scapular protraction is maintained before wrist un-cocking occurs, just before the point of contact between the club head and the golf ball (McHardy and Pollard, 2005). A delayed straightening of the left elbow maintains a lower moment of inertia (Loftice *et.al.*, 2004) and maximises stick head acceleration during the Acc phase of the golf swing (Egret *et.al.*, 2006; Zheng *et.al.*, 2008). The golf swing has also been shown to be planar with inclination of the golf swing plane to horizontal varying, falling within a range of 59.1° when swinging a pitching wedge to 47.2° to when swinging a driver, becoming more shallow with the use of longer clubs (Kwon *et.al.*, 2012).

The EFTh phase starts immediately at the moment that ball contact is initiated and continues until the club is horizontal to the ground, forward of the performer's original starting position (McHardy and Pollard, 2005). Also called the 'deceleration' phase (Escamilla and Andrews, 2009), the EFTh is characterised as being the phase during which deceleration of the trunk rotation occurs accompanied by left arm external rotation and right arm internal rotation (McHardy and Pollard, 2005). Lastly, the LFTh starts when the club reaches horizontal to the ground after ball impact and continues to the completion of the swing (Jobe *et.al.*, 1986; McHardy and Pollard, 2005).

2.3 Biomechanical mechanisms

From kinematic studies of the golf swing, it has been suggested that movement of the body segments in a sequential motion is one of the most predetermining factors for the successful performance of the motion pattern for the golf swing (Okuda *et.al.*, 2010). Therefore, theoretically, more proximal body segments should attain their peak velocities before more distal segments in order to implement a powerful and coordinated motion during the swing (Okuda *et.al.*, 2010). Through optimisation calculations it has been confirmed that maximal golf club head speed is achieved when the ‘torque generators commence in sequential order from proximal to distal’ (Hume, 2005, pp. 435). Joint contribution to the golf swing has been determined at 70% for the wrists, 20% for the shoulders and 5% for both the spine and the hips (Hume, 2005). Okuda *et.al.* (2002) proposed that technique and proximal to distal timing patterns of EMG activation were more important than stature or muscular strength for the optimal transfer of momentum through the kinetic chain, however, this study made assumptions based upon data from only one player. Moreover, elements of technique are individual to the performer, necessitated by physical stature. A skilled golf swing will use a conservation of angular momentum and centrifugal force to maximise club head velocity at impact (Hume, 2005).

The earlier rotation of the hips back towards the target line whilst the shoulders are still rotating backwards during the BSw promotes the stretch-shortening cycle (SSC) (Ferdinands, 2010). The modern golf swing is a powerful SSC activity during which the muscles of the trunk and upper limbs are ‘rapidly stretched prior to shortening’ (Hume *et.al.*, 2005, pp. 436). The action of stretching and then shortening of a muscle group in a short period of time should augment efficiency in a concentric contraction thus the effective utilisation of the SSC will facilitate the golfer in hitting the ball greater distances (Ferdinands, 2010). After the instigation of the SSC during transition, the ‘major power accentuating muscles are most strongly activated during eccentric contractions’ (Ferdinands, 2010, pp. 72). Hume *et.al.* (2005) proposed that the left shoulder complex supplies a large portion of the power of the golf swing.

Thus, it is essential that the shoulder musculature and the other muscles that are active during the downswing be stretched during the late BSw. Alongside this, musculature of the shoulder may have already been activated at that point to help bring the BSw to an end.

Increases in muscular activity of the agonists of the BSw, such as the left subscapularis and the right upper trapezius and increased rotation of the trunk would stretch the muscles utilised during the downswing thus increasing shoulder turn at the top of the golf swing by increasing the rotation of the shoulders.
Whilst the stretching of the muscles involved in the downswing during the BSw may be fundamental to performance of the golf swing, the magnitude of the subsequent shoulder turn in relation to hip rotation at the top of the golf swing may be a more pertinent measure of performance. McLean (1992) termed this the 'X-factor' and he suggested that the X-factor might be of more importance than the absolute turn of the shoulders. An offset between shoulder and hip rotation has been observed in both skilled and lower skilled golfers (Cheetham, 2001) with increases in the X-factor at the top of the golf swing being attributed to improved performance. Moreover, increased X-factor at the top of the swing has also been used as an indicator of ability level and of the performance of variables such as drive distance (McLean *et.al.*, 1992; McTeigue *et.al.*, 1994; Burden *et.al.*, 1998; Cheetham *et.al.*, 2001).

The maximal X-factor generated during the EFSw has been termed the 'X-Factor stretch' (Cheetham, 2001). During transition, muscles of the trunk are being stretched because the shoulders are still rotating backwards even as the hips rotate forwards. Okuda *et.al.* (2002) found that as the club head was completing the BSw and musculature of the right shoulder continued to aid club elevation, musculature of the right lower body was initiating abduction and extension of the right hip, possibly providing additional eccentric contraction of the upper body as the hips return back towards the target line.

The X-factor stretch has proven to be a more consistent measure of performance than the X-factor at the top of the swing, with professional players having a significantly greater X-factor stretch compared to amateur players (Cheetham, 2001). This significant increase in X-factor stretch during the EFSw was a result of professional players initiating the downswing ‘by rotating their hips back towards the hole’ (Hume, 2005, pp. 437), a trait more pronounced in higher skilled golfers (McTeigue *et.al.*, 1994; Burden *et.al.*, 1998) as they continued to rotate their shoulders away from the direction of the target as the hips began turning back to the target line (Burden *et.al.*, 1998). Continuing to turn the trunk and upper body away from the target whilst leading with the hips would result in an increase in the X-factor stretch during the EFSw, allowing the golfer to utilise a greater SSC and for the the transfer of momentum from proximal to distal body segments to be its most effective (Okuda *et.al.*, 2010).

2.4 Kinematics of the hockey hit

The kinematics of the hockey hit have been previously studied, yet information still remains sparse. The plane of the hockey stick face, the differing shapes of the backswing and the variability of temporal parameters of the hit have all been studied but only begin to provide an insight into the motion.

In field hockey, the shape of the path that the stick face follows during the BSw has been shown to vary (Willmott and Dapena, 2012). In their work on the planarity of the field hockey hit, Willmott and Dapena (2012) found that their participants utilised two different stick face paths to execute the hit. The first stick face path was a path that was similar during both the backswing and the downswing. The second was a curved stick face path that was ‘above its path during the subsequent downswing’ (Willmott and Dapena, 2012, pp. 373). These two techniques were categorised as ‘straight’ and ‘looped’ respectively. Ultimately, the stick face path and therefore the swing shape differed between the two groups, with the length of the downswing being longer in the looped swing (2.88 ± 0.28m) compared to the straight swing (2.45 ± 0.28m) (Willmott and Dapena, 2012). Due to the employment of different swing shapes when executing a field hockey hit, it may be difficult to define exactly where the BSw ends and the EFSw begins, especially when analysing the looped hit. Willmott and Dapena (2012, pp. 373) proposed that the criterion for determining the transition between the BSw and the EFSw to be the ‘instant when the stick face began its final uninterrupted increase in speed through to impact’.

The motion of the stick face in the field hockey hit has been shown to be planar for large portions of the downswing; on average being planar for the last 83 ± 12% of the downswing (Willmott and Dapena, 2012). This is a trait more prevalently seen with a straight swing yet is also apparent in the looped swing, with the portion of the downswing over which the stick face motion is planar being similar to the planar portion of the downswing of the club head in golf (Willmott and Dapena, 2012). In field hockey, the planar region of the stick shaft in the downswing starts on average

35° and 20° above horizontal during the EFSw for straight and looped swings, respectively (Willmott and Dapena, 2012).

In the field hockey hit, the straightening of the right arm (Wein, 1979) and wrist uncocking (Anders and Myers, 1999) causes the final acceleration of the stick face and the stick acts as an extension of a straight left arm at ball impact (Read, 1976; Gros, 1979). At impact with the hockey ball, left arm extension reaches approximately 170°, whilst extension of the right elbow during Acc causes the right elbow to extend to approximately 140°. For the first half of the downswing the wrists remain cocked (Chivers and Elliott, 1987), before extending to 165-170° at ball impact (Chivers and Elliott, 1987). The angles of the elbows and wrists indicate that the hands lead the stick head at ball impact (Chivers and Elliott, 1987; Elliott and Chivers, 1988).

The inclination of the plane of the hockey hit was orientated at 42.2 ± 4.5° for the straight swing and 38.2 ± 7.3° to horizontal for the looped swing (Willmott and Dapena, 2012) and is much shallower than that of the golf swing. The hockey stick shaft becomes planar before it becomes horizontal during the EFSw. Therefore, the stick face motion for the 'period when most speed is added to the stick face' remains planar throughout continuing to impact with the hockey ball (Willmott and Dapena, 2012, pp. 376).

Temporal parameters of the field hockey hit have been shown to be subject to variability. Franks *et.al.* (1985) reported that with varying uncertainty of task demand, hockey players utilised changes in the spatial location of the start of the

BSw and showed increases in BSw variability to ‘produce a consistent and ballistic downswing’ (Franks *et.al.*, 1985, pp. 91), with both novices and more experienced hockey players conserving temporal consistency despite differing technical parameters to employ a more temporally consistent and less variable downswing (Burges-Limerick *et.al.*, 1991; Kusuhara, 1993; Brétigny *et.al.*, 2008). Bootsma (1988) proposed that continuously, players attend to visual information and fine-tune movement during its execution. The variability seen during repetitive actions is a mechanism to adapt to interactions between organismic, environmental and task constraints (Abernethy *et.al.*, 1990). The step towards the ball in the hockey hit would bring about variability in left foot placement in terms of distance and angle from the ball being struck and produce differences in the angle between the trunk and shoulders and the target line. Even if hitting a stationary ball, these changes would therefore manifest themselves in subtle alterations in task performance, possibly affecting underlying muscle recruitment and EMG activation patterns for each hit. Brétigny *et.al.* (2011) proposed that the high standard deviation seen in joint kinematics during the hockey hit were indicative of several different hit solutions with movement coordination patterns changing as a determinant, not necessarily of task variability, but of playing position. Differing muscular activation patterns could cause the changes in temporal parameters and hit coordination profiles demanded by task variability, or the hit shape differences based upon playing position.

2.5 The role of the arms

Little is known to guide us about the kinematics of the hockey hit and the role that each arm plays during the hit. The only studies that focus upon three-dimensional kinematics of the stick and the body during the field hockey hit are provided by

Chivers and Elliot (1987) and Elliott and Chivers (1988), with little expansion on the role of the upper limbs.

In sports where the main emphasis of the impact is on velocity, it would be reasonable to assume that the optimal sequencing pattern of the upper limbs would be one of three segments, consisting of the upper arm and the forearm in addition to the striking implement, as suggested by Elliot and Chivers (1988), to theoretically allow the maximisation of proximal-to-distal sequencing and to allow elbow musculature to contribute to the movement. However, Milburn (1982) reported a double pendulum, pivoting at the shoulder joint and hinged at the wrist, to be the pattern during the golf swing. Elliot and Chivers (1988) theorised that the hockey hit adopts a double pendulum for the left arm and stick system and a three-segment model for the right upper arm, forearm and stick system (Figure 2). This figure however, presents difficulties in its interpretation. Firstly, the figure makes the presumption that the proximal ends of the arms rotate around a fixed axis mid-shoulders throughout the hit, which, from photographic movement sequencing, Elliott and Chivers (1988) show does not happen. Furthermore, the definition of the left and right arms is unclear and there remain seven time instances before impact presented alongside only three shoulder positions.

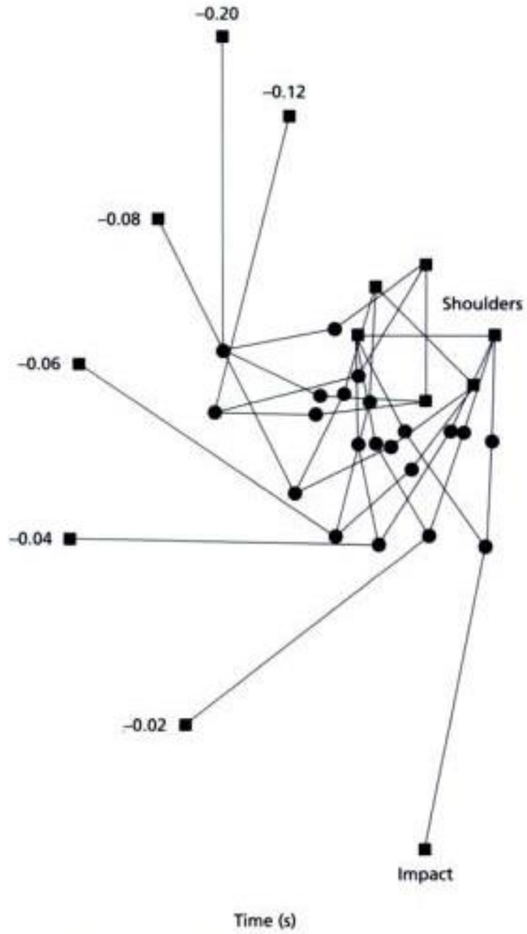


Figure 2. Motion of the left and right arms and the hockey stick during the downswing of a male penalty corner striker, demonstrating the double pendulum motion of the left upper limb and hockey stick system and the triple pendulum motion of the right upper limb, right lower limb and hockey stick system. The values at each stick head position represent the time relative to ball impact (from Elliott and Chivers, 1988).

It was suggested that much of the power in the field hockey hit is derived from the lower limb action and the rotation of the trunk and the shoulders is such that the upper limbs and then the stick are finally rotated towards the ball (Elliott and Chivers, 1988). At the start of the EFSw of the field hockey hit, Chivers and Elliott (1987) reported that, on a different plane to which the hockey stick was moved during the BSw, the right elbow increases to 80°-90° of flexion. After this early flexion of the right elbow, the left arm dictates the plane of the stick (Chivers and

Elliott, 1987) and ‘the left arm guides the stick motion, whereas the right arm serves as a support to the movement’ (Brétigny *et.al.*, 2011, pp. 342). Despite a few studies, there remains little kinematic data on the hockey hit and no experimental EMG data for musculature of the arms during the hit. The roles of the arms and the contribution of muscular activity to the kinematics of the hockey hit have therefore not been measured empirically and have only been speculatively summarised.

Budney and Bellow (1990) reported that during the golf swing the left arm applied force to the golf club before the right arm did during the golf downswing and that the left hand had control of the club at impact with no force from the right hand. However, Hume (2005) assumes that the right arm does provide power in the latter part of the downswing. The role of the arms therefore, remains unclear and there is little biomechanical evidence to support any of the assertions made as to the roles of the arms during the hockey hit, the golf swing or during other hitting motions.

2.6 Muscular activity

As there are no EMG analyses in the scientific literature on upper limb musculature during the field hockey hit and data on trunk muscular data is sparse and speculative, information must be gleaned from EMG studies into the closest comparable motions to the hockey hit for which EMG analyses have been performed. Most extensively, EMG analysis focuses upon the performance of the golf swing.

2.6.1 Backswing

During the BSw of the golf swing, to aid the rotation of the shoulder complex and the abduction of the right arm, the muscles displaying the greatest amount of EMG activity in the upper body on the right side during the golf swing are the upper trapezius (working at 52% of its maximal manual muscle strength test (MMT)) and the middle trapezius (37% MMT) (Kao *et.al.*, 1995; McHardy and Pollard, 2005), which display their highest activity during the BSw when compared to their activity across the other phases of the golf swing. Alongside trapezius activity, Kao *et.al.* (1995) also show notable activity from the levator scapulae and the rhomboids of the right arm (29 ± 19% and 30 ± 18%, respectively).

The lower and middle trapezius, as well as the levator scapulae exhibit moderate activity during the BSw to elevate and upward rotate the scapula (Escamilla and Andrews, 2009) whilst the right levator scapulae also aids the rhomboids to retract the scapular during the BSw then proceed to stabilise it throughout the rest of the swing (Kao *et.al.*, 1995).

The supraspinatus (approximately 45% MMT) was noted as being the 'only active muscle on the right side' during the BSw (Jobe *et.al.*, 1986, pp. 390) possibly causing abduction of the right arm and aiding the stabilisation of the shoulder complex (McChesney, 2004), however, lower activity was recorded by both Pink *et.al.* (1990) and Jobe *et.al.* (1989). To cause lateral right arm humeral rotation and to work in synergy with the supraspinatus to stabilise the shoulder, the right infraspinatus demonstrated similar activity levels to that of the supraspinatus throughout the BSw (Jobe *et.al.*, 1989; Pink *et.al.*, 1990). Both infraspinatus and supraspinatus activity in the right arm were highest during the BSw, firing around 25% MMT (Pink *et.al.*, 1990) and showed similar firing patterns after the commencement of the EFSw with infraspinatus activity dropping to 13 ± 16% MMT and supraspinatus activity falling to 14 ± 14% MMT (Jobe *et.al.* 1989), therefore indicating contributory activation only during the BSw and implying relatively low rotator cuff activity for the remainder of the swing (Escamilla and Andrews, 2009).

Jobe *et.al.* (1989) noted right arm posterior deltoid activity (17% MMT) as being a contributory factor to the BSw, moving the arm backwards and aiding the lateral rotation of the humerus. However, as the supraspinatus tendon and insertion is attached to the joint capsule of the shoulder, it begins to abduct the arm prior to contraction of the deltoid (McChesney, 2004), which may result in suppression of deltoid activity, especially as the BSw is not a strenuous activity (Escamilla and Andrews, 2009). Other muscular activity was recorded but was deemed low enough to be non-contributory to the backswing motion (< 15% MMT; Jobe *et.al.*, 1986).

In the left arm during the BSw of the golf swing, there was found minimal activity from all the muscles studied except for the subscapularis, which was reported as showing ‘marked’ activity of 33% MMT (Pink *et.al.*, 1990). Pink *et.al.* (1990) also showed activation of the left supraspinatus (21 ± 12% MMT) and of the left pectoralis major (21 ± 32% MMT), possibly aiding the adduction and medial rotation of the left upper limb during the BSw. Low levels of activity were also seen from the latissimus dorsi (17 ± 13% MMT), infraspinatus (14 ± 12% MMT) and the anterior deltoid (13 ± 13% MMT) (Pink *et.al.*, 1990).

There was little activity of the scapular muscles of the left arm throughout the BSw with the exception of the upper serratus anterior (30 ± 15% MMT) (Kao *et.al.*, 1995) and the lower serratus (27 ± 11% MMT) (Kao *et.al.*, 1995). It was also proposed by Kao *et.al.* (1995) that little left trapezius activity was recorded in the left arm as a consequence of allowing for scapular protraction. Moreover, this explanation was also attributed to account for the diminished levator scapulae and rhomboid muscle activity recorded for the duration of this phase (Kao *et.al*, 1995). Therefore it could be expected that pectoralis minor activity could be increased during this phase in order to anteriorly rotate the left shoulder as the left arm moves across the body, yet this has not yet been studied empirically.

