AN EXAMINATION OF POSTURAL MUSCLE SYNERGIES

by

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Abstract

It is well known that the coordination of limbs is important for the maintenance of upright posture. The aim of the present investigation was to examine the contribution of muscle synergies to the preservation of upright stance. A 'muscle synergy' is the coordination of muscles into sets, the result being that onset times of muscle activity are formed such that limbs are constrained to act as a single unit in order to achieve the intended task. Synergies are understood to emerge as a component of postural strategies such as the 'hip strategy' or 'ankle strategy'. Previously it has been demonstrated that ankle strategies are utilized for small perturbations and hip strategies are employed for large perturbations. The reaction time (RT) protocol has been used in postural studies as a means for detecting preparation of rapid movements or perturbations. In these experiments the preparation for the task was studied using a simple reaction time (SRT) and choice reaction time (CRT) protocol.

The first experiment examined whether more consistent synergistic patterns existed under the CRT relative to the SRT condition. Also, it was expected that an ankle strategy would be used under the short movement condition and a hip strategy would be employed for the long movement condition. The task involved subjects holding a weighted bar with both hands and performing a rapid straight upper limb flexion of either small or large amplitudes. A significant difference in the RT between SRT and CRT was revealed and occured earlier under the SRT condition compared to the CRT condition. Analysis of strategies revealed that the hip strategy was dominant for both conditions. Within the hip strategy, synergistic patterns were consistent (40% - 100% within conditions) for at least the first two postural muscles activated in both conditions.

A second experiment elucidated the findings of the first experiment. The task was similar to experiment one except that subjects held a dumbbell in each hand. This allowed the difference between the short and long movement extents to be increased. The short movement was under 20° and the long movement was above 80°. A significant difference of RT was found between the SRT and CRT conditions, reaction time occured earlier under the SRT condition compared with the CRT condition. A hip strategy was found to be used for both movement extent conditions. Muscle activation was revealed to be consistent (20% - 90% within conditions) for at least the first two muscles activated.

Dedication

To the Henstridge and Robinson/Bidwell Clans

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Chapter I

INTRODUCTION

It is well known that the coordination of limbs is crucial for the maintenance of upright posture. The control of upright posture is crucial to most motor acts. When a movement is made by an individual, whether simply raising an arm or performing a skilled motor act, gravity and inertial forces have to be overcome if the individual is to remain upright. The aim of the present thesis is to examine the contribution of muscle synergies to the maintenance of upright stance. The term 'synergy' has been used in a number of ways in the literature, however its literal meaning is 'acting together' (Lee, 1980). Therefore, in the present context 'synergy' has been defined as muscles acting together. In addition to a more detailed explanation of synergies, a brief background of areas pertaining to postural control is provided in this introduction. Also, factors relating to maintenance of upright posture, theoretical mechanisms proposed to control posture as well as strategies used to remain upright are highlighted. Finally, a brief methodological background is presented leading to the problem identified for investigation.

General Introduction

A number of functions contribute to ensuring that upright posture is maintained. The major functions of postural control is to maintain equilibrium and to stiffen the linkage between body segments (Belin'kii et al., 1967; Pal'tev et al., 1967; Frank & Earl, 1990). This adjustment ensures that the center of gravity remains in a 'safe' position between an area bounded by the heels and toes (Frank & Earl, 1990; Dietz & Horstmann, 1991). Once equilibrium has been achieved, the stiffened linkages between body segments act as a reference point from which movement may be made to a target position (Nashner & Cordo, 1981; Frank & Earl, 1990; Massion & Deat, 1991).

When a minor disturbance is applied to the body, the visco-elastic properties of the muscles, ligaments and tendons may be sufficient to compensate for most of that disturbance

(Frank & Earl, 1990), however, a large perturbation to the system may require that the individual take a step to prevent falling over. This larger compensation ensures that the center of mass is maintained over the base of support in order to keep an upright position. Inertia is another factor which plays a role in ensuring that upright posture is maintained. This is particularly true for high frequency movements. When the amplitude of an imposed displacement is increased, muscular activity becomes more important for restoring the initial position (Diener, et al., 1984; Frank & Earl, 1990).