2.6.2 Early forward swing

The muscle displaying the greatest amount of activation in the right arm during the EFSw (65% MMT) (Jobe *et.al.*, 1986) was the pectoralis major (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990). Activation of the pectoralis major would cause the flexion and adduction (McChesney, 2004) seen during the early downswing and aid the medial rotation of the arm, and subsequently the golf club, prior to the Acc phase. Also active, but firing at moderate levels (50 ± 38% MMT) were the latissimus dorsi (Jobe *et.al.* 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990) and the subscapularis (49 ± 31% MMT) (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990), both detailing activation to protract the scapula and to produce right arm adduction and internal rotation (Escamilla and Andrews, 2009).

Opposed to the pectoralis major, Clarys and Cabri (1993) found that the latissimus dorsi showed the greatest amount of activity in the downswing alongside marked activity from the triceps, increasing right elbow extension, with only moderate activity being collected from the pectoralis major accompanying the initiation of adduction and medial rotation of the upper right limb throughout this phase. Being the only segment of the deltoid to do so, the anterior deltoid showed an increase in activity from the BSw, rising from 5 ± 6% MMT to 21 ± 23% MMT (Jobe *et.al.*, 1989), however this was not described as being significant. Pink *et.al.* (1990) also documented activation of the anterior deltoid yet both the middle and posterior deltoids of the right arm remained firing at low levels throughout the EFSw (Jobe *et.al.*, 1989). Despite increases in activation, it was noted that all segments of the deltoid were still firing at only a minimal level throughout all phases of the golf swing (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989).

Kao *et.al.* (1995) attributed increased activation of both the right upper serratus anterior and lower serratus anterior (58 ± 39% MMT and 29 ± 17% MMT, respectively) to aiding scapula protraction, which subsequently stayed active for the remainder of the swing. Right arm activity of the upper and lower trapezius, initiated before the EFSw during the BSw, rapidly tapers off during the EFSw and remains low for the remainder of the swing phases to allow for right arm scapula protraction (Kao *et.al.*, 1995).

Despite showing little activity during the BSw phase, the rhomboids (46 ± 27% MMT) and the levator scapulae (38 ± 39% MMT) increase their activity into and throughout the EFSw to retract the scapula (Kao *et.al.*, 1995). The increases in activity indicate that these muscles play a role in stabilisation and control of the scapula rotation and protraction, possibly eccentrically, in the right arm (Kao *et.al.*, 1995). Despite reports by Pink *et.al.* (1990) and Kao *et.al.* (1995), it was documented that the pectoralis major (64% MMT) was the most active muscle during the EFSw, followed by the upper serratus (58% MMT) (Jobe *et.al.*, 1989).

The latissimus dorsi is the most active muscle on the left side during the EFSw (46 ± 25% MMT) (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989). There was more activation of this muscle during the EFSw than in any other phase of the golf swing; however this was not of a significant level (Pink *et.al.*, 1990). Left subscapularis activity was also recorded, dropping only slightly from 33% MMT during the BSw to 29% MMT during EFSw, and was the second most active muscle behind the latissimus dorsi (Jobe *et.al.*, 1989). Alongside subscapularis activity, marked activity of the supraspinatus and the posterior deltoid was recorded by Jobe *et.al.* (1989). However, the rhomboids (68 ± 27% MMT), the middle trapezius (51 ± 26% MMT) and the lower trapezius (49 ± 27% MMT) have also been shown to be highly active (Kao *et.al.*, 1995; McHardy and Pollard, 2005). The levator scapulae and rhomboid muscles show increases in activity from the BSw into the EFSw as the arms move the club towards ball contact to aid in scapula stabilization, retraction and elevation (Kao *et.al.*, 1995; Escamilla and Andrews, 2009). Data from Pink *et.al.* (1990) show that left infraspinatus and the left supraspinatus demonstrated the least amount of activity of the muscles they studied.

2.6.3 Acceleration

During Acc on the right side, the musculature recorded as being the most active were the latissimus dorsi (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Clarys and Cabri, 1993), the pectoralis major (Jobe *et.al.*, 1986; Jobe *et.al.*, 1990; Pink *et.al.*, 1990; Clarys and Cabri, 1993), both reaching values in excess of 100% MMT, and the subscapularis (Jobe *et.al.*, 1986; Jobe *et.al.*, 1990; Pink *et.al.*, 1990).

Bursts of muscle activity, such as seen from both the latissimus dorsi and the pectoralis major during Acc, can reach values in excess of 100% MMT as values obtained from MMT normalisation contractions are for a sustained effort (Jobe *et.al.*, 1986) and not from dynamic, ballistic muscular contractions. The latissimus dorsi and the subscapularis both fire at moderate levels during the EFSw before combining with the pectoralis major to produce power and therefore club head speed during Acc (Jobe *et.al.*, 1986). The major drive of the Acc phase (the timing of latissimus dorsi and pectoralis major activity) is such that the Acc phase drives the golf club toward its maximum potential velocity just prior to impact (Jobe *et.al.*, 1986). Thus, these muscles may be the most important muscles of the upper extremity for producing 'power' and acceleration of the arm during the golf swing (Escamilla and Andrews, 2009).

From these studies it appeared that these were the only three active muscles on the right side during the Acc phase, and consequently the only muscles to show increases in activity during this phase compared to the EFSw: from 52 to 112% MMT for the pectoralis major, from 44 to 82% MMT for the subscapularis and from 43% MMT to 81% for the latissimus dorsi (Jobe *et.al.*, 1989). However, right latissimus dorsi activation has been noted to drop between the EFSw and Acc, yet remained considerably more than was observed throughout the BSw and the EFTh, and was still the third most active muscle during Acc behind the pectoralis major and the subscapularis, respectively (Pink *et.al.*, 1990). Bilaterally, in the field hockey hit, the latissimus dorsi and pectoralis major appear to be most crucial for power development during the downswing (Murtaugh, 2000).

All other muscles, notably the supraspinatus, were found to demonstrate declines in activity. No other rotator cuff muscle or any deltoid muscle on the right side was significantly active during this phase (Jobe *et.al.*, 1989). However, Clarys and Cabri (1993) determined that muscular activity on the right side was not confined to the pectoralis major, latissimus dorsi and the subscapularis. They showed a marked activity burst from the triceps brachii prior to and at ball impact, causing late extension of the right elbow and possibly aiding wrist un-cocking in the latter part of the Acc phase. Also, Clarys and Cabri (1993) observed activity of the middle trapezius, posterior deltoid and the wrist flexors and extensors, perhaps aiding power production and club head velocity, stabilising the shoulder joint, or helping to un-cock the wrists.

Kao *et.al.* (1995) found significant activity of the upper serratus (69 ± 29% MMT) and lower serratus (51 ± 33% MMT) yet this was not compared to muscles demonstrating activity from other studies, as the focus of this research was solely upon scapular muscles. Serratus anterior activity, increasing from already marked activity during the EFSw, can be seen during Acc suggesting that increases in club head speed may be helped by a combination of protraction of the right scapula and trunk rotation (Kao *et.al.*, 1995).

Firing at levels in excess of 90% MMT, the muscles on the left side during Acc firing at high rates are the pectoralis major (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990), the latissimus dorsi (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990) and the subscapularis (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989). These are the only muscles demonstrably to do so (Jobe *et.al.*, 1986), with no other muscles showing considerable firing activity on the left side during Acc (Jobe *et.al.*, 1989).

Kao *et.al.* (1995), in their study of scapular muscles, found the most active muscle in the left arm during the golf swing to be the levator scapulae (62 ± 46% MMT), showing significantly more activation in this phase than at the extremes of the golf swing (Kao *et.al.*, 1995). The second highest activity was found from the rhomboid muscles (Kao *et.al.*, 1995) and activity was also found from all three portions of the trapezius to retract and upwardly rotate the scapular with the upper portion during Acc showing relative peak activity (Kao *et.al.*, 1995).

As a possible aid to wrist un-cocking, Abernethy *et.al.* (1990) noted activity from the left posterior deltoid in the late downswing, particularly prior to wrist un-cocking. 'The need to provide muscle force is accentuated by the fact that the reaction force at the wrist would tend to bring about an acceleration in the opposite direction to the one required by the shot' (Abernethy, *et.al.*, 1990, pp. 3). Therefore, the increased posterior deltoid activity and consequent muscular action is consistent with the need to continue to provide a torque around the shoulders in order to keep the upper arm moving in the direction of the target (Abernethy *et.al.*, 1990). A greater force will be applied to the hockey ball at impact if the joints of the arms are braced by muscle activity (Gros, 1979; Wein, 1979).

2.6.4 Early follow-through

During the EFTh the pectoralis major (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990), the latissimus dorsi (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*,

1990) and the subscapularis (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990) of the right arm continued to express high EMG activity, although the activity was slightly smaller in magnitude and the muscular contraction more eccentric when compared to the Acc phase (Escamilla and Andrews, 2009). These were the most active muscles during the EFTh, with the subscapularis the only muscle in the right arm to show increases from Acc (Jobe *et.al.*, 1986).

The infraspinatus, supraspinatus and anterior deltoid all show low levels of activity and the middle and posterior deltoids minimal activity (Jobe *et.al.*, 1986). The posterior was the most active portion of the deltoids yet still failed to fire significantly (17 ± 16% MMT). All other muscles showed minimal activity also (Jobe *et.al.*, 1989). Kao *et.al.* (1995) found comparatively low activation of all the scapula muscles on the right side, the highest being exhibited from the upper serratus (52 ± 18% MMT) and the lower serratus (47 ± 25% MMT). All parts of the trapezius fired between 23 and 26% MMT, rising from values obtained during Acc, and displayed more activity during this phase than in any other with exception of the BSw (Kao *et.al.*, 1995). Both the rhomboid muscles and the levator scapulae exhibited declining activity abating to 21 ± 12% MMT and 12 ± 12%MMT, respectively (Kao *et.al.*, 1995).

High subscapularis activity on the left side (>100% MMT) (Jobe *et.al.*, 1986) continues into the EFTh from the Acc phase (Jobe *et.al.*, 1989; Pink *et.al.*, 1990), while left pectoralis major activation and left latissimus dorsi activation both subside to moderate levels (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989). Alongside this, the infraspinatus was also found to be active (61 ± 32% MMT), showing significantly more activity throughout this phase of the golf swing than any of the first three (Jobe *et.al.*, 1989; Pink *et.al.*, 1990). Additionally, left anterior deltoid activity was more active during the EFTh (21 ± 25% MMT) and the LFTh than in any other swing phases and was most active of the three deltoids studied (Pink *et.al.*, 1990).

Of the scapular muscles of the left arm, activity was greatest from the levator scapulae (39 ± 26% MMT) (Kao *et.al.*, 1995) however, the magnitude of the activation during EFTh was significantly less than displayed during Acc. This was followed by activity of the upper trapezius (34 ± 29% MMT), maintained from the Acc phase, and the upper serratus (31± 18% MMT), which demonstrated no declines in activation from the previous swing phase (Kao *et.al.*, 1995).

Research into muscular activity during the golf swing asserts the concept of synchrony of movement of scapular muscles and the muscles of the shoulder girdle (Kao *et.al.*, 1995; Pink *et.al.*, 1990). Reinforcing the significance of specific roles that each muscle plays throughout the golf swing - each muscle plays its part at a given moment – the timing patterns of activity should assure rhythmic movement (Pink *et.al.*, 1990). These results of golf-EMG studies indicate that muscular synchrony is paramount to provide a fluid swing, consistent from the scapular muscles to muscles of the upper torso and upper limbs (Jobe *et.al.*, 1989; Pink *et.al.* 1990, Kao *et.al.*, 1995). Firing patterns of the scapular muscles demonstrate that the golf swing is a movement that requires neither extremes of ranges of motion nor extremes of muscular activity, but a balance of forces to present a normal swing (Jobe *et.al.*, 1989; Pink *et.al.*, 1990; Kao *et.al.*, 1995). Golf therefore, is not a strenuous arm activity thus revealing subsequently small contributions to activation patterns from the three deltoids bilaterally (Pink *et.al.*, 1990). Despite not eliciting maximal ranges of motion or muscular strength concerns, the golf swing is still a rapid and ballistic movement requiring the rotator cuff muscles to fire in synchrony to provide both ‘coordinated’ and ‘harmonious’ movement in order to protect the glenohumeral complex (Pink *et.al.*, 1990), as is reflected by the observed firing patterns of rotator cuff musculature (Jobe *et.al.*, 1989; Pink *et.al.*, 1990).

From further analysis of data, Pink *et.al.* (1990), proposed that there were identifiable and specific roles for each different muscle during the golf swing. Acting in concert, both the infraspinatus and supraspinatus provide most activity when ‘the club and ipsilateral shoulder are at the greatest height’ when the arm is in its maximum external rotation and slight abduction (Pink *et.al.*, 1990, pp. 140). As an external rotator (McChesney, 2004) the infraspinatus, when compared to the supraspinatus, has relatively high amplitude EMG throughout the swing. It is together though, that these muscles act to ‘approximate and stabilize the glenohumeral joint’ (Pink *et.al.*, 1990, pp. 140). The subscapularis as an internal rotator is differentiated from the infraspinatus and supraspinatus by displaying most activity during Acc (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990).

Pink *et.al.* (1990) concluded that the left arm is displaying greater internal rotation when compared to the right arm throughout the BSw, revealing higher magnitude EMG throughout this phase. Moreover, movement of the left arm is less pronounced in terms of internal rotation than in the right arm throughout the remainder of the swing and as a consequence of this, lower relative EMG amplitudes are observed (Pink *et.al.*, 1990). The right arm begins to move into internal rotation during the

EFSw and continues this throughout the concluding swing phases. Across the Acc phase, it was proposed that the right arm is moving internally the most forcefully (Pink *et.al.*, 1990).

It is notable during the EFSw and Acc phases that the power from the shoulder to drive the club head from the top of the golf swing towards ball contact is generated by the latissimus dorsi and the pectoralis major (Jobe *et.al.*, 1989; Pink *et.al.*, 1990; Okuda *et.al.*, 2002; Escamilla and Andrews, 2009). The latissimus dorsi contributes higher amplitude activity and thus its mechanical power to the golf swing during the EFSw and into Acc whereas the pectoralis major plays an increased role during Acc and EFTh (Pink *et.al.*, 1990; Escamilla and Andrews, 2009). It is proposed that the earlier activation of the latissimus dorsi is a consequence of its role as an internal rotator of the right arm (Pink *et.al.*, 1990), which is more prevalent during the EFSw. Additionally, the pectoralis major shows greater activity than the latissimus dorsi, and more activity than any other muscle, probably due to the dual role of adduction and internal rotation it has to perform to provide power to the swing (Pink *et.al.*, 1990).

Both Jobe *et.al.* (1986) and Jobe *et.al.* (1989) demonstrated data that concluded a relatively non-contributory role to the golf swing from any of the three deltoid muscles. Jobe *et.al.* (1986) demonstrated little deltoid activity in all phases of the swing, describing the swing as being unlike other upper extremity sports by presenting ‘a picture of deltoid quiescence and rotator cuff activity’ (Jobe *et.al.*, 1986, pp. 391). However, Pink *et.al.* (1990) concluded that the anterior deltoid was active on the right side during the EFSw and most active on the left side during the follow through; both these phases having ‘corresponding and reciprocal shoulder heights’ (Pink *et.al.*, 1990, pp. 140), thus it was concluded that the anterior deltoid assisted with both flexing and lifting of the arm during the golf swing. Moreover, integrated EMG collected by Abernethy *et.al.* (1990) show that the left posterior deltoid is ‘extremely active’ in the late part of the downswing – in the latter of the Acc phase – particularly as wrist un-cocking occurs. The role of the deltoids therefore, remains questionable.

Serratus anterior firing patterns appear similar in both the upper and lower portions in both the left and right arms (Kao *et.al.*, 1995). Kao *et.al.* (1995) noted that this was to be expected due to the lack of shoulder elevation during the golf swing, affirming the assumption made by Jobe *et.al.* (1989) and Pink *et.al.* (1990). In sports such as swimming and baseball pitching that elicit higher shoulder elevations and increased upwards rotation in comparison with the golf swing, differences have been recorded between the upper serratus and lower serratus (DiGiovine *et.al.*, 1992; Pink *et.al.*, 1991; Scovazzo *et.al.*, 1991). As each phase of the golf swing progresses, it is the synchronous action of the medial scapula retractor muscles and the protractor muscles that work to rotate, elevate, protract and retract the scapula (Kao *et.al.*, 1995).

Similarly, in baseball pitching, peak scapular muscle activity was high during the arm cocking and arm deceleration phases of the pitch with peak EMG activity of the serratus anterior being recorded at 69-106% MVIC, peak upper, middle and lower trapezius activity being 51-78% MVIC, peak rhomboid activity 41-45% MVIC and peak levator scapulae activity 33-72% MVIC (Escamilla and Andrews, 2009, pp.

588). Like the golf swing, the baseball pitch exemplifies and utilises ‘a synchronous coiling and uncoiling motion to maximise performance’ (Kao, *et.al.*, 1995, pp. 23).

In actions similar to that of the baseball pitch, during the windmill softball pitch serratus anterior activity peaked at approximately 60% MVIC, during the tennis serve and forehand and backhand volley, approximately 75% MVIC and during baseball hitting, approximately 30-40% compared to approximately 70% MVIC during the golf swing (Escamilla and Andrews, 2009, pp. 588). Shoulder muscle activity in other upper extremity sports was also high. Rotator cuff activity was high to resist distractive forces in excess of 100% bodyweight during arm cocking and deceleration during overhead throwing (Escamilla and Andrews, 2009). In baseball pitching during arm cocking, rotator cuff activity was shown to peak at 49-99% MVIC and peak at 37-84% MVIC during the arm deceleration phases (Escamilla and Andrews, 2009). 41-67% MVIC was peak rotator cuff activity in American football throwing during arm cocking and 86-95% MVIC during deceleration (Escamilla and Andrews, 2009). Escamilla and Andrews (2009) also noted high rotator activity in the windmill softball pitch (75-93% MVIC), the volleyball serve and spike (54-71% MVIC) and during baseball hitting (28-39% MVIC), compared to the golf swing which educed 28-68% MVIC.

2.7 EMG Analysis

In the current literature there is a lack of specific information on the electrode placement sites and on the methodologies, such as the MVC test position used to determine the MVC reference values used for normalisation purposes. Moreover, EMG signal processing techniques are again largely overlooked with information on rectification and the filtering of the raw EMG signal remaining unreported. Therefore, the rigor with which EMG data has been previously collected remains questionable. From a methodological viewpoint, precautions must be taken to quantify and normalise EMG data and to limit the impingement of the EMG equipment on the performance of the swing.

2.7.1 Fine wire and surface EMG

When recording EMG data, the choice of the type electrode to be used depends largely upon the muscles under investigation. For larger, superficial muscles, surface electrodes should be used, whereas for small superficial muscles or for muscles situated under others, intramuscular electrodes should be used (Türker, 1993). Both types of electrodes have advantages and disadvantages. Fine wire electrodes can record EMG from muscles located deeper in the body and can also record motor unit activity (Rudroff, 2008) depending on the size of the uninsulated active area of the injected electrode (Türker, 1993). Alongside giving access to deep musculature, fine wire EMG is extremely sensitive and can record single muscle activity with a lower concern for cross-talk detection (Rudroff, 2008). Because of this, for EMG recordings of thin or deep muscles, the use of fine wire electrodes are preferable to surface electrodes. However, fine wire EMG is invasive and can cause discomfort to the participant (Rudroff, 2008), which could subsequently alter kinematic patterns of the movement under observation. Moreover, fine wire EMG can only cover a small detection area and presents problems in the repositioning of electrodes. Therefore, in most EMG investigations focusing on superficial musculature, surface electrodes are used due to their non-invasive nature (Konrad, 2005). Surface EMG, however, has its own limitations.

2.7.2 Factors influencing the amplitude of the sEMG signal

A drawback of any EMG analysis is that amplitudes recorded are subject to influences that can vary between given detection conditions. Recorded EMG amplitudes can be different from one experimental session to the next, despite using similar methodological procedures (Türker, 1993). Since EMG is often used as an indicator of muscle activity it is important to appreciate the factors that can affect the fidelity of the EMG signal.

DeLuca (1997) grouped the factors that affect the EMG signal into a number of categories. The factors that affect the EMG at a basic level have been categorised as intrinsic and extrinsic factors (DeLuca, 1997). Extrinsic factors are associated with the electrode structure and placement. The electrode shape and size of the detection zone determines the number of motor units that are detectable, due to the number of muscle fibres in the detection zone. Larger detection zones render the sEMG electrodes more susceptible to cross talk due to the volume conduction of neighbouring musculature, making their use for measuring smaller, thinner musculature undesirable (Konrad, 2005). Alongside this, the location of the electrode with relation to the lateral edge of the muscle is also a determinant of the amount of crosstalk that could be detected by the electrode (DeLuca, 1997). Moreover, the orientation of the electrode with respect to the underlying muscle fibres affects the measured conduction velocity of the action potentials and, consequently, the amplitude of the signal (DeLuca, 1997). It is clear therefore that when placing EMG electrodes it is best to ‘keep constant as many conditions as possible between recording sessions and among subjects to minimise variability' (Robertson *et.al.*, 2004, pp. 170).

Intrinsic factors are the physiological and anatomical factors that can affect the EMG signal (DeLuca, 1997). DeLuca (1997) lists them as being: the number of active motor units at a given time that contributes the amplitude of the signal; the fibre type composition of the muscle; the fibre diameter which influences the amplitude and conduction velocity of the action potentials that make up the signal; the depth and location of the active fibres with respect to the electrode detection surface; and the amount of tissue between the surface of the muscle and the electrode, including the skin-electrode impedance which will also differ between electrode applications, which may affect the shape of the underlying MUAPs (Burden, 2008).

During dynamic muscular contractions, which result in conditions where both force and posture may change (Farina, 2006), three main influences emerge that can affect the collection of EMG: the extent of signal nonstationarity, the comparative electrode dislocation due to muscle migration with respect to action potential origin (Konrad, 2005), and conductivity changes of the tissue separating the muscle fibres and the electrode (Farina, 2006). In addition to this, these influences may be more prevalent as the ballistic nature of the movement increases (Egret, 2004) or when greater ranges of motion are utilised, which could further exacerbate the issues raised by DeLuca (1997).

Despite the practical issues involved with sEMG data collection and analysis under dynamic test conditions, its importance within movement analysis has led to its widespread use with numerous relevant applications (Farina, 2006). However, precautions must be taken to quantify and normalise EMG data and to limit the impingement of the EMG equipment on task performance.

2.7.3 Normalisation

Due to the numerous factors that influence EMG signals, absolute EMG amplitude recordings are not necessarily reliable for analysis (Farina, 2006). Thus, EMG research is limited by the difficulties that arise in making comparisons between values obtained from the same muscle from the same participant on different testing occasions, different muscles of the same participant or the same muscle in different participants (Kelly *et.al.*, 1996). However, if the sEMG data are normalised, it is possible to make quantitative evaluations between participants as this reduces the variability of the EMG recordings (Türker, 1993), reduces the influence of detection conditions (Konrad, 2005) and circumvents the problems of comparison (Kelly *et.al.*, 1996) whether inter or intra participant (Burden, 2010). Therefore, EMG signal normalisation is essential for making accurate comparisons between test sessions, muscles and participants (Kelly *et.al.*, 1996; Burden and Bartlett, 1999).

All normalisation techniques have in common the conversion of absolute EMG signal recordings from microvolts into relative values based upon comparison with a measure of reference muscular electrical activity (Kelly *et.al.*, 1996; Konrad, 2005; Burden 2010) obtained during standardised and reproducible conditions (Mathiassen *et.al.*, 1995). Amplitude normalization only changes the 'Y-axis' scaling, not the 'shape' of the EMG traces (Konrad, 2005).

The Peak and the Dynamic Mean of the task EMG signal can both be used as a reference value (Konrad, 2005) whereby each task EMG data point is divided by either the peak or the mean EMG recorded during the same task (Burden, 20008). Both Yang and Winter (1984) and Burden *et.al.* (2003) reported that the most effective way of improving group homogeneity is to use either the Dynamic Peak or the Dynamic Mean normalisation methods. Despite this, Knutson *et.al.* (1994) reported that EMG records obtained from the gastrocnemius were more reliable when they were normalised to a maximal isometric reference contraction as opposed to either Peak or Mean dynamic EMG data. Moreover, Burden (2008) states that neither the Peak nor the Mean Dynamic methods can be used when comparing the amplitudes from different muscles and different individuals as any innervation level information is eliminated when EMG is normalised in this way (Konrad, 2005).

Within the scientific literature, the most prevalent practice for normalisation has involved expressing points of the processed task EMG as a percentage of the peak EMG from an isometric MVC (MVIC) (Burden, 2008) of the same muscle, whereby the peak EMG is collected from an arbitrary mid-range joint angle (Burden, 2010). In addition to allowing comparison of EMGs from different muscles, Burden (2010) notes that normalising task EMG to a maximal reference contraction could also allow for assessment of what percentage of the maximal activation capacity of a muscle the task EMG represents.

The use of MVICs has, however, been criticised. Clarys (2000) found that Isometric MVCs are limited by the poor reliability of the EMG recorded. This would therefore render the MVIC method unreliable and its value for comparing normalised EMG and a muscle's activation required to perform the movement under observation limited. Furthermore, De Luca (1997) advocates the use of EMG traces from contractions below maximal level (less than 80per cent MVC) to produce more stable reference values from which normalisation can take place in comparison with the MVIC method. When the focus of the investigation is towards muscular activation, there has been debate as to whether or not a MVIC actually elicits the maximal capacity potential of a muscle (Burden, 2008). Outputs from the MVIC method of normalisation have been shown to be in excess of 100 per cent and this, as Burden (2008) notes, therefore signifies amplitude recorded during a single task can be larger than amplitude recorded during the isometric normalisation contraction (e.g. Jobe *et.al.*, 1994; Farber *et.al.*, 2009).

Alongside isometric MVCs, the use of other maximal amplitude-based MVC normalisation techniques is also debatable. Collected during a maximal contraction of an individual muscle whilst performing a dynamic MVC with the same muscle kinematics, the Isokinetic MVC method, despite accounting for changes in muscle length and shortening rate, was found to be only minimally different in its output compared to Isometric MVC normalisation output (Burden and Bartlett, 1999; Burden *et.al.*, 2003).

The MVIC method has been shown to produce more reliable reference values than those obtained from non-isometric voluntary contractions with the same muscle action and joint angle as the task EMG (Rouffet and Hautier, 2008), from isokinetic voluntary contractions with the same demands as the task EMG (Burden *et.al.*, 2003) and from peak EMG from sub-maximal isometric voluntary contractions (Lehman, 2002).

Nieminen (1993) and Westgaard (1988) recommended that normalisation tests should be performed in a postural position equivalent to the mid range of the movement. However, they neglected to specify explicit test positions for the performance of maximal isometric contraction normalisation tests. Despite MVC normalisation providing an estimation of ‘invested’ neuromuscular effort (Konrad, 2005), predetermined identification of specific MVC test positions that reproducibly illicit maximal muscular innervation have not been discussed in detail (Kelly *et.al.*, 1996). Comparison of EMG from isometric MVCs has shown that joint angle has little effect on maximal EMG. Moreover, the modes of contraction and muscle/joint kinematics have not yet been proven to affect EMG-angle and angular velocity relationships (Burden, 2010). Therefore the use of isokinetic MVC methods that recreate task conditions over isometric, arbitrary joint angle MVC methods remains unjustified (Burden, 2010).

Resent research suggests that the use of isometric MVCs utilising a mid-range joint angle, will provide results with good reliability and no strong evidence exists to suggest that isokinetic MVC methods are preferable to isometric methods (Burden, 2010). If the study is interested in how active a muscle is in relation to maximal activation, then an MVIC can be used to provide an indication of this, as well as to compare EMG traces across participants and muscles as both ISEK (Merletti, 1999) and SENIAM (Merletti *et.al.*, 1999) recommend.

2.7.4 sEMG hardware

The sEMG hardware itself has been found to impact upon the detection of the EMG signal. The participant's range of motion and freedom of movement could be restricted due to the wearing of 'cumbersome' EMG equipment (Egret *et.al.,* 2004). Results form Egret *et.al.*, (2004) indicated that EMG equipment induced changes in muscular activity patterns during performance of the golf swing when sEMG electrodes are attached and related auxiliary hardware worn. There were significantly greater shoulder joint angles attained at the top of the backswing when not wearing EMG equipment, with lesser joint angles attributed to eventual cable tension on the electrodes for trials where EMG hardware was worn. Moreover, right elbow flexion amplitude was greater for the swings with EMG than those without EMG at both ball address and at the top of the backswing. Again, it was assumed that cable tension was the cause of this difference. Alongside this, EMG equipment also slowed club head speed before ball impact.

Despite these changes, the wearing of EMG equipment induced no changes in the timing of the golf swing. These results therefore signify the importance of electrode wire placement (Egret *et.al.*, 2004). If electrode wire placement is carefully controlled it should reduce the extent to which EMG hardware might affect the kinematics of the swing when under observation, particularly at the extremes of ranges of motion exhibited.

2.7.5 Issues with golf based EMG

All current EMG studies of shoulder musculature during the golf swing use indwelling electrodes (Jobe *et.al*., 1986; Jobe *et.al.*, 1989; Pink *et.al*., 1990; Kao *et.al*., 1995), which could affect the comfort of the participant, possibly altering the mechanics of the golf swing. No studies exist in the literature that use surface electromyography (sEMG) to assess shoulder muscle activity, despite sEMG being considered less invasive than fine wire EMG and more representative of the overall myoelectrical activity produced by a muscle (Marta *et.al.*, 2012).

Jobe *et.al.* (1986) classified golf swing muscular activity into four categories; minimal activity, low level, moderate and marked activity. These categories though are arbitrary and based upon little more than the opinion of the researcher. No justification was provided as to the choice for the 'cut-off' for each category and the definitions not based upon the contribution of activity, but only to the amount of activity recorded. To categorise EMG activity levels into such bands neglects the temporal aspects of the EMG signal or the contribution of the activity to the kinematics of the swing. Moreover, no indication is given as to when a muscle becomes active or ceases it's activation, which could further detail timing pattern similarities or disparities. Furthermore, little kinematic data is provided to accompany EMG data, resulting in very few links being made between recorded muscular activity and the mechanics of the motion under analysis.

2.8 The role of segmental interactions

EMG-based studies also ignore the important role which segmental interactions have been shown to have on movement. As demonstrated by Putnam (1993), a muscle may not necessarily need to be active for a joint to move. Joint forces may be caused by the interaction or acceleration of other segments in a system. 'The interactive moments resulting from the forward acceleration of the proximal segment and/or the linear acceleration of the proximal end of the extremity play large roles in causing the initial backwards acceleration of the distal segment' (Putnam, 1993, pp. 134). If the angular acceleration of a joint is in a given direction, the accompanying joint moment does not necessarily have to be in the same direction. This would have the effect of causing more distal segments, in turn, to lag behind more proximally accelerating ones. Moreover, more distal segments would need to resist the angular velocity and joint moment dependent interactions of a more distal segment angular acceleration, which would cause the proximal segment to decelerate (Putnam, 1993). In overarm pitching, lateral rotation of the shoulder and elbow flexion at the onset of forward rotation has been seen to cause the forearm and hand to lag behind the elbow and the shoulder (Putnam, 1993). Similar lagging of the pitching arm behind the trunk during overhead pitching has been observed by Escamilla and Andrews (1999) and of the tennis racquet during the serve, again attributed to lower extremity and trunk rotation (Elliott *et.al.*, 1986). Consequently, high muscle activity of the shoulder is needed to keep the arm moving with the rapidly rotating trunk as well as to control shoulder external rotation (Escamilla and Andrews, 1999). These assumptions, though, are based upon single-handed techniques with greater amounts of shoulder abduction than seen during the field hockey hit.

The contributions of segmental interactions to the hockey hit have not been discussed in the scientific literature. Moreover, muscular activity throughout the field hockey hit would have to contribute to the creation of the desired movement, brought about by performance demands, as well as resisting the segmental joint moments, torques and the lagging of more proximal segments, generated by segment interactions during the hit.

3. Methodology

3.1 Participants

Ten male university standard hockey players volunteered for this study. Prior to testing, each participant was given an information sheet outlining the nature of the project (Appendix 1.). Participants completed an informed consent form (Appendix 2.) and were screened for injury by the completion of a physical activity readiness questionnaire (PAR-Q) (Appendix 3.). Ethical approval for this study was granted by the Ethics committee of the School of Sport and Exercise Science at the University of Lincoln. All testing was conducted indoors in the Human Performance Centre at the University of Lincoln. The mean age, height, mass and playing experience of the participants were 21.3 ± 3.1 years, 180.3 ± 3.8 cm and 76.16 ±10.28 kg and 7±3 years, respectively. All participants were free from injury at the time of testing and were right handed.

3.2 Electromyographic set-up

Based on previous EMG studies of various swing motions and the limitations of surface EMG to collect EMG form smaller, thinner or deeper musculature, the muscles investigated in this study were the biceps brachii, triceps brachii (lateral head), anterior deltoid, posterior deltoid, upper trapezius, latissimus dorsi and clavicular and sternal heads of the pectoralis major. All muscles were monitored bilaterally.

Prior to electrode placement, and after location of the muscle electrode placement site as detailed by Cram *et.al.* (1998), the skin-electrode interface for each muscle detection site was rubbed vigorously and cleansed with an alcohol wipe to reduce skin impedance and to aid adhesion of the electrodes (DeLuca, 1997). Sixteen DE-2.3 single differential, rectangular, Ag sEMG electrode sensors with an inter-electrode distance of 10 mm (Delsys Inc, Boston, MA, USA) with pre-amplifier gain of 1000V/V were attached to skin muscle sites for the eight muscles on each side of the body (Appendix 4.). All electrodes were orientated parallel to the underlying muscle fibres and positioned to remain over the belly of the muscle for as much of the expected range of motion as possible. As reference electrodes, two Dermatrode HE-R (American Imex, CA, USA) round electrodes of 5.08cm diameter were attached to the skin at electrically neutral locations over the greater trochanters of the left and right femurs (Rutkowska-Kucharska *et.al.*, 2009).

The pre-amplified lead wires were connected to a Myomonitor IV Wireless Transmission & Data-logging System (Delsys Inc., Boston, MA, USA), which was worn around the waist of the participant, positioned so as not to restrict the range of motion of the participant or to obstruct the hitting motion. Loose lead wires were taped together but not taped to the body as pilot testing suggested the latter contributed to greater movement artefact being detected. All EMG data were sampled at a rate of 2000Hz, were transmitted wirelessly and recorded using EMG Works 3.6 Acquisition (Delsys Inc., Boston, MA, USA) computer software.

Behavioural tests, outlined by Cram *et.al.*, (1998), by which voluntary muscle activation was induced for each muscle were conducted to confirm correct placement for each electrode, to check for signal contaminants such as volume conduction, and to verify the quality of the preparation of the skin-electrode interface to ensure the fidelity of the recorded signal (Burden, 2008).

3.3 Motion analysis set-up

Passive, spherical retro-reflective markers of 16mm diameter were affixed bilaterally to the skin of the participant using double-sided adhesive tape over the acromion process, the medial and lateral epicondyles of the humerus, and the ulnar and radial styloid processes. Two hockey sticks, one 0.927 m long (mass 0.575 kg) and the other 0.953 m (mass 0.595 kg) were used in this study. Four tracking markers were attached onto the shaft along the midline of each stick; two were placed on the anterior, or flat side, 0.1 m and 0.5 m proximally from the distal end of the stick shaft, and two on the posterior, or curved, side, 0.1 m and 0.5 cm proximally from the distal end of the stick shaft. These markers were termed the anterior stick shaft, the anterior stick grip, the posterior stick shaft and the posterior stick grip, respectively. One additional marker was attached to the stick face during a static trial only at the position ball impact was expected to take place. All participants used one of the pre-markered hockey stick for their hits, chosen dependent upon the length of their usual playing stick. A $1cm^2$ piece of retro-reflective tape was attached to a non-dimpled field hockey ball that complied with International Hockey Federation regulations (FIH, 2012).

Eight ProReflex MCU500 motion capture units (Qualisys, Gothenburg, Sweden) were orientated to capture the whole of the hit motion, sampling at a rate of 240Hz. The origin of the system was at ground level below the centre of the ball at its pre-impact position and the global reference frame was orientated so that the X-axis ran horizontal and parallel to the target line, the Z-axis was vertical and the Y-axis was the cross product of **X** and **Z**. The capture volume extended 2.5 m in the X-axis, 3 m in the negative X-axis, 2 m in the Y-axis, 0.3 m in the negative Y-axis, 2.5 m in the Z-axis and 0 m in the negative Z-axis. All motion capture data was recorded using Qualisys Track Manager (QTM) (Qualisys, Gothenburg, Sweden). Calibration was conducted using a calibration wand 500 mm in length and the cut-off for residuals was 0.4 mm.

3.4 Synchronisation

A Myomonitor IV tethered trigger module (Delsys Inc., Boston, MA, USA) was connected to the Myomonitor datalogger. A 5V leading edge output pulse emitted by the trigger module as EMG collection started was A/D converted before being inputted to a MCU500 motion capture unit, where it was recorded alongside the motion capture data as an analogue channel in QTM. The timing of the leading edge of the output pulse was subsequently identified to allow synchronisation of the EMG and motion analysis data.