The investigation of postural mechanisms has taken many different approaches. For example, biomechanists have studied postural control as a means of revealing the physical properties of movement. Several groups (Oddsson, 1989; Bourbonnais et al. 1992; Eng et al., 1992) have looked at mechanisms of control for specific body positions and others have examined the biomechanical effects of perturbations to upright postural balance (Bouisset & Zattara, 1990). Modeling techniques have been used to simulate postural control of voluntary movement through the mapping of muscle activations and joint angular accelerations (Kuo & Zajac, 1993). Levine (1992) applied multi-input/multi-output control theory to the study of postural control with the intention of creating a dynamic systems model. Computer algorithms have also been used to assess balance control through the observation of muscle latency reaction to an unexpected perturbation (Andres, 1992).

Researchers in motor control have examined posture in order to gain further understanding of how humans coordinate upright stance. Experiments have been undertaken to investigate coordination by disturbing stance using perturbations of voluntary arm movements (Marsden, Merton & Morton, 1981; Friedli, Hallett & Simon, 1984; Kasai & Komiyama, 1991). Often, a behavioural approach has been employed in an attempt to further understand the mechanisms which control sway and adaptive reflexes for maintaining posture (Nashner, 1976, 1977; Nashner, Woollacott & Tuma, 1979; Woollacott, Bonnett & Yabe, 1984; Cresswell, Oddsson & Thornstensson, 1992).

Although maintenance of upright posture has been studied extensively from a behavioural viewpoint, a clear understanding of control mechanisms for coordination remains elusive. Maintaining upright posture after a disruption to the system is a complex process, involving the efficient integration of afferent information from proprioceptors, vision and the vestibular system. Dietz, Trippel, Ibrahim & Berger (1993) focused on the close interactions of different inputs of the sensory system. The relationship between the sensory systems has made it difficult for researchers to assess the relative contribution of each individual system to the overall control of upright posture.

Theoretical Background

One of the primary objectives of the study of motor control , has been to understand and explain coordination and regulation of movement (Bernstein, 1967). Such theories include serial-ordering, integration of perceptual and motor information, skill acquisition and the degrees of freedom problem. Degrees of freedom refers to the number of independent variables to be controlled (Turvey, 1990) a reduction of which has been suggested as a solution for coordination of movement including upright posture. In order for the system to reduce the degrees of freedom, three mechanisms have been identified. First, biomechanics may contribute to control by reducing degrees of freedom through the use of gravity or muscle properties. Second, control may be achieved by making movements efficient, for example by acting through smooth, direct movement paths. Finally, synergistic control can be demonstrated by temporary linkage of muscles which act as a unit and reduce the degrees of freedom. This form of synergistic control provides an interesting explanation for the study of postural control for example, by the dependence between limb segments or muscles (Rosenbaum, 1991).

The term 'synergy' has been used with different emphases for explanations of various investigations (Nashner et al., 1979; Lee, 1984; MacPherson, 1991). Bernstein (1967) introduced the concept of synergy as the coordination of muscles into 'sets'. The result being that onset times of muscular activity are formed such that limbs are constrained to act as a single unit in order to achieve the intended task (Kelso, 1982; Tuller, Fitch & Turvey, 1982; Goodman, 1985; Soechting & Laquianti, 1989; Turvey, 1990). In the literature, the terms 'synergy' and 'strategy' have been widely used in relation to muscular control for upright posture. Although definitions or qualifications of these expressions have not always been clear, a distinction is made here between synergy and strategy. Thus, the term 'synergy' is used to describe the discrete temporal and spatial patterns of leg and trunk muscle contractions for posture. 'Strategy' is used in the broader context to incorporate sensory, motor and mechanical processes subserving postural movements of a given pattern (Nashner & McCollum, 1985).