3.5 Data Collection Protocol

After ensuring neither the EMG nor motion analysis equipment restricted their range of movement, each participant was allowed to warm up by exercising until they felt comfortable. EMG data were then collected during functional Maximum Voluntary Contraction (MVC) tests for each muscle under observation. These tests consisted of three 5 second static, full effort contractions, with a rest period of 30 seconds between each contraction, and were adaptations of both functional MVC test position exercises and EMG behavioural tests documented by both Konrad (2005) and Cram *et.al.* (1998) (Appendix 4.).

A 5 s static trial was then recorded with the participant holding the hockey stick in his right hand and standing in the anatomical position. This trial was used for marker identification and to determine the stick face marker's position relative to the four permanent stick markers, for use in reconstruction of the stick face marker's path during subsequent dynamic trials (see below). Once the static trial was collected, the retro-reflective marker on the stick face was removed and a second warm up period was permitted where participants were allowed to perform unlimited practice hits until they felt comfortable with the execution of the experimental task. Before hitting the hockey ball, it was orientated so that the ball marker was positioned parallel with the negative Y-axis was visible to the camera system setup.

Participants hit a stationary hockey ball utilising a single step approach and 'classic drive' technique (England Hockey, 2005) from a 3 m by 2 m piece of synthetic cricket matting into an indoor net. To standardise the task, the ball was stationary and the participants were allowed only to take a single step during their approach to the ball. All participants were instructed to hit the ball with maximum possible velocity in a straight line. Each subject performed five, full effort hits during which synchronised EMG and motion capture data were recorded.

3.6 Data Analysis

3.6.1 Kinematic data

Identification of the markers in the static and dynamic trials was performed in QTM. Positional data were then exported to MATLAB 7.11.0 (R2012b, MathWorks Cambridge, UK) where all kinematic analysis and digital signal processing was performed using custom-written code. The XYZ coordinate data for all landmarks were smoothed using a 4th order Butterworth filter with zero phase lag with a cut off of 12Hz (Mitchell *et.al.*, 2003).

A virtual distal stick landmark was calculated as the mid-point between the anterior and posterior distal stick shaft markers. A second virtual proximal stick marker was calculated as the mid-point between the anterior and posterior proximal stick shaft markers. The vector running from the proximal to distal virtual stick shaft markers defined the longitudinal axis of the hockey stick. Virtual elbow and wrist joint centres were also created for each arm, half the distance between the medial and lateral humeral condyles and half the distance between the ulnar and radial styloid processes for the elbow and wrist joints, respectively.

The location coordinates of three of the stick markers were used to calculate the 3-dimensional coordinates of the virtual stick face. A stick-based coordinate system was defined for each frame of the trial, the origin of the system being the mean position of the four tracking markers. $\mathbf{X_s}$ pointed from the mean position of the four tracking markers to the anterior proximal stick marker. The cross product of $\mathbf{X_s}$ and a vector pointing from the mean tracking marker position to the posterior stick shaft marker gave $\mathbf{Z_s}$. The cross product of $\mathbf{Z_s}$ and $\mathbf{X_s}$ gave $\mathbf{Y_s}$.

The position of the stick face marker was calculated in the stick coordinate system at each instant, before the mean of the X_s, Y_s and Z_s values were taken across the static trial. These offsets were then used to reconstruct the stick face location in each frame of the dynamic trial from the direction of the stick-based coordinate system axes and the projection of the average offsets along these axes, allowing quantifiable tracking of the stick face for determination of the transition of the stick face between each swing phase.

3.6.2 Swing phases

The hit motion was broken down into four phases; the Backswing, the early forward swing, acceleration, and the early follow-through (McHardy and Pollard, 2005). These phases were identifiable in all of the hits of all of the participants. Analysis of the hit motion began at the start of the backswing, which was defined as the instant at which the virtual stick face displayed its first movement in the negative X direction (Franks *et.al.*, 1985). The frame at which the virtual stick face commenced its final uninterrupted increase in speed through to impact (Willmott and Dapena, 2012) was defined as the top of the swing (the transition between the backswing and the early forward swing). The frame in which the longitudinal axis of the stick was closest to horizontal marked the transition between the end of the early forward swing and the commencement of the acceleration phase. Ball impact and the end of the acceleration phase was defined as the last instant before the ball marker first moved. After ball impact, the frame in which the longitudinal axis of the stick was closest to horizontal defined the end of the early follow-through phase. Inter-participant differences in the times that each swing phase took to complete were normalised by interpolating both joint angle data and EMG amplitude data to 100 samples per swing phase, thus giving EMG data at the same time-normalised instants as the kinematic data.

3.6.3 Elbow and wrist angles

For each frame of the dynamic trials, on both sides of the body, unit vectors were created running from the mid-elbow to the acromion and from the mid-elbow to the mid-wrist. The elbow angle was calculated as the inverse cosine of the dot product of these two unit vectors. The angle between the forearm and the stick was calculated as the cosine of the dot product between the unit vector running from the mid-wrist to the mid-elbow and a unit vector parallel to the longitudinal axis of the stick and was termed the 'wrist angle'.

3.6.4 EMG analysis

All raw EMG signals were band-pass filtered automatically by the Delsys datalogger with a bandwidth of 20 – 450Hz. For each static EMG signal, starting at each EMG sample, the RMS of the following one-second period was calculated. The peak MVC amplitude of each static EMG signal was then calculated as the RMS of the one-second period demonstrating the largest sustained maximal muscle amplitude activation from the three contractions for each muscle.

For each muscle, the dynamic EMG signal was full wave rectified and smoothed using a 4^{th} order Butterworth filter with zero phase lag with a low-pass cut-off frequency of 50Hz (Kamen and Gabriel, 2009). Both time and amplitude normalisations were performed for each EMG channel at each instant of the dynamic trials. After calculation of the duration of each swing phase and synchronisation of the motion capture data with the dynamic EMG data, dynamic trial EMG samples were ascertained for the same synchronised duration of each swing phase. These

EMG data were then linearly interpolated to 100 samples per swing phase to generate time-normalised EMG amplitudes at 1% intervals of each swing phase. The time-normalised EMG samples were then normalised to their respective MVCs before mean percentage of MVC activation across participants was ascertained.

4. Results

Participants in this study utilised both of the swing techniques described by Willmott and Dapena (2012). Eight of the participants adopted the ‘straight’ backswing hit, with the remaining participants preferring the ‘looped’ backswing hit. As the backswings of each type of hit elicited minimal levels of muscular activity, it was chosen that, for this study, muscular activity from both swing types would be combined for analysis.

4.1 Elbow and wrist joint kinematics

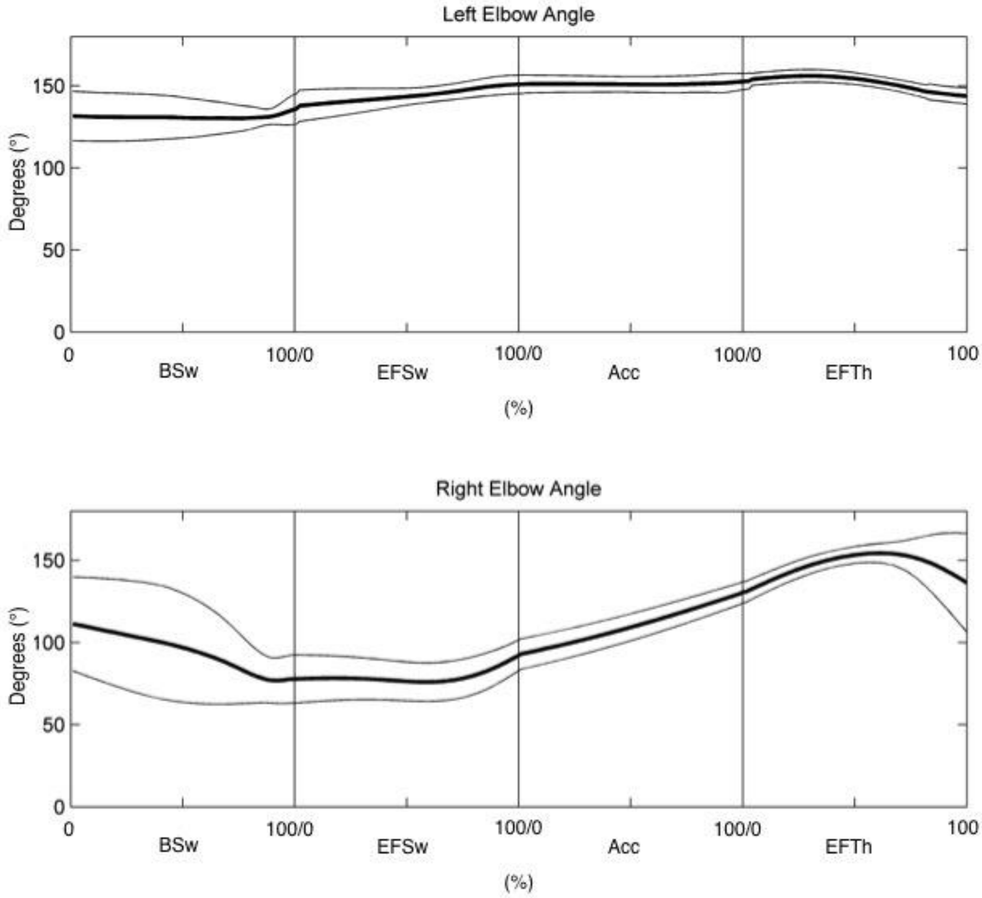


Figure 3. Left and right elbow angles during the field hockey hit. The values shown are the mean angles across all participants for each normalised percentage of each swing phase ± SD, whereby 180 degrees is full extension.

At the commencement of the BSw, left and right elbow angles were 133° and 111°, respectively (Figure 3.). This level of extension of the left elbow was apparent for the first 90% of the BSw at which point the left elbow began to extend slightly. For the duration of the hit, the left elbow remained more extended than the right elbow. The left elbow angle remained relatively constant as wrist 'uncocking' occurs, from the late EFSw through to the first 10% of the EFTh, and especially during the Acc phase. At impact with the hockey ball, the left elbow angle was 154°.

The right elbow moved into flexion from the initiation of the hit up until approximately 80% of the BSw. It, however, did not extend immediately from this point but maintained flexion of approximately 78° through to 75% of the EFSw. At this point the right elbow started to extend again, the commencement of which corresponded with the timing of wrist 'uncocking'. Extension continued throughout the Acc phase with the right elbow reaching approximately 130° at impact. The angle reached its maximum value of 152° during the mid EFTh.

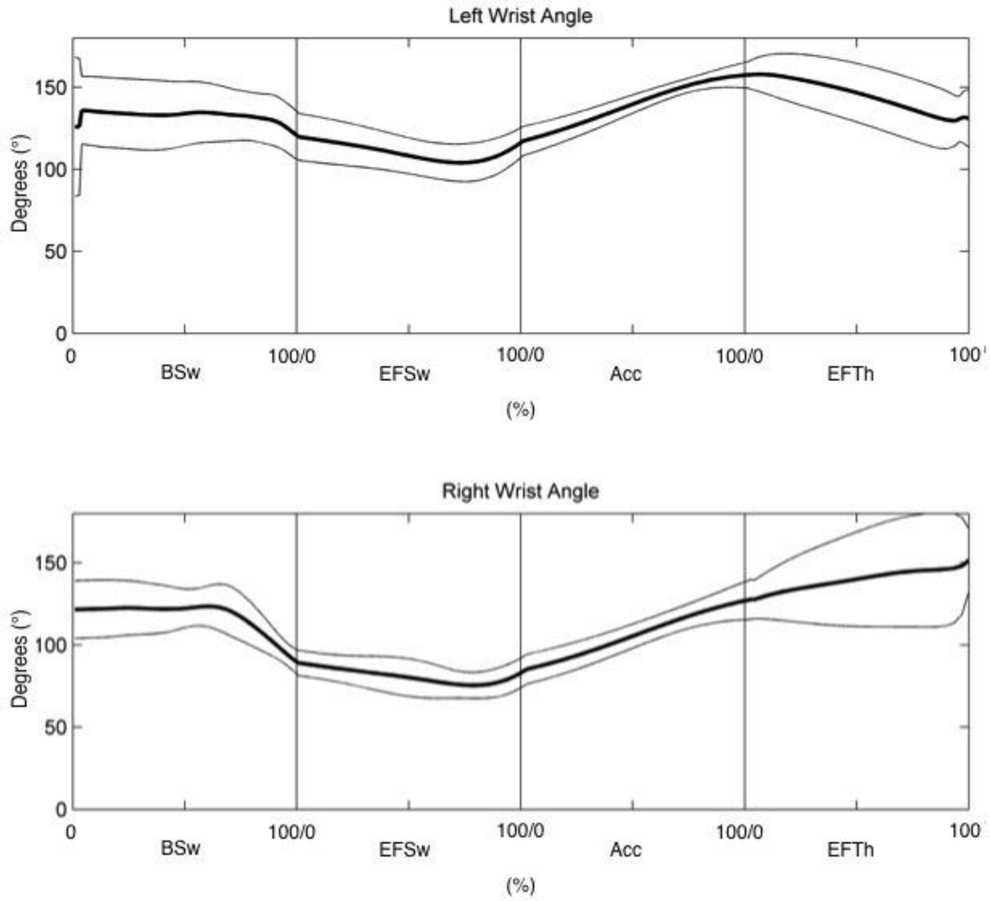


Figure 4. Left and right wrist angles during the field hockey hit. The values shown are the mean angles across all participants for each normalised percentage of each swing phase ± SD, whereby 180 degrees is full extension.

Up until ball impact, the both the left and right wrist angles followed the same pattern of increasing and decreasing. The degree of 'cocking' and 'uncocking' of the wrists also appeared similar and was relative to the initial wrist angles at the initiation of the hit. Wrist angle at the start of the BSw was 136° and 121° for the left and right wrist, respectively. The left wrist angle remained greater than the angle of the right wrist due to the fact that the left hand was placed more proximally on the stick grip than the right hand and that the hockey stick was drawn to the right during the BSw before being swung from left to right during the downswing.

For approximately the first 60% of the BSw, the wrists maintained their initial angle before beginning to cock for the remainder of the BSw. From the top of the swing, the angle of both wrists increased during the EFSw and reached values of 104° for the left wrist and 75° for the right wrist at 70% the duration of the EFSw. The wrist angles then began to immediately become greater and continued to do so throughout the Acc phase to reach 157° and 127° at impact for the left and right wrists, respectively. This uncocking of the wrists is concurrent with the time over which the right elbow demonstrated extension and the left elbow angle appeared to become more ‘fixed’ (Figure 4.). At the start of the EFTh, the left wrist angle demonstrated decreases whilst the right wrist angle continued to increase for the duration of this phase. It appeared, therefore, that the wrists worked together for the first three phases of the hit, up until ball impact and worked differently to aid the deceleration of the stick during the follow through.

4.2 Muscle Activity

Table 1. Peak normalised amplitude of muscle activity by swing phase during the field hockey hit (peak mean ± SD% MVC across all participants)

Muscle		Swing Phase			
		BSw	EFSw	Acc	EFTh
Left	Biceps brachii	7 ± 3	33 ± 68	31 ± 34	30 ± 19
	Triceps brachii	12 ± 21	60 ± 45	49 ± 39	25 ± 25
	Anterior deltoid	18 ± 17	19 ± 25	50 ± 49	50 ± 49
	Posterior deltoid	16 ± 25	49 ± 30	35 ± 26	25 ± 21
	Upper trapezius	22 ± 39	85 ± 88	81 ± 48	61 ± 69
	Latissimus dorsi	62 ± 59	153 ± 120	102 ± 90	33 ± 30
	Clavicular p. major	16 ± 19	45 ± 37	67 ± 62	42 ± 28
	Sternal p. major	17 ± 18	57 ± 73	54 ± 42	61 ± 145
Right	Biceps brachii	14 ± 21	3 ± 3	11 ± 16	11 ± 15
	Triceps brachii	43 ± 39	81 ± 37	67 ± 63	26 ± 23
	Anterior deltoid	100 ± 81	115 ± 124	64 ± 76	26 ± 32
	Posterior deltoid	10 ± 13	8 ± 12	12 ± 15	15 ± 18
	Upper trapezius	35 ± 37	17 ± 13	51 ± 69	38 ± 37
	Latissimus dorsi	54 ± 52	88 ± 85	79 ± 70	72 ± 78
	Clavicular p. major	40 ± 36	76 ± 66	66 ± 70	26 ± 21
	Sternal p. major	29 ± 16	81 ± 52	51 ± 26	27 ± 30

During the BSw, the only muscle on the left side to demonstrate highest activation was the latissimus dorsi. On the right side, the anterior deltoid, the latissimus dorsi and the triceps brachii are the three most active muscles. Activity of the right side appeared to be higher for six of the eight muscles.

The left latissimus dorsi activity peaks during the EFSw, alongside the left upper trapezius. It appears that these two muscles are the major contributors to the EFSw on the left side; however, all of the muscles of the left side show increases in activity from the BSw. High activation levels of over 75% are apparent from the anterior deltoid, latissimus dorsi, triceps brachii, sternal pectoralis and the clavicular pectoralis muscles of the right side. With exception of the biceps brachii, posterior deltoid and the upper trapezius, all muscles of the right side demonstrate greater activity during the EFSw compared to the BSw.

Activity of both the left latissimus dorsi (>100%MVC) and the left upper trapezius, remain high during the Acc phase. Both portions of the left pectoralis major demonstrate increases in activity from the EFSw into the Acc phase. On the right side, both portions of the pectoralis major show declines in activity. All other muscles on the right side also demonstrate diminishing activity with the exception of the right biceps brachii the right posterior deltoid and the right upper trapezius.

The sternal pectoralis is the only muscle to show an increase in activity from Acc to the EFTh on the left side. Alongside this, despite not showing increases, the left anterior deltoid and the left upper trapezius remain active into the EFTh. All muscles of the right side demonstrate declines in activity from Acc into the EFTh except for the biceps brachii, which remains at 11%MVC. Although showing declines from Acc, the right latissimus dorsi remains more active than any other muscle of the right side.

As peak activation values do not provide information on activation changes within each swing phase, the following figures show the time course of activation for the duration of the hit for each of the individual muscles, comparing each bilaterally. The figures show the average activation across all participants at each normalised time instant.

4.2.1 Biceps Brachii

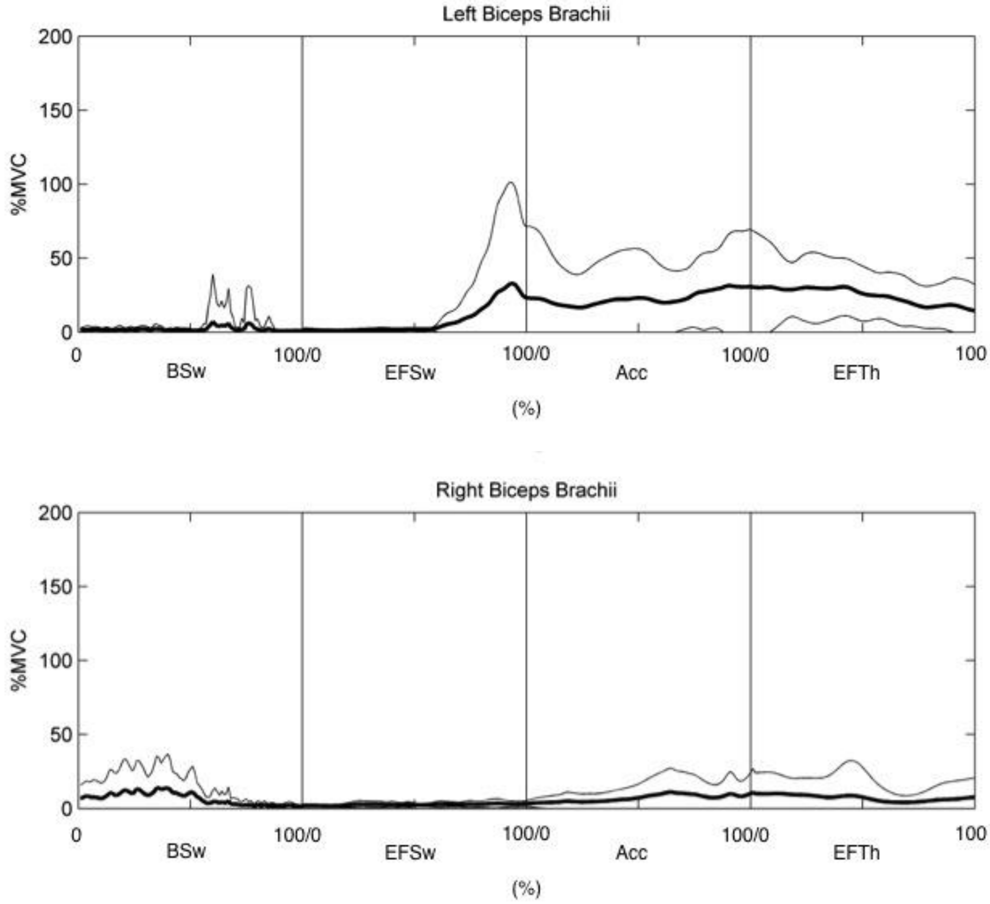


Figure 5. Biceps brachii activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

There was no appreciable activation of the left biceps brachii until 65% of the EFSw, after which it was active at 20-30% MVC through to the middle of the EFTh, from which a sharp increase in activity is seen peaking at 32% MVC at 90% of this phase. From a small decline over the first 15% of the ACC phase, left biceps brachii, activity climbs from 23 to 31% MVC, which remains for the rest of the phase. The consistent level of activity, remaining around 30% MVC, persists for the first 40% of the EFTh before beginning to decline for the remaining 60% of the EFTh to the end of the phase.

Activity during the BSw for the right biceps is low (<14% MVC). Later in the BSw, from 50% of the phase onwards, right biceps brachii activity diminishes and plateaus, remaining that way for the rest of the BSw and into the EFSw. Throughout the EFSw, little activity is demonstrated. During Acc, activity does climb yet remains below 12% MVC. For the duration of the EFTh the right biceps remains quiescent.

4.6.2 Triceps Brachii

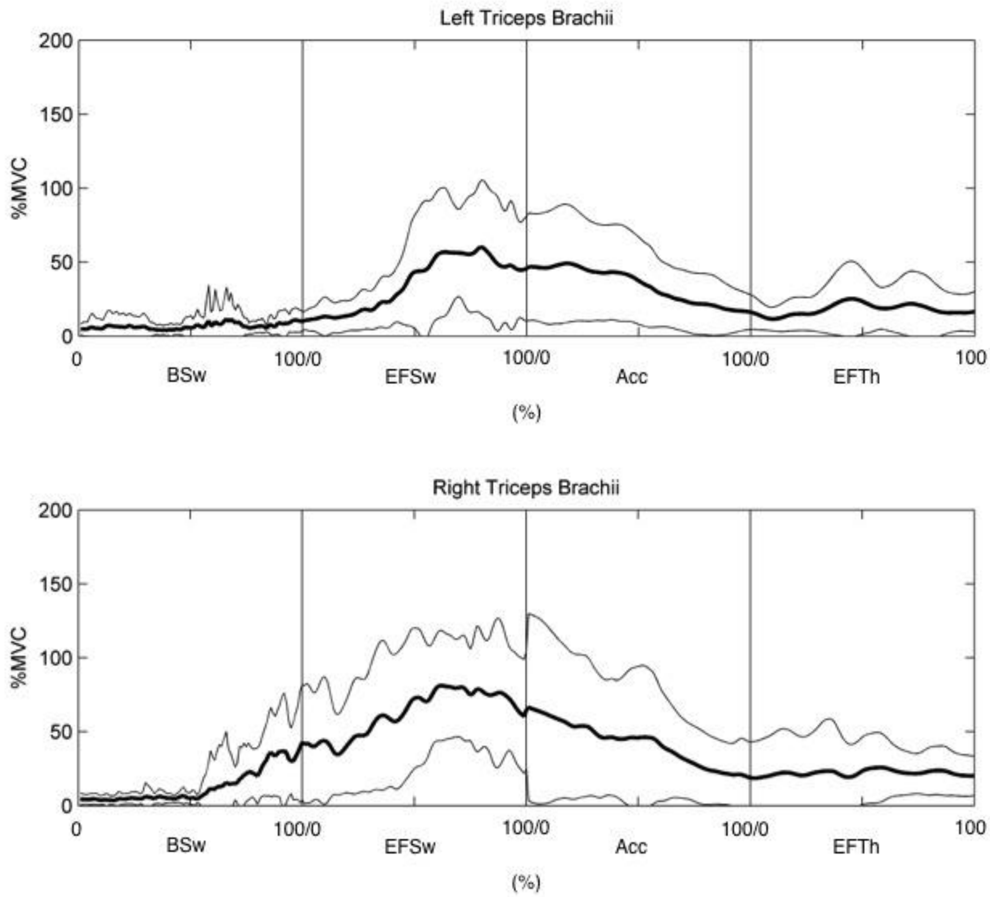


Figure 6. Triceps brachii activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

Left triceps brachii activity stayed below 12% for the first 65% of the BSw at which point activity started to increase. This increase continued through the transition from the BSw into the EFSw, climbing steadily to 20% MVC at 18% of the EFSw before increasing more rapidly to peak at 60% MVC at 80% of this phase. Activity from here began to recede, decreasing progressively for the duration of the Acc phase, dropping to 19% MVC at ball impact. In the EFTh, left triceps brachii activity climbed slightly to 25% MVC before plateauing for the remainder of the phase.

During the first half of the BSw, right triceps activity remained below 5% MVC before a considerable increase in activity was seen, climbing to 40% MVC. It is notable that the point at which right triceps brachii activity increased, right biceps brachii activity receded. A continuation of this increasing activity level remained during the first 20% of the EFSw, before right triceps activity increased more rapidly, peaking at 81%MVC at 61% of the EFSw. Despite remaining active, from this peak, activity then declined for the rest of the EFSW and throughout Acc, before activity plateaued around 23%MVC at the transition between Acc and the EFTh and this plateau remained for the entirety of the EFTh.

4.6.3 Anterior Deltoid

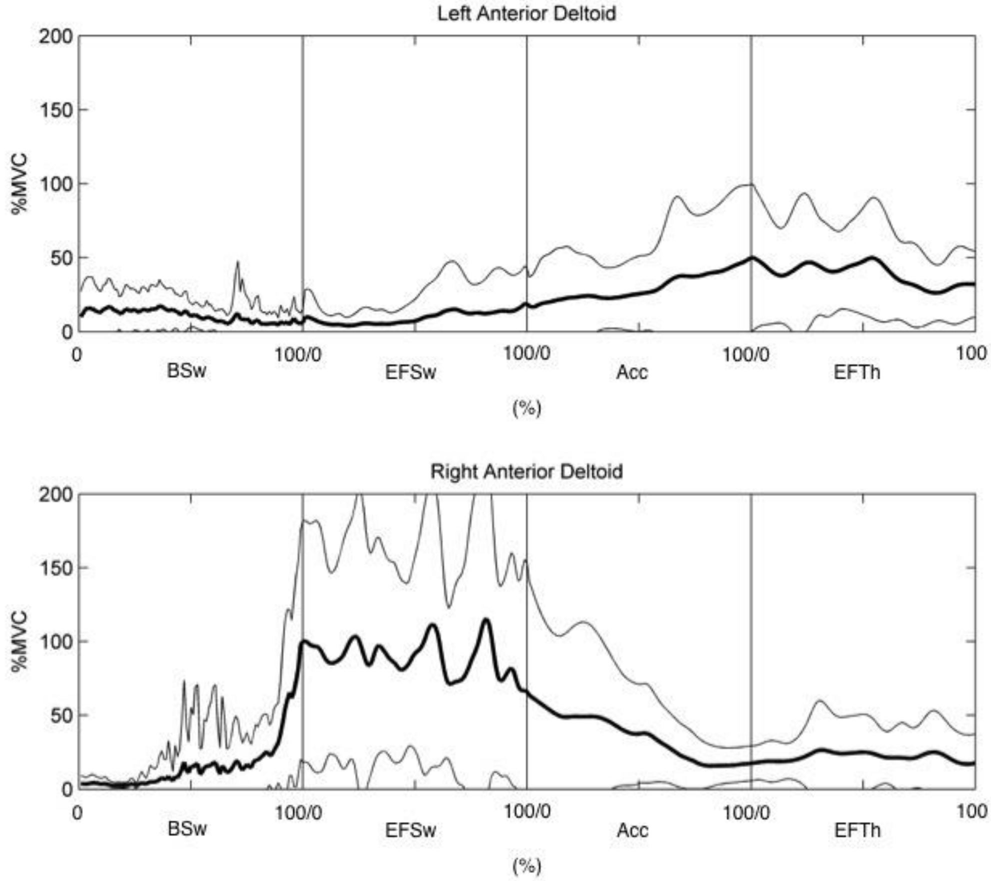


Figure 7. Anterior deltoid activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

Activity of the left anterior deltoid for the duration of the BSw remained below 17% MVC before activity started to increase during the mid-EFSw. This increase continued up until 85% of the Acc phase where the activity increases quickened, peaking at 50% MVC at impact with the hockey ball. After impact and into the EFTh, the anterior deltoid remained active for the first 55% of the EFTh until declines are apparent the end of the phase dropping to 17% MVC as the stick becomes horizontal at the end of the EFTh.

Activity of the right anterior deltoid increased slowly from 30% up until 80% of the BSw, before a sharp increase was seen form 19% MVC climbing to 100% MVC at the end of the phase. Activity remained high into and through the EFSw, peaking at 115% MVC at 82% the duration of the EFSw. From this peak, activity dropped throughout the Acc phase yet declines steadily, plateauing from 74% of Acc between 18 and 26% MVC through the EFTh.

4.6.4 Posterior Deltoid

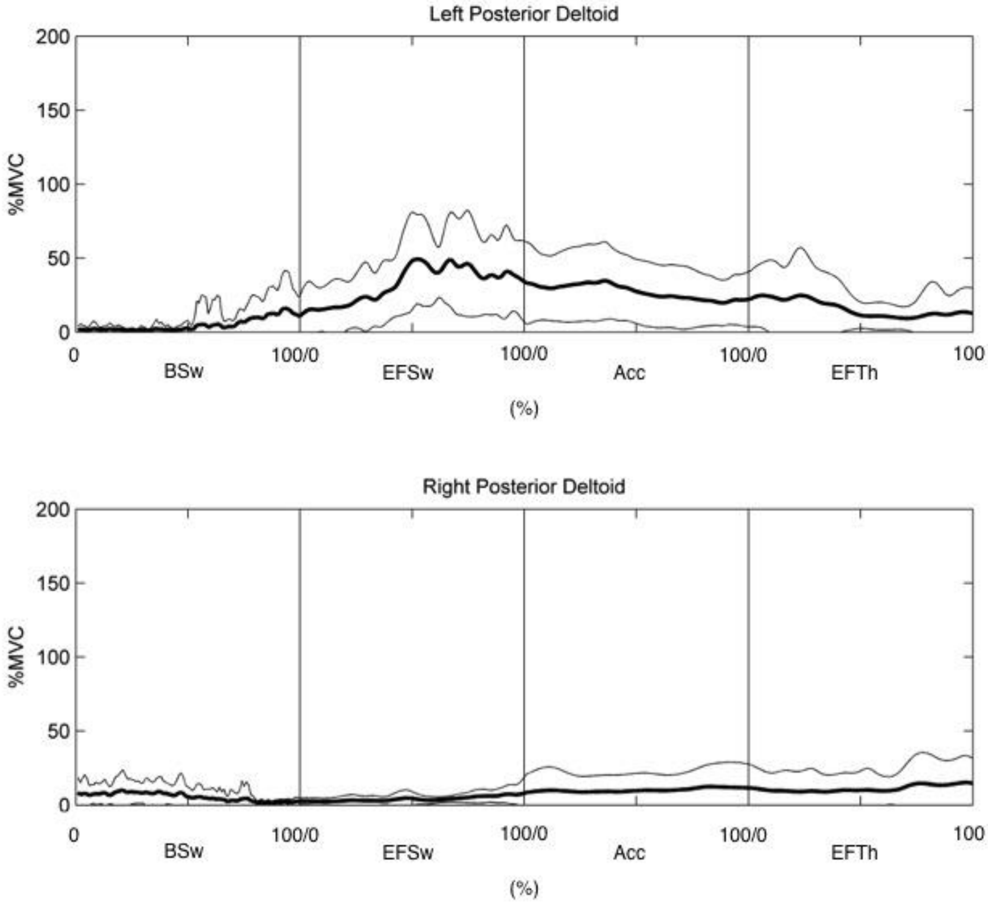


Figure 8. Posterior deltoid activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

During the first half of the BSw, activity levels of the left posterior deltoid remained below 2% MVC up until 50% of the BSw, at which point activity began to climb, peaking during the BSw at 16% MVC at 93% of this phase. This incline continued for the first 20% of the EFSw until activity started to increase more rapidly, climbing from 17% MVC to peak at 49% MVC at 55% duration, matching closely the time over which right triceps activity climbed. From this peak, left posterior deltoid activity demonstrated declines from its activity during the EFSw, declines which continued through the late Acc phase and throughout wrist uncocking, dropping from 33% at the start of the Acc phase to 22% at the end. Diminished activity between 22 and 25% MVC for the first 23% of the EFTh was apparent, before activity further declined to 9% MVC at 60% of the EFTh, a level which it remained around for the rest of the phase. The right posterior deltoid showed little appreciable activity across all four hit phases, remaining quiescent throughout the entirety of each swing phase (< 15%MVC) and was therefore non-contributory to the hit.

4.6.5 Upper Trapezius

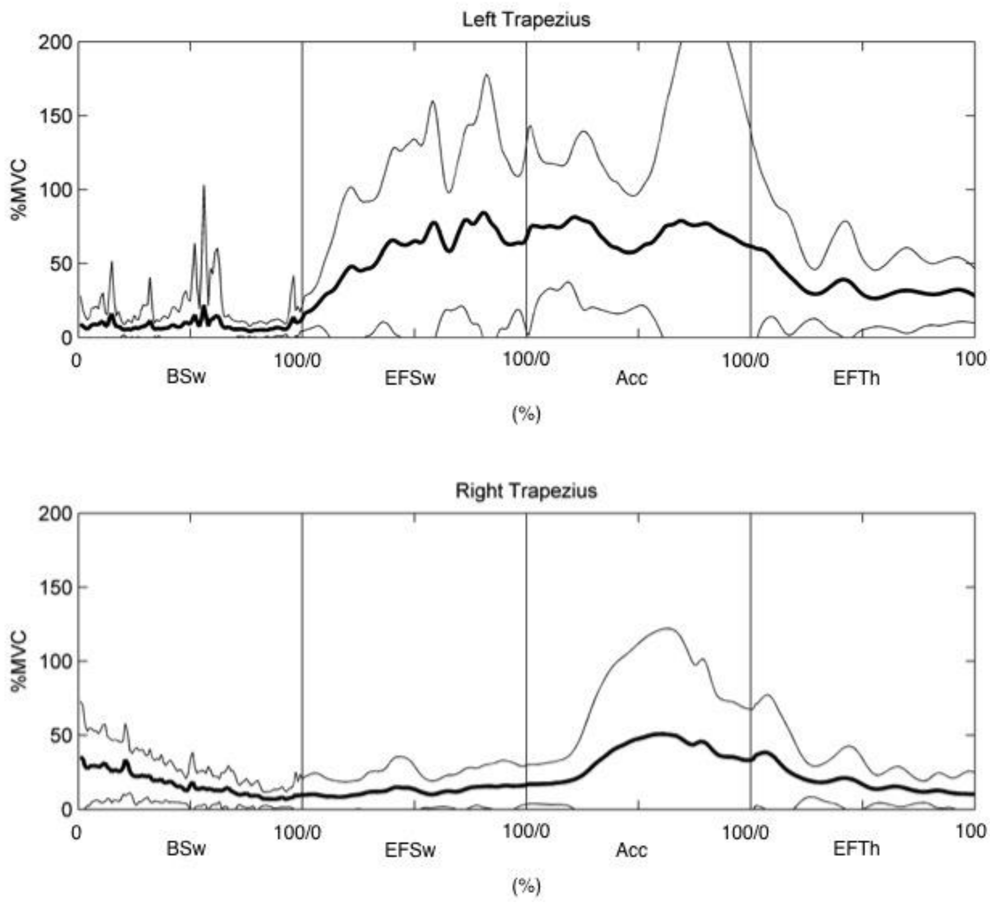


Figure 9. Upper trapezius activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

During the BSw, the left upper trapezius demonstrated little activity, remaining for the most part below 10% MVC, peaking only once at 21% MVC. Activity began to increase during the final 10% of the BSw through to 59% of the EFSw, reaching 77% MVC before a second incline was seen, peaking at 85% MVC at 80% of the EFSw, the peak here being the highest % MVC the left upper trapezius upper reached over any phase of the field hockey hit. Activity of the left upper trapezius then showed a decline from 80% through to 92% of the EFSw before commencing to climb again through to 20% of the Acc phase, peaking during Acc at 80% MVC. A decline in activity was then apparent between 20 and 45% of Acc, dropping to 57% MVC. At 45% of the Acc phase, activity increased again and climbed to 79% MVC at 69% the duration of this phase before declining into the EFTh. In the EFTh, activity continued to decline up until 30% of the EFTh at which point activity levels stabilise around 28%MVC.