Behaviourally, there are at least two strategies which may be used to achieve the goal of remaining upright. Horack & Nashner (1986) termed these the ankle and hip strategies. An ankle strategy is understood to be characterized by the initial muscle activated about the ankle joint, with subsequent muscles activated more proximally. Conversely, the hip strategy is identified by a proximal to distal order of muscle activation with the initial muscle activated about the hip joint. The existence of many possible solutions for maintaining upright stance requires that a mechanism exist to choose the appropriate strategy. Once a strategy has been chosen it must then be implemented by activation of a group of muscles in the relevant sequence. This is to say that a coordinated pattern is triggered. MacPherson (1991) has argued that these muscle patterns are not fixed, rather they are formed and reformed with every movement .

While synergies are a possible solution to coordination, understanding how synergies are brought about poses a problem (Weeks & Wallace, 1992). Reflexes, hierarchical control and central programming have all been proposed as possible explanations for how strategies and synergies are controlled. A number of theorists believe that movement is controlled by reflexes. While reflexes are now known not to be the sole means of postural control, they are understood to be continuously elicited for control of postural sway (Marsden, Merton & Morton, 1981). Indeed it has been found, that for small perturbations to the support surface, stretch reflexes are triggered (Woollacott, Bonnet & Yabe, 1984). Hierarchical methods of control suggest that a higher 'executive' directs lower levels to provide a general form of the solution needed to achieve a given task. The lower levels then fine tune the command by integrating sensory information to achieve the final output (Nashner & Cordo, 1981; MacPherson, 1988, 1991). Central programming has also been proposed as yet another means for control of muscle synergies (Woollacott et al., 1984; Horack & Nashner 1986; Forssberg & Hirshfeld, 1994). One of the main components of central programming by the central nervous system (CNS) occurs at lower levels (i.e.. the central pattern generators in the spine), (Forssberg & Hirshfeld, 1994).

Muscle synergies have been further defined on a morphological basis (Lee, 1984). Originally it was believed that these groups were rigid or fixed (Nashner, 1977). If obligatory linkages did exist between muscles, then a reduction in the degrees of freedom would cause individual control to be forfeited (MacPherson, 1991). It may not be possible for fixed synergies to satisfy the number of solutions required. At the extreme, the CNS could control each muscle independently. Separate signals sent to each muscle would create the problem of too many degrees of freedom to be controlled (MacPherson, 1991). More recent work has suggested synergies are flexible (MacPherson, 1991). It appears that synergies provide an acceptable solution for reducing the degrees of freedom to be controlled. Reports in the literature initially implied that postural synergies occurred in a fixed order. Recent studies suggest that the control of synergies occurs in a flexible manner. This indicates that while muscles are activated temporally as a 'set', the ordering of muscle initiation may vary.

Posture Under Perturbations

A number of studies have focused on the factors which influence posture. Belin'kii et al. (1967) and Pal'tesev & E'ner (1967) were the first to demonstrate that for a simple rapid movement, activation of postural muscles preceded activation of the prime mover. Similar findings have been made by other researchers where, in a bimanual task, Biceps femoris was found to be activated almost simultaneously with the trunk muscles which preceded Anterior deltoid (e.g., Friedli, Hallett & Simon, 1984). Belin'kii et al. (1967) proposed that the sequence of muscle activation was stable relative to the motor task.

A few investigators interested in motor responses have looked carefully at muscle preparation and activation before and during a perturbation. (Belin'kii et al. 1967). According to Belin'kii et al. (1967), two relatively stable components constitute the onset responses of muscle activity. They defined the 'preparatory response' as the change in muscle activation of the focal muscle prior to execution of the voluntary arm movement. The change in activation of postural muscles during and after the occurrence of a movement was referred to as the 'compensatory movement' (Belin'kii et al. 1967). More importantly, he stated that the voluntary movement takes place against a background of continuous dynamic stabilization for the body. Lee (1984) has suggested that certain postural muscles are activated in order to reduce inherent sway. The muscle activation comes as an addition to muscles controlling upright posture due to the movement. The background activity may be interpreted as either reflex activity or synergistic activation. Few authors have addressed the issue of background activity specifically nor have they looked at the interactions that may occur between synergies, however Henstridge, Franks & Goodman (1993) have suggested that while a synergy was employed to control posture due to the perturbation caused by the voluntary arm movement, activation of muscles apparently independent of the synergy were executed to maintain upright posture, possibly due to inherent sway.