During the early stages of the BSw, the trapezius was the most active of all the muscles studied here, however, after the initiation of the BSw, right upper trapezius activity declined from 34% MVC to 14% MVC. During the EFSw, right upper trapezius activity remained low as a continuation from the latter part of the BSw. From 10% of the Acc phase, activity levels began to increase rapidly from 17% MVC to peak at 51% MVC at 59% of Acc. After this peak though, activity tapered throughout the remainder of this phase and continued to taper for the duration of the EFTh.

4.6.6 Latissimus Dorsi

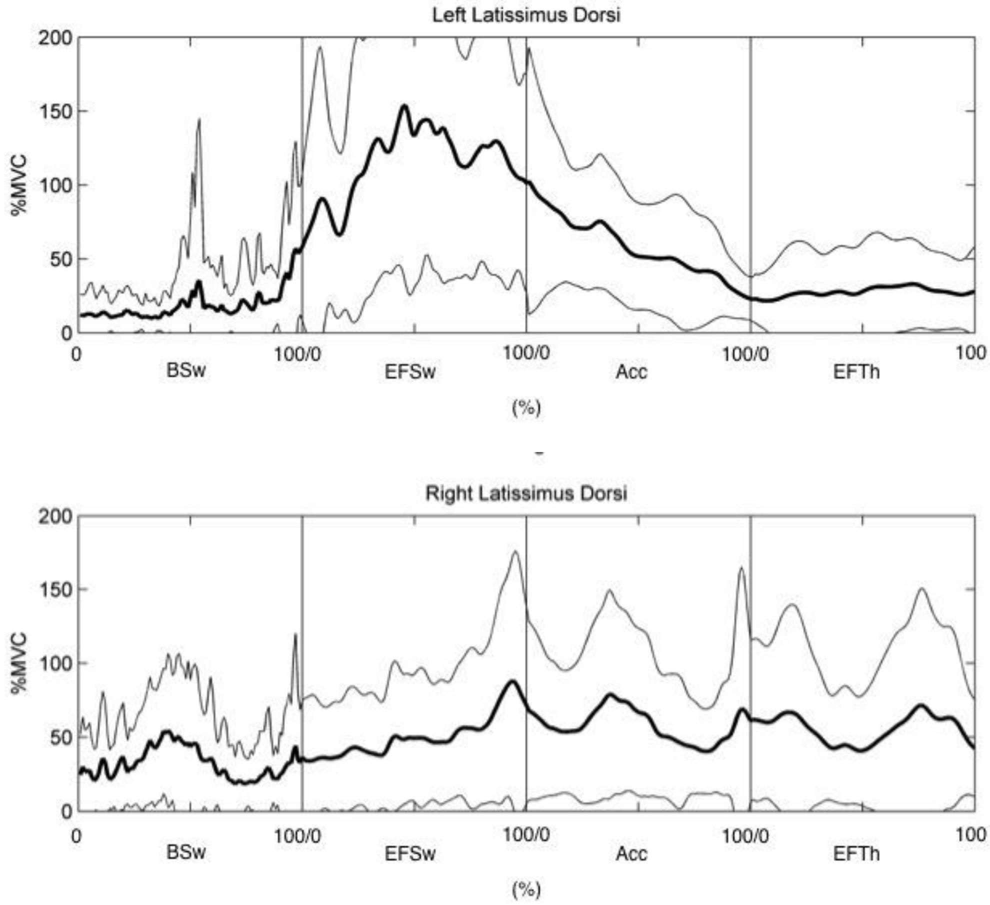


Figure 10. Latissimus dorsi activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

During the early part of the BSw, activation of the left latissimus dorsi was low. The first change in activity showed an increase starting at 40% of the BSw. This though receded before activity increased again towards 80% of the BSw. From the start of this increase late in the BSw, activity continued to increase into the EFSw phase to peak at 153% MVC. The left latissimus dorsi was the most active muscle during this phase, displaying the highest peak of any muscle studied over any of the swing phases. Notably, after the left latissimus dorsi activity had peaked, the moment the left latissimus dorsi activity level started to decrease was the same percentage of the Acc phase (approximately 90%) at which left clavicular pectoral activity started to increase. During the Acc phase, latissimus dorsi activity continued to recede up until impact at which point activation plateaued through the EFTh, remaining above 22% MVC and peaking at 33% MVC at 72% of the EFTh.

At the initiation of the BSw, activity of the right latissimus dorsi began to climb to 54% MVC at 40% of the phase before receding up until 70% of the BSw, where an increase in activity was again apparent. Like the left latissimus dorsi, the right side also displayed increases in activation during the EFSw, however, activity levels of the right side did not climb as high as those displayed on the left side during the EFSw. The right latissimus dorsi displayed peak activation (88% MVC) over any swing phase during the EFSw just prior to the stick becoming horizontal near the transition into the Acc phase. During the first 20% of Acc, the activity of the right latissimus dorsi dropped before climbing again to 79% MVC. After dropping to 40% MVC at 80% of Acc activity increased sharply to 68% MVC at 95% of Acc. Activation into the EFTh declined to 43% MVC rising once to 72% at 77% the EFTh before it declined to 47% MVC by the end of the phase.

4.6.7 Clavicular Pectoralis Major

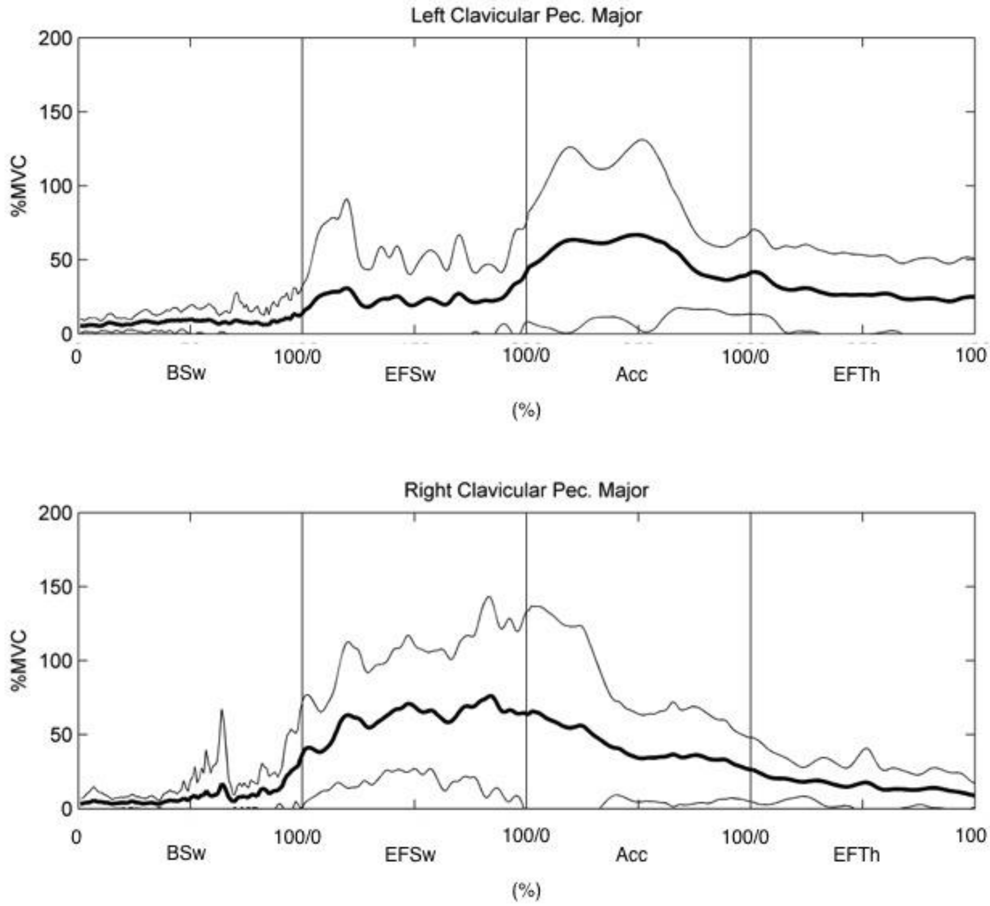
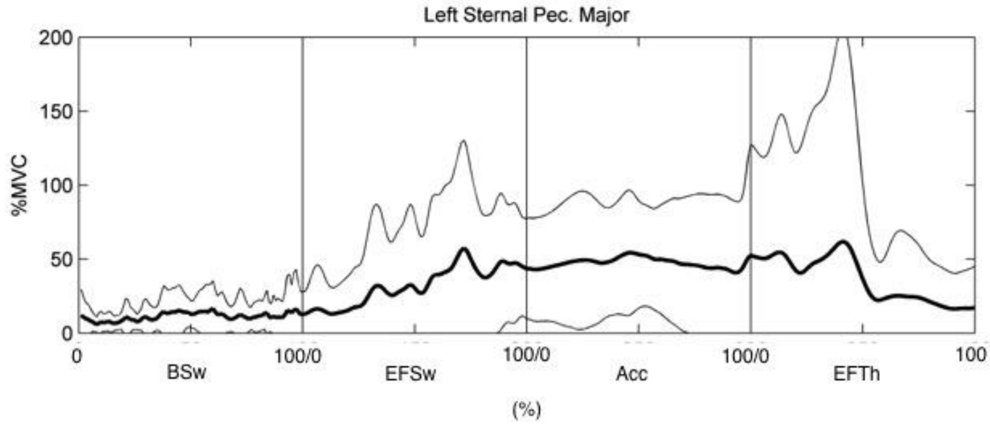


Figure 11. Clavicular pectoralis major activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

BSw activity of the left clavicular pectoralis was low, remaining below 8% MVC. Although slight, activity started to climb slowly halfway through the BSw, increases occurring at the same time mid-BSw increases in left latissimus dorsi were apparent. From 85% of the BSw, activity started to rise more significantly; again concurrent with increases in left latissimus dorsi activity. At 90% of the EFSw, as left latissimus dorsi activity receded, left clavicular pectoralis activity increased. This climb in activity continues into Acc climbing from 60% MVC at 15% of Acc, up to and peaking at 66% MVC at 55% of the Acc phase. After this peak, activity dropped for the remainder of Acc yet activity was still apparent into the EFTh, remaining around 25% MVC.

Like the left side, activation of the right clavicular pectoralis major during the BSw also remained low (<5% MVC) until a small incline was seen at 35% of the phase. This incline continued up to 80% of the BSw before a further increase was evident into the EFSw. Activation continued to rise up until 84% of the phase to peak at 76% MVC. This peak in activation was later than the EFSw peak seen in right sternal pectoral activity, yet was earlier than that of the right latissimus dorsi. Moreover, the peak during the EFSw was the highest activation of the right clavicular pectoralis across all the swing phases. Unlike sternal pectoral activity, clavicular activity remained high throughout the late EFSw (>65% MVC). Throughout the duration of the Acc phase, right clavicular pectoral activity declines and this continual decline the EFTh.

4.6.8 Sternal Pectoralis Major



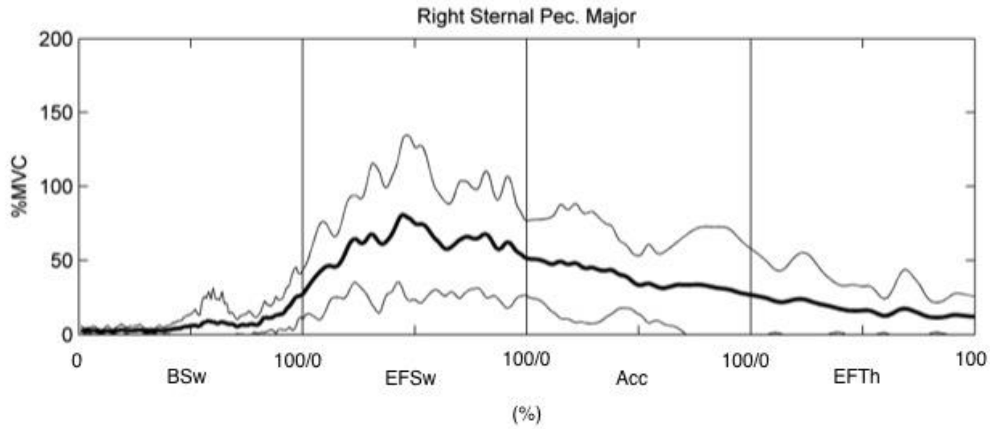


Figure 12. Sternal pectoralis major activation, by percentage of swing phase, during the field hockey hit (mean % MVC ± SD across all participants).

Activity of the left sternal pectoralis major remained at low levels (<15% MVC) before, between 34% and 65% of the BSw, sternal pectoralis activity increased and increased to a level higher than the clavicular pectoralis over the same period. In the late BSw, left sternal pectoral activity started to increase with activation increasing after an increase in clavicular pectoral activity and after a larger increase in left latissimus dorsi activity, which occurred during the mid BSw. Continuing the increase in activity from the BSw, activity continued to climb for the first 70% of the EFSw. During Acc, the left sternal pectoralis remained consistently active between 42% MVC and 54% MVC, appearing to work eccentrically like the left clavicular pectoralis. The eccentric activity from the Acc phase and through impact with the hockey ball remained into the EFTh and was higher through the transition than activity of the left clavicular pectoralis. Activity peaked during this phase at 61% MVC, which was also the highest activation seen during the whole hit.

For the first 35% of the BSw, right sternal pectoralis major activity remained low before a small increase in activation is seen up until 85% of the phase at which point activity starts to significantly climb. The activation level of the left sternal pectoralis though, at the transition between the BSw and the EFSw, is comparably less than the right clavicular pectoralis major yet climbs more rapidly and peaks earlier at 81% MVC at 44% of the EFSw. From peak activation in the EFSw, activity declined and continued to do so for the rest of the hit through Acc and the EFTh. From peak activation in the EFSw, activity declined and continued to do so for the rest of the hit. Despite showing declines during the field hockey hit, activity of the right sternal pectoralis remained moderately high through the Acc phase.

5. Discussion

This study has produced the most detailed picture to date of muscle activity during the field hockey hit. It has also provided detailed information on joint kinematics of both the elbows and the wrists during the hit, and these joint kinematic data have confirmed Elliott and Chivers' (1988) suggestion about the roles of the left and right arms. The left arm does tend to act as a single segment, whereas the right arm acts as two segments, with flexion and extension of the right elbow. Adding a distal stick segment to the two systems gives the double and triple pendulums for the left and right arms, respectively, as described by Elliott and Chivers (1988).

This is also the first study in which EMG has been synchronised with three-dimensional kinematics. The data presented in this study provide more accurate three-dimensional kinematics of the upper limbs and the hockey stick and, in combination with the EMG data, have allowed exploration of the underlying kinetics of the field hockey hit. To provide a greater understanding as to the changes in muscular activity during each swing phase and to provide a more thorough insight into each muscle's roles during the field hockey hit to begin to provide an understanding into their effect on the kinematics of the hit, temporal aspects of changes in muscular activity must not be overlooked. Together, these EMG and kinematic data can suggest how the two and three-segment patterns are produced and whether muscular activity alone is responsible for the production and control of the field hockey hit or whether the observed kinematics are caused by a combination of muscular activity and segmental interactions of the type described by Putnam (1993). The EMG amplitude values in excess of 100% MVC recorded in this study could have been caused by two main factors. Firstly, the amplitude of the reference contraction may not have accurately reflected the participant's potential to produce a larger amplitude than the one recorded. This may have been due to the untrained nature of the participant, or the fact that a static rather than dynamic contraction was used as the reference. Secondly, the EMG signal collected from the dynamic trial could have been significantly boosted by the presence of crosstalk from adjacent muscles that were also active. While the closed kinetic loop formed by the arms and stick complicates the making of definite statements about the causes of observed motions, some inferences can be made.

5.1 The role of the arms

The coaching literature provides little information on the role of the arms during the hit, reporting only evidence or qualitative observations. Little justification is provided as to the assumptions made for the roles of the arms, just observations of the movements seen are reported. From these data, quantitative observations can be made, clarifying the movement patterns of the arms and suggestions made in the coaching literature.

Both the left and right wrists display a similar pattern of decreasing wrist angles during the late BSw before increasing from approximately 75% of the EFSw, through the Acc phase and into the EFTh. The differing roles of the arms are thus dependent upon the degree of flexion and extension of the elbows during the hit. As wrist 'cocking' and 'uncocking' is a feature of in both the two and three-segment systems, the two systems differ in whether or not the elbow angle changes and, subsequently, whether the arm itself acts as one or two segments. Throughout the field hockey hit, the left elbow angle remains relatively constant, especially during

Acc and as wrist ‘uncocking’ occurs. The right elbow however, demonstrates considerable flexion during the BSw before extending during the late EFSw and throughout the Acc phase. These elbow and wrist patterns remain consistent with Elliot and Chivers’ (1988) description of the field hockey hit and supports Elliot and Chivers’ (1988) assumption that the arms each have differing roles. From the greater consistency of the left elbow angle, as compared to the right elbow angle, these data show that a two segment sequencing pattern is applicable to describe the motion of the left arm and stick system, whereas a three segment pattern would be a better description of the right (Figure 3.).

Some suggestions about the functional role of these elbow kinematics may be made. Maintaining an extended left elbow may serve to keep the stick away from the body to increase the distance through which the stick head travels and could also contribute to the left arm and forearm unit setting the plane of the hockey hit for the stick head during Acc, as proposed by Chivers and Elliott (1987). The right arm flexes at the elbow to allow a greater range of movement of the stick head to the right during the BSw. Elliott and Chivers (1988) reported that the wrist joints of elite penalty corner hitters remained relatively constant for the first half of the downswing and that delayed wrist ‘uncocking’ which, combined with increased right elbow flexion, caused the stick to rotate further backwards, a pattern similarly seen here (Figure 3.). The extension of the right elbow to straighten the right limb during the downswing is a possible cause of the increase in velocity of the stick head towards impact (Chivers and Elliot, 1987).

5.2 The Backswing and wrist cocking

At the start of the BSw, right shoulder girdle rotation away from the ball is caused by the right upper trapezius and the right latissimus dorsi. Furthermore, increased upper right trapezius activity could possibly cause the initial elevation of the clavicle and the scapula of the right side as the right shoulder begins to become abducted and extended. Left latissimus dorsi activity may contribute to the internal rotation of the left shoulder causing the stick to rotate about its longitudinal axis in the same direction and the stick face to open during the mid-BSw is possibly caused by increased left latissimus dorsi activity. Moreover, increases in trunk and shoulder girdle rotation to the right, and the diminished left upper trapezius and increased right upper trapezius activation could be caused by left side scapula protraction in combination with right side scapula retraction. This pattern of trapezius activity is apparent up until the latter stages of the BSw, at which point possible synergist rotator cuff and scapular muscle activity may elevate the clavicle and cause scapular retraction as opposed to right upper trapezius activity, hence the decline in activity seen during the late BSw and through the EFSw. A similar explanation for declining trapezius activity was proposed by Kao *et.al.* (1995), during their work on the golf swing.

The decrease of the angle of the wrists seen during the EFSw could be caused by forearm muscular activity or by segmental interactions where angular acceleration of the arms will cause the hands to make forces on the proximal stick in the direction of the hit. The resultant clockwise torque on the stick (as seen by the player) will tend to produce wrist 'cocking'. Segmental interactions due to the acceleration of the upper arm, which would cause a joint force made on the forearm by the upper arm would tend to flex the elbow if increasing triceps activity did not resist this. The observed isometric left triceps activity would mean that the flexion does not occur at the elbow but is transferred more distally to the wrists. Over this period, the left arm is therefore acting as a single segment.

Both the left and the right wrists remain ‘fixed’ for most of the BSw, only ‘cocking’ at the end of the phase. To maintain possible elevation of the left shoulder at the same time as left wrist ‘cocking’ begins, and maintenance of a torque about the left shoulder to aid the left shoulder in rotating back to the left in the direction of the hit during the late BSw, can largely be explained by activation increases of the left upper trapezius and the left posterior deltoid. Moreover, retraction and upwards rotation of the left scapula would possibly be apparent as the stick moves forward, similar to patterns seen in golf (Kao *et.al.*, 1995), concurrent with left upper trapezius activity.

5.3 Transition and the initiation of the early forward swing

Alongside gravity, the slowing of the right humerus as the stick face nears the end of the BSw is caused by activity of the right latissimus dorsi, the right anterior deltoid, the right clavicular pectoralis and the right sternal pectoralis. Activity of these four muscles would at first appear to be eccentric, slowing the right arm, before the pectoralis muscles and the right anterior deltoid contract concentrically and initiate the EFSw in the right arm by creating a torque about the right shoulder. They then combine activity with a second burst of right latissimus dorsi activity to bring about horizontal adduction and internal rotation of the right upper arm, thus causing acceleration of the upper right arm during the EFSw. Throughout the BSw, right anterior deltoid activity controls right shoulder flexion and extension after the stick head's initial movement away from the direction of the target and appears to be one to the most active muscles during the late BSw and for the duration of the EFSw. The right anterior deltoid therefore does not display the quiescence previously reported in studies into the golf swing by Jobe *et.al.* (1986), Jobe *et.al.* (1989) and Escamilla and Andrews (2009).

Maintenance of lumbar spine extension as the hips and the trunk rotate as the X-factor at the top of the swing is produced is possibly caused by synergist right latissimus dorsi activity. Unlike muscular activation studies on the golf swing which have found suppressed activity of the latissimus dorsi on the right side during the BSw (Jobe *et.al.*, 1986; Jobe *et.al.*, 1989; Pink *et.al.*, 1990), the right latissimus dorsi during the BSw of the field hockey hit is one of the most active, possibly due the greater degree of flexion of the spine and the step towards the ball employed during the field hockey hit compared to the golf swing and also due to its role of initiating internal rotation of the right upper arm.

To cause the left arm to adduct and internally rotate, and to provide the resultant pull along the stick by causing the initial angular acceleration of the left arm system, the left latissimus dorsi and the left posterior deltoid show activation increases at the end of the BSw, concurrent with the timing of activity increases of the right side pectoral muscles and the right latissimus dorsi. Rotation of the hips and the trunk back towards the target occurs as the stick head is still reaching the top of the swing, a trait accentuated by increased wrist 'cocking' at the top of the swing before the stick head itself starts its downswing. This earlier rotation of the hips and trunk initiating the EFSw prior to the phase transition from the BSw, as measured from the stick head, causes increases of more proximal musculature to be measured during the late BSw.

Whilst the right biceps brachii is active during the right elbow flexion up to 70% of the BSw, activity decreases during the late BSw and EFSw. During this period the elbow angle is held constant by isometric triceps activity opposing a torque about the forearm centre of mass, which arises from the force made on the forearm by the upper arm as a result of the latter's angular acceleration in the direction of the hit. This torque is caused as a consequence of musculature producing a force at the shoulder to accelerate the upper arm and would act to move the left elbow into greater flexion, thus accounting for diminished right bicep brachii activity. However, increasing right triceps brachii activity over this period resists this increasing joint flexion torque and maintains a constant degree of elbow flexion until the wrists 'uncock'.

5.4 The early forward swing

The initial angular acceleration of the right upper arm at the start of the EFSw can largely be explained by increased activity of the right clavicular and right sternal pectoral muscles. This continues up until the mid-late EFSw where activity declines as the arm has moved into greater adduction and is moving across the trunk. Moreover, activity continues to decrease during Acc after the initial acceleration of the upper right arm has occurred. Furthermore, a shallower swing plane is employed during the field hockey hit than during the golf swing (Willmott & Dapena, 2012), possibly caused by greater flexion of the right shoulder. This flexion of the shoulder could be attributed to increased right clavicular pectoral activity during the EFSw.

Activity of the right pectoral muscles appears earlier than activity of the left pectoral muscles, possibly due to the right upper arm being more abducted than the left arm and that the BSw and rotation about the trunk happen to the right and that the hockey stick is swung from the left to the right during the downswing. Moreover, right clavicular pectoral activity during the initial stages of the EFSw stops the humerus lagging at the start of the downswing prior to acceleration of the upper arm. A similar pattern of right clavicular pectoralis activity is also found during the golf swing (McHardy and Pollard, 2005). In addition to this, increasing activity of both portions of the left pectoralis major muscle during the late BSw and the start of the EFSw aids left arm adduction and sustains the X-factor at the top of the swing and into the EFSw as activity of the left sternal pectoralis works reciprocally with activity of the left latissimus dorsi to control the rate of adduction and extension of the left shoulder. This pattern is consistent with golf-based data which consistently show increases in left pectoral activity from the EFSw into Acc (Jobe *et.al.*, 1989; Pink *et.al.*, 1990; McHardy and Pollard, 2005; Escamilla and Andrews, 2009).

During the EFSw, the left shoulder moves in the direction of the hit (Chivers and Elliott, 1987). The initial angular acceleration of the shoulders back towards the target can be explained by left posterior deltoid and right anterior deltoid up until the late EFSw, at which point declines in activity occur.

The extension of the right elbow during the EFSw and an increase in the angular acceleration of the distal end of the hockey stick as it starts its downswing would affect the angular displacement of the left arm. During this period, left posterior deltoid activity remains consistent with the requirement to provide a torque about the left shoulder to keep the left arm moving in the direction of the target, especially as the wrists ‘uncock’, resisting an oppositional torque brought about by wrist uncocking itself, a pattern similarly noted by Abernethy *et.al.* (1990) during the golf swing.

The sharp increase in right anterior deltoid activity provides a torque at the right shoulder, which is contributory to the initial acceleration of the right upper arm as the shoulder begins to internally adduct the humerus. Furthermore, the torque at the right shoulder applied by the right upper arm to the shoulder as a result of the acceleration of the upper arm is resisted by right anterior deltoid activity, keeping the upper arm moving in the direction of the target, stabilizing the shoulder joint and possibly aiding internal rotation of the right arm and shoulder. The employment of a shallower swing plane in the field hockey hit as opposed to the golf swing could initiate greater extension of the right shoulder, which can mainly be explained by increased right anterior deltoid activity.

The deltoids during the EFSw of the field hockey hit do not display the same latency previously observed in the golf swing by Jobe *et.al.* (1986), Jobe *et.al.* (1989) and Escamilla and Andrews (2009). In the field hockey hit, the left posterior deltoid appears to show activation increases to provide a torque at the left shoulder during the EFSw and the right anterior deltoid appears to be one of the most active muscles during the late BSw and for the duration of the EFSw.

At the end of the BSw, and up until approximately 75% of the duration of the EFSw, the right elbow angle remains constant whilst the right wrist continues to ‘cock’.

Over this period, as the right elbow 'fixes', the right arm system would therefore work as a two-segment system and not as a triple pendulum system. The fixing of the right elbow over this period would possibly allow segmental interactions caused by the acceleration of the upper arm from activity of shoulder musculature to work about the wrists and help them 'cock', as with the left side. If the right elbow did not 'fix' over this period, segmental interactions would cause the left and wrist wrists to possibly oppose one another. This 'fixing' remains up until wrist 'uncocking', at which point the right elbow moves into greater extension, therefore allowing segmental interactions or muscular activity to increase the angle of the wrists.

The maintenance of the left elbow angle at approximately 140˚ and the 'fixing' of the right elbow angle at approximately 80˚ (Figure 3.) at the start of the downswing can be attributed to increased left triceps brachii activity and increased right triceps brachii activity, respectively. The angular acceleration of the upper left and right limbs during the EFSw causes a joint force at the distal end of these more proximal segments, acting at the elbows, which, if triceps brachii activity were not apparent, would cause the elbows to move into flexion. Both increased left and right triceps brachii activity resist this moment acting at the elbows to maintain left elbow extension and maintain the degree of flexion seen at the right elbow by overcoming the joint moments generated by the initiation of the downswing from the shoulders, preventing left elbow flexion and lagging of the stick as more proximal segments begin to accelerate.

The left latissimus dorsi is active during trunk rotation to the left during the EFSw but its activity declines during the late EFSw and into Acc. At the start of the EFSw, activity of the left latissimus dorsi continues the abduction and extension of the left shoulder seen during the late BSw. It appears that the left latissimus dorsi is the primary mover of the left arm during the early downswing, providing ‘power’ during the hit. The acceleration of the upper left arm and the power from the left shoulder during the hit comes from the combination of left latissimus dorsi and left pectoral muscle activity, with the left latissimus dorsi activity preceding increases in activity of the left pectoral muscles, which are more active during Acc and into the EFTh, possibly due to the latissimus dorsi’s role in causing trunk rotation to the left and acceleration of the upper left arm during the EFSw. A similar pattern of activity was found on the left side during the golf swing (Pink *et.al.*, 1990). Activity of the left pectoral muscles during Acc would maintain flexion of the shoulder as the wrists ‘uncock’ allowing the left arm to remain straight and this flexion of the shoulder possibly aids maintenance of the swing plane during this phase. Notably, after left latissimus dorsi activity has peaked, the moment the left latissimus dorsi activity level starts to decrease considerably is the same percentage of the Acc phase (approximately 90%) at which left clavicular pectoral activity starts to increase as both muscles would be required to work in concert to promote flexion, adduction and medial rotation of the left shoulder during the EFTh.

Activity of the right side during the EFSw appears to be sustained until wrist ‘uncocking’ is apparent. Activity of the right anterior deltoid and right pectoral muscles provide a torque about the right shoulder up until the late EFSw, where decreases in muscular activity at the shoulder on the right side possibly allow the interactive moments caused as a reaction to wrist ‘uncocking’ and the acceleration of the distal hockey stick to act about the right elbow to cause the right elbow to extend through Acc.

5.5 Elbow extension and wrist uncocking

The slight increase in left elbow extension during the late BSw and through most of the EFSw can be largely explained by increasing triceps brachii activity up until the late EFSw. From this point, further elbow extension results from the slowing of the shoulders whereby segmental interactions cause the extension of the left elbow instead of the elbow extensor muscles, as demonstrated by Putnam (1993). Putnam (1993) demonstrated that elbow extensor muscle activity is not a requirement for elbow extension and that joint extension can instead be caused by segmental interactions.

The deceleration of the left upper arm at the shoulder would create a force at the distal end of the segment, acting at the elbow, which would tend to cause the right forearm to rotate about its centre of mass creating a torque in the opposite direction to the deceleration. This would subsequently cause the right elbow to tend to move into greater extension. The left elbow retains its level of extension in order to keep the stick away from the body and to increase the distance through which the stick head travels. The ‘fixing’ of the left elbow joint in extension allows the left arm to act as a double pendulum during the EFSw and through the Acc phase (Elliot and Chivers, 1988), with the left arm pivoting at the shoulder and the stick pivoting about the wrist.

A contribution to the initiation of the increase in the left wrist angle at the end of the EFSw can possibly be explained by increases in left sternal and left clavicular pectoralis activity over the same period. Activity increases of these muscles would act to decelerate the upper left arm at the shoulder and the deceleration of the left shoulder would consequently cause an interactive moment at the distal end of the left arm segment, which, due to the 'fixing' of the left elbow, acts instead about the left wrist, causing the left wrist angle to increase and wrist 'uncocking' to occur. Actively slowing the shoulder may not be the only mechanism that possibly produces wrist 'uncocking'. A torque about the wrists produced by musculature of the forearms to initiate wrist 'uncocking' would produce an interactive moment that would act upon the left shoulder in the opposite direction to the hit, which would subsequently cause the left shoulder to slow. Therefore, wrist 'uncocking' could be caused by a combination of actively slowing the shoulder and the production of a torque at the wrists.

However, as wrist 'uncocking' occurs, a reaction joint torque is created caused by the angular acceleration of the hockey stick acting on the left forearm at the wrist. This interaction possibly acts to move the left elbow into flexion, yet, as the left elbow remains 'fixed', this acts instead about the shoulder. Therefore, after the wrists begin to 'uncock', a further decrease in the angular velocity of the left arm system is caused primarily by interactive moments resulting from the acceleration of the distal stick. Consequently, the left upper trapezius and the left posterior deltoid display activity to counteract the effects of the hockey stick's angular acceleration on the proximal end of left arm system at the shoulder, thereby decreasing the resulting loss of angular momentum by providing a torque at the left shoulder to keep the left arm moving the left arm system in the direction of the target during Acc. Wrist ‘cocking’ continues up until the late EFSw before rapid wrist ‘uncocking’ is seen into and throughout the Acc phase.

The triceps brachii of both the left and right sides are active from the late BSw up until the late EFSw to resist segmental interactions of wrist ‘cocking’ and to maintain extension of the left elbow and to ‘fix’ the right elbow up until wrist ‘uncocking’. As little elbow extensor muscle activity is seen, from this point it appears that segmental interactions are predominant at causing and maintaining elbow extension and that elbow musculature activity is prevalent for the regulation of these segmental interactions in order to maintain the double pendulum of the left arm and the three-segment pattern of the right arm. As left triceps brachii activity declines due to segmental interactions causing extension of the elbow rather than the extensor muscles, consequent increases in left biceps brachii activity concentrically resists this increasing joint moment and controls and regulates left elbow extension through the late EFSw and the Acc phases. Over the same period, right biceps brachii activity decreases to allow extension of the right elbow. Therefore, increases in elbow extension during the Acc phase are likely to be caused by segmental interactions. This would facilitate elbow extension throughout the EFSw and would require lesser, or possibly no, direct contribution from triceps brachii activation for the elbow to move into greater extension, hence the reduction in extensor activity observed during the EFSw and for the duration of the Acc phase.

From the late EFSw and throughout Acc, the right elbow demonstrates extension whilst right triceps brachii activity reduces (Figure 5.). The deceleration of the trunk creates a force that would cause segmental interactions at the right elbow due to the deceleration of the proximal end of the upper right arm acting on the distal end at the elbow. However, as the right forearm lies approximately in the same plane as the stick head yet the right upper arm is at about 60° to the plane of the swing (Willmott & Dapena, 2009), the torque may cause the elbow to move into flexion. Change in the right elbow angle might also follow torques made by the left hand on the stick, yet this is difficult to define due to the nature of the closed loop created by having both hands on the hockey stick.

As there is a lack of extensor muscle activity to actively straighten the right elbow and segmental interactions would not produce the extension seen due to the angle of the right forearm and right upper arm in relation to the plane of the stick head and the subsequent forces acting on the right arm system, the right elbow could possibly be passive in its extension, extending only as a consequence of allowing the left arm to remain in greater extension as the wrists 'uncock' and towards impact with the ball through the Acc phase due to the consequence of having both hands on the stick. Greater contribution to the hockey hit from the right arm system would therefore appear to be from internal rotation of the right upper arm during the EFSw and Acc, rather than from extension of the right elbow. Therefore, Elliott and Chivers' (1988) pendulum model can only be used so far as a description of the hockey hit because the upper arm segments do not lie, and the joints may not hinge freely, in plane (Willmott & Dapena 2009).

5.6 The early follow-through

Deceleration of the left arm during the EFTh can be largely explained by sustained left latissimus dorsi, left clavicular and left sternal pectoral activity. Before the arm slows, the trunk has already started to decelerate and as the upper left arm starts to abduct, extend and elevate away from the trunk, the eccentric activity of these muscles would aid the deceleration of the left arm, yet a slight drop in left clavicular pectoralis major activity allows for lateral rotation of the left humerus to continue after ball impact. At the shoulder, the left posterior deltoid activity plays a role in the deceleration of the left shoulder and the left arm after impact with the hockey ball. Both pectoral muscles of the right side appear non-contributory to the slowing of the right arm as activity demonstrates declines, unlike during the golf swing. Right side deceleration of the upper arm during the field hockey hit is attributable to the maintenance of activity of the right latissimus dorsi from the Acc phase and this appears to be the only muscle of the right side that does not demonstrate declines in activity during the EFTh. It would therefore appear that the left side is more dominant in causing the deceleration of the stick.

5.7 Muscular activity and segmental interactions

It is apparent that the observed kinematics of the field hockey hit arise from a combination of muscular activity and segmental interactions. It appears that muscular activity is more predominant in accelerating both the left arm and right arm systems during the EFSw. The acceleration of the stick during wrist 'uncocking' and through the Acc phase causes muscular activity of the arms to maintain the double pendulum of the left arm and the three-segment system of the right arm, controlling the hit and the subsequent segmental interactions. Muscular activity of the trunk may be more influential in creating the angular acceleration of the upper arms by acting at the shoulders to accelerate the two arm systems before resisting interactive moments at the shoulders during wrist ‘uncocking’ to maintain movement of the shoulders in the direction of the hit during Acc.

Like Putnam (1993), this study has also provided evidence that local muscular activity is not a requisite for joint movement to occur. During the field hockey hit, muscular activity is apparent to firstly produce the initial acceleration of the left and right arm systems and then to control segmental interactions, caused as a consequence of those accelerations.

This study has confirmed Elliott and Chivers’ (1988) suggestion that during the field hockey hit, the left upper limb system acts as a double pendulum consisting of the left arm and hockey stick whereas the right upper limb works in three separate segments consisting of the right upper arm, the right forearm and the hockey stick. This assumption, however, can only provide an insight into the role of the arms. A more complicated picture of the hit exists than simple pendular action because the segments of the right arm system do not all lie in the stick head’s swing plane and because of the nature of the closed loop system with two arms being connected through the stick. This study has provided an increased understanding of the techniques employed when performing a field hockey hit and has begun to detail the mechanics of how the hit is performed and controlled, determining links between the kinematics and the underlying kinetics of the field hockey hit.

Until the kinematics of the hit have been more fully investigated, biomechanical mechanisms used during the hit remain hard to quantify. Measurement of the X-factor and the SSC of muscles of the hit would benefit from more accurate investigation of bodily kinematics. Without measurement of hip and shoulder rotations, for example, the X-factor and it's contribution to the hit will remain unclear, yet would be worthy of investigation due to the consistency of an increased X-factor stretch and performance in golf (Cheetham, 2001).

5.8 Delimitations and limitations

There are a number of factors that could limit the generality of the findings of this study.

- The use of participants that were male and of the same playing ability limits the findings of the study to the same population.

- There was an inability to measure all muscles that could possibly affect the hit due to the use of sEMG. For example, due to issues with cross talk, EMG from wrist musculature would have been difficult to analyse validly. Moreover, more deep-seated muscles – or muscles on which the detection site is close to the myotendinous junction, for example the upper serratus anterior – would prove inaccessible to sEMG.

- The use of a different stick to the participant's own and by hitting a stationary hockey ball effects the generality of the findings, yet was necessary for standardisation of the task during data collection.

There were also a number of unforeseen pragmatic issues that became apparent once pilot testing had begun, against which choices were made to limit their effect on the study.

- There was found to be slight contamination of the pectoral EMG signals by EEG.

- The placement of retro-reflective markers had to accommodate the attachment of EMG electrodes. Especially for the shoulder, joint centres were unable to be measured or tracked as accurately as would have been possible without the auxiliary EMG hardware. This lead to assumptions being made about the shoulder joint centre during analysis.

- An issue with the tracking of the medial elbow markers was also apparent due to the upper limbs obscuring the tracking systems view. Moreover, marker movement due to the acceleration and velocity of the stick during the downswing made tracking and digitising of the stick and wrists markers difficult.

- The hands presented an inability to be tracked due to consistent marker detachment, therefore resulting in the calculation of a pseudo-wrist angle between the forearm and the hockey stick.

A number of methodological limitations were also taken into consideration. All possible precautions were taken to minimise the know limitations inherent with EMG.

- The consistency of electrode placement was carefully monitored to reduce the possibility of cross talk boosting the recorded EMG signal. Furthermore, minimising the effects of electrode migration was also considered during placement.

- Precautions were taken to limit the impingement of wearing EMG hardware on the performance of the hit. The data logger and electrode lead wires were carefully positioned so as not to affect the hitting motion and to reduce movement artefact.

- When normalising the EMG signal, the ability of the participant to perform maximal contractions and the MVC test position used to isolate the tested muscle most effectively would have limited the generation of the largest EMG amplitude possible. Furthermore, the size of the moving window used for the RMS calculations could have effected the amplitude used as the reference value.

- The Participant's muscle composition also affected the collection of EMG. Fibre type of the muscle being monitored and the amount of tissue between EMG electrode and MUAP origin affected the fidelity of the signal, yet this was beyond the control of the study methodology.

- Lastly, electrical noise from the electrode lead wires and form other extraneous electrical sources could have effected the EMG signal, yet were accounted for when band-passing and filtering the collected EMG signal.

5.9 Recommendations for future studies

Future study should be focused towards detailing activation of a greater number of muscles of the trunk and the upper limbs. Isolation of sixteen muscles of the arms, shoulders and of the trunk can only begin to provide an insight into muscular activity of a motion in which numerous joints and muscles are utilised. Due to difficulties in measuring sEMG from smaller, thinner muscles, activity of forearm musculature was not collected for this investigation. However, activity of forearm musculature and its contribution to wrist 'cocking' and 'uncocking' would be worthy of further investigation to begin to clarify the role of the wrists and the contribution of segmental interactions to the field hockey hit. Alongside this, rotator cuff function would be worthy of examination as it has been shown to be influential to the performance of the golf swing (Jobe *et.al.,* 1986) and could account for changes in activity of shoulder musculature studied here. As it is proposed that the lower limbs produce large amounts of power during the performance of the hit (Elliot and Chivers, 1988), the influence of lower limb musculature must be gauged to provide an overview of muscular activity of a movement that requires employment of the whole body.

Due to restraints of task consistency, this study focused upon the hitting of a stationary hockey ball. However, muscular recruitment could change if the ball being hit is moving as has become more common with the introduction of the self-hit rule (FIH, 2012). Changes in the kinematics of the hit have already been noted as the speed of an approaching ball being hit increased (Franks *et.al.*, 1985), yet changes in the underlying kinetics remain unknown.

Experienced field hockey players have been shown to have more consistent hits than less experienced players (Kusuhara, 1993). A comparison of the timing of muscle activity, and of the consistency of that timing, between expert and novice players could reveal activity of muscles more predominately used by more skilled performers.

With further understanding of the muscles used during the hit, their magnitude, their timing patterns and their contribution to the production and control of the hit, changes in technique could be advocated with the aim of refining hit performance variables such as maximising accuracy and ball velocity or minimising swing time.

5.10 Study implications and future directions

This study has made valuable additions to the understanding of the hockey hit, especially through the combination of kinematics and muscle activation, and to what is known about the possible contributors to stick motion. This does not yet present a full picture, but has moved the discussion forwards, helping biomechanists and coaches alike.

- For biomechanists this is the first study to synchronise temporally normalised EMG data with kinematic data in a swing motion with the presentation of

EMG data so that temporal aspects of muscle activity changes can be assessed alongside kinematic variables. This has also provided evidence that EMG is not solely responsible for the cause of movement in the hockey hit.

- For coaches this study starts to address anecdotal accounts of the performance of the hit, presenting valuable quantitative evidence of body and stick motions. It also provides confirmation of previously suggested aspects of technique, such as the two and three pendulum model for the arms and stick. Furthermore, this study also highlights muscles that can be targeted for strength training regimes.

Using this study as a basis for further research, future studies could take a number of directions.

- Studying the activity of more musculature that could contribute to the hit would provide a greater overview of the associations between muscular activity and segmental interactions, allowing a more in-depth overview of the causes of movement. Using sEMG, this could incorporate lower body musculature to assess the contribution of the lower limbs to the hit. Due to the limitations of sEMG, musculature of the forearm, trunk and rotator cuff could not be measured here. Investigation of the contributions of these muscles to the hit would prove beneficial to further understanding the movement and acceleration of the shoulders and arms, and the contribution of wrist musculature to ‘cocking’ and ‘uncocking’ of the stick.

- The changes in EMG activity could be measured during various conditions. As variability of movement has been shown to be more prevalent in a hit with task inconsistency, and especially since the introduction of the self-pass rule, changes in EMG activity whilst hitting a moving hockey ball, and how these changes differ as the direction and/or velocity of the ball changes, would be worthy of investigation. Moreover, expert/novice differences in terms of both the timing and consistency of EMG activity of the hits of both a stationary and a moving hockey ball could start to detail modifications in muscular activation, the control of segmental interactions and the adaptations to technique of more skilled players.

- With the identification of muscles that can be targeted for strength training regimes, strength training interventions and their effects on hitting performance could be studied.

- If new techniques become available, a more detailed look at kinematics, particularly of the wrist and elbow, would further confirm kinematic patterns during the hit, and could give greater validity to the assumptions of the contributions of muscular activity and segmental interactions.

6. Conclusions

This study has shown that the field hockey hit progresses as a result of a combination and balance of muscular activity and segmental interactions. Muscular activation appears to initiate the downswing of the hit and causes the initial acceleration of the upper arms before being apparent to regulate the effects of segmental integrations, caused by the acceleration of the trunk, the arms and the hockey stick.

The BSw of the field hockey hit requires little muscular activation from those studied. Activity of trunk musculature generally peaks during the EFSw, consistent with earlier rotation of the trunk and shoulders back towards the target line prior to increased acceleration of the arms and hockey stick. As wrist ‘uncocking’ occurs, shoulder musculature resists the segmental interactions to keep them moving in the direction of the target, whilst arm musculature, particularly of the left side, regulates the maintenance of a more extended left elbow and allows the right arm to become more extended.

Muscular activity proceeds to resist segmental interactions during the late EFSw and through Acc. The combined effects of muscular activity and segmental interactions lead the left arm and stick system to function as a double pendulum consisting of the left arm and the hockey stick whilst the right arm system more closely resemble a triple pendulum consisting of the right upper arm, right forearm and the hockey stick.

The left arm system acts as a double pendulum due to the maintenance of a more extended left elbow throughout the hit and appears to be more predominant in setting the plane of the hit. The right arm system acts in three segments, yet the right elbow does not proceed immediately into extension after flexion. The 'fixing' of the right elbow during the transition between flexion and extension allows segmental interactions, caused by the acceleration of the trunk and the shoulder, to act about the right wrist as opposed to at the right elbow as the wrists 'cock'. The 'fixing' of both elbows allows the shoulders to accelerate the arms and the hockey stick during most of the EFSw before segmental interactions as the wrists 'uncock' cause extension of the right elbow during the Acc phase. As wrist 'uncocking' occurs, trunk musculature resists the interactions at the shoulders to keep them moving in the direction of the target, whilst arm musculature, particularly of the left side, regulates the maintenance of a more extended left elbow and allows the right arm to become more extended.

Muscles acting about the shoulder joint, particularly the anterior and posterior deltoids, do not provide a picture of quiescence as seen in other similar hitting motions. Musculature of the shoulder during the field hockey hit appears responsible for causing the initial acceleration of the arms at the shoulders and may also be attributable to greater shoulder flexion during the downswing as a result of both a shallower swing plane and the step taken towards the ball, both of which may also account for lesser pectoralis activity recorded here compared to the golf swing.

Little activity of right side musculature after the EFSw suggests that the right arm is relatively passive and does not contribute to the acceleration of the stick once the elbow starts extending. The right arm therefore controls the stick and acts more with a supporting role during the downswing. Acceleration of the hockey stick during the downswing appears to come firstly from muscular activity at the shoulders before the wrists ‘uncock’ and it is this ‘uncocking’ that continues to move the stick through the Acc phase towards impact with the hockey ball. The cause of wrist uncocking remains not entirely clear, however evidence suggests that the active slowing of the shoulders may contribute to its initiation.

This study has shown that EMG analysis alone is not sufficient to explain the nature of muscular activity patterns and that the temporal aspects of EMG analysis are paramount to ascertaining the role of muscular activity during movement. A combination of kinematic data and EMG analysis is needed to help fully explain observed EMG activity patterns.

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8. Appendices

Appendix 1. Participant Information Sheet
Appendix 2. Consent Form
Appendix 3. Pre-Physical Activity Questionnaire (PAR-Q)
Appendix 4. Muscle-electrode interface sites and MVC tests.

Participant Information Sheet

Study Title: The Timing and Magnitude of Muscular Activity Patterns During a Field Hockey Hit.

You are invited to take part in the above research project. Before you decide to participate it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask if anything is unclear or if you would like more information.

What is the purpose of the study?
This study will investigate the timing of activity of a range of arm and trunk muscles during the field hockey hit.

What would be involved for me?
At the start of the session, 16 electromyography (EMG) electrodes will be attached to your upper body using adhesive tape. These electrodes passively record muscle activity. Twenty spherical reflective markers will also be attached, to allow your motions to be tracked.

You will then be asked to perform a warm-up, under the instruction of the researcher, before executing six hits. During these hits, your muscle activity and body movements will be recorded.

The entire session should last approximately 60 minutes.

Where will the research take place?
All testing will occur in the Biomechanics Laboratory at the University of Lincoln's Human Performance Centre.

Why have I been invited?
As an experienced hockey player you will be familiar with the hitting activity, and will be able to perform it in a consistent way.

Do I have to take part?
Your participation in this study is entirely voluntary. If you do decide to participate, you have the right to withdraw from the study at any point and to request that your data not be used.

What do I need to do if I wish to take part?
Please read this Information Sheet and ask any questions that you may have relating to the proposed study. If you still wish to proceed then please read and sign

the Consent Form, and return it to the investigator. The latter will ask you to complete a physical activity readiness questionnaire before confirming your participation.

Will my taking part in the study be kept confidential?
Your name will not be revealed in any report or publication, and no reference will be made which could link you to the study. All data collected will be handled in strict confidence, and will be seen only by the members of the research team.

What are the possible disadvantages and risks of participation?
There is a slight risk of injury associated with performing the hits, similar to the risks encountered when hitting a ball during regular practice or competition. These risks will be minimised by the warm-up and by a risk assessment carried out by the researcher prior to the testing session.

Some people may experience minor skin irritation resulting from the adhesive tape used to attach the reflective markers or electrodes, or from the alcohol wipes used to clean the electrode sites.

What are the possible benefits of taking part?
The results of your EMG and motion analyses will be made available to you on request, as will the findings of the completed study. This information may help you to improve your performance.

What if I have any concerns or queries?
For issues relating to the project, please contact either the researcher (Anthony Gorman, anthonygorman@hotmail.com, (07725194914) or the project supervisor (Sandy Willmott, swillmott@lincoln.ac.uk, (01522) 886651).

If you would like to talk to someone about ethical issues relating to the project please contact either Hannah Rigby (hrigby@lincoln.ac.uk, (01522) 837092) or Sandy Willmott (swillmott@lincoln.ac.uk, (01522) 886651) at the University of Lincoln.

Thank you for taking the time to read this information.

Anthony Gorman

Consent Form

Study Title: The Timing and Magnitude of Muscular Activity Patterns During a Field Hockey Hit.

I agree to take part in this research project, and acknowledge that I understand the following statements:

- The full details of the research have been explained to me and I am fully aware of what is expected of me as a participant.
- I am responsible for providing information relating to my health status and/or previous experiences of unusual sensations/reactions caused by physical activity.
- I am not aware of any injury and/or illness that will affect my ability to perform the assessment.
- I am also responsible for reporting any unusual feelings or discomfort felt by myself during the assessment.
- I am aware that I am not obliged to complete the assessments and that I am able to stop at any point, for any reason.
- I am aware that my research results and any information I provide are fully confidential and will only be communicated to others if agreed so in advance.
- My participation in this study is completely voluntary. I understand that I may withdraw from the study at any time and may ask that any data concerning me that have been collected are destroyed.

I have read and understand the information above, and any questions that I had have been fully answered. I agree to participate in this study.

Name (Print):
Signature of Participant: Date:

I declare that I have explained the testing procedure in full and have made myself available for any questions the participant may wish to ask.

Name (Print):
Signature of Researcher: Date:

Appendix 3. Physical Activity Readiness Questionnaire (PAR-Q)

<u>Pre-Physical Activity/Laboratory Questionnaire</u>

Name:____

Date of Birth: ____/____/____

Age: _______

OFFICE USE ONLY		
Date checked:	____/____/____	
Screened by:		
Status: (circle)	Passed	Flag

The purpose of this questionnaire is to ensure that you are physically able to complete the exercise test(s) outlined to you in the Participant Information Sheet. Please answer the questions below honestly and completely. **All information provided is strictly confidential** and will only be viewed by the appropriate departmental staff member. Your co-operation is greatly appreciated.

*Please **CIRCLE** the most appropriate option/s and use **BLOCK CAPITALS** when providing further detail.

1. How would you describe your <u>present level of activity</u>?

Sedentary moderately active active highly active*

2. How would you describe your <u>present level of fitness</u>?

Very unfit moderately fit trained highly trained*

3. Have you had to consult your doctor within the last 6 months? Y/N*

If YES, please give brief details and alert the test/activity supervisor ________________________________

4. Are you presently taking any form of medication? Y/N*

If YES, please give brief details and alert the test/activity supervisor ________________________________

5. Do you suffer, or have you ever suffered from, any of the following:

Asthma? Y/N* Diabetes? Y/N* Bronchitis? Y/N*

Epilepsy? Y/N* High blood pressure? Y/N*

6. Do you suffer, or have you ever suffered from, any form of heart complaint? Y/N*

7. Is there history of heart disease in your family? Y/N*

8. Do you currently have any form of muscle or joint injury? Y/N*

9. Have you had any cause to suspend your normal training/activity during the past two weeks? Y/N*

10. Is there anything to your knowledge that may prevent you from successfully completing the tests that have been outlined to you? Y/N*

Declaration

I have completed this questionnaire honestly and completely and all questions were answered to my complete satisfaction. I undertake to ensure that any change to my ability to participate in physical activity safely is communicated to immediately to an appropriate Department of Sport, Coaching and Exercise Science staff member.

Signature of Subject: _______________________________Date: ____________

I declare that I have reviewed this form in its entirety and have made myself available for any questions the student may wish to ask.

Signature of Researcher: ____________________________Date: ____________

Appendix 4. Muscle-electrode interface sites and Maximal Voluntary Contraction (MVC) tests.		
Muscle	Electrode Placement Site	MVC Test
Biceps brachii	On the muscle mass on the anterior of the upper arm.	Standing with the shoulder in 0° adduction and 0° internal rotation, the hand supinated and the elbow in 90° flexion, resistance on the forearm was applied against flexion of the elbow joint.
Triceps brachii	Two centimetres medial of the midline of the arm, approximately fifty per cent of the distance between the acromion process and the olecranon fossa.	Standing with the shoulder in 0° adduction, 0° flexion and 0° internal rotation, the hand supinated and the elbow in 90° flexion, resistance on the forearm was applied against extension of the elbow joint.
Anterior deltoid	To the anterior aspect of the arm approximately 4cm below the clavicle.	Standing with the shoulder in 0° adduction, 0° internal rotation and in 45° flexion, the hand supinated and the elbow in 0° flexion, resistance on the forearm was applied against forwards flexion of the shoulder joint.
Posterior deltoid	Approximately two centimetres below the lateral border of the spine of the scapula and was angled on an oblique angle towards the arm.	Standing with the shoulder in 0° adduction, 0° internal rotation and in 45° extension, the hand supinated and the elbow in 0° flexion, resistance on the forearm was applied against extension of the shoulder joint.
Latissimus dorsi	Approximately four centimetres below the ridge of the inferior tip of the scapula, half the distance between the spine and the lateral edge of the torso, orientated in a slightly oblique angle of approximately twenty-five degrees.	In a seated position with the shoulder at 45° of abduction, 90° external rotation and 0° of horizontal adduction and the elbow in 90° of flexion, resistance was applied under the elbow against adduction of the arm at the shoulder.
Upper trapezius	Along the ridge of the right shoulder, slightly lateral to and one half the distance between the cervical spine at C7 and the acromion.	Standing with the shoulder in 0° adduction, 0° flexion and 0° internal rotation, the hand supinated and the elbow in 0° flexion, resistance over the acromion process was applied against elevation of the shoulder.
Clavicular pectoralis major	On the chest wall at an oblique angle towards the clavicle, approximately two centimetres below the	In a prone, press-up position with the shoulder in 90° abduction and 0° internal rotation and the elbow in 90° of flexion, resistance on the

	clavicle, just medial to the axillary fold.	upper back was applied against extension of the elbow and flexion and horizontal adduction of the arm at the shoulder.
Sternal pectoralis major	Horizontal on the chest wall, approximately two centimetres medial to the axillary fold, over the muscle mass that arose as the participant medially rotated the arm under resistance.	