Methodological Issues

Although various theories have been put forward for control of synergies, evidence has not always been consistent. A wide range of methodological approaches have been taken. Interpretation of data in a number of studies indicate discrepancies between subjects for onset times of muscle activation (Nashner & McCollum, 1985; Crenna, Frigo, Massion & Pedotti, 1987; Weeks & Wallace, 1992). It has been proposed that investigations should aim at determining how the activation timing of postural and focal muscles are related to the task requirements and at which level the central nervous system controls this timing (Lee, 1980). It has also been suggested that rather than collapsing the timing of onsets and losing variability, inter-trial and inter-subject variability should be considered (MacPherson, 1991).

A methodological approach pertinent to this investigation was the use of the reaction time paradigm. This paradigm has been used for postural studies as a means of reducing preparation or anticipation of sudden movements or perturbations. Reaction time has been defined as the measure of the time from when a stimulus is presented to the beginning of the response for that stimulus (Schmidt, 1988). Two paradigms exist for reaction time: 1) simple and 2) choice (CRT). Under the SRT tasks paradigm, reaction time has been found to increase as elements of the task increased in complexity (Henry & Rogers, 1960). The difference between the SRT and CRT methods is the number of choices available to the subject when the stimulus is presented. For SRT, only one choice is available which encourages the preparation of response parameters in advance of the stimulus. For CRT a number of choices are available, which discourages the preparation of response parameters.

A number of researchers investigating postural control (Belin'kii, 1967; Pal'tsev & El'ner, 1967; Lee, 1980; Bouisset & Zattara, 1981; Woollacott et al, 1984; Weeks & Wallace, 1992) have used reaction time to control for anticipation prior to the movement and as a possible means to index factors related to the movement, for example mechanics of the muscle movement (Nashner & Cordo, 1981). Results have not been entirely consistent (Nashner, 1976; Nashner & Cordo, 1981; Williams, 1992). For example, a study by Friedli, Hallett & Simon, (1984) revealed that while relative timing of bursts was specific for certain conditions and varied with the focal movement, reaction time varied across conditions. It was suggested therefore that the changes in focal movement with postural muscles does not depend on the subjects reaction time.

Purpose

The purpose of the present investigation was to investigate the strategies used for control of posture when short and long voluntary arm movements were carried out. In addition, the aim was to examine the muscle synergies used for postural control when these movements were performed. Based on present evidence, the required task was kept as a simple, goal directed shoulder flexion. While some evidence in the literature has shown that synergies are controlled as flexible sets (Lee, et al., 1987; Weeks & Wallace, 1992) it has also been noted that under certain conditions a minimal choice of synergistic solutions are possible (Weeks & Wallace, 1992). The experiments therefore, were designed to force the system to use a limited range of synergistic patterns. The present study specifically sought to reveal similar synergies within constrained conditions. Also of interest was preparation of synergistic patterns under different reaction time conditions.

Chapter II

LITERATURE REVIEW

It is well known that the coordination of limbs is important for upright stance to be maintained. Postural strategies encompass synergies as a component and have been examined in light of their role in maintaining upright posture. Muscle synergies were of interest in this investigation and therefore literature pertaining to synergies has been reviewed. More specifically, preparatory responses prior to execution of a movement have been discussed. In addition, postural responses elicited under a reaction time protocol have been considered.

Postural strategies

The term 'Strategy' has been used in a broad context in the literature to incorporate sensory, motor and mechanical processes subserving postural movements of a given pattern (Nashner & McCollum, 1985). Strategies provide the means to categorize some control mechanisms to maintain upright posture. Thus a few authors have proposed models which utilize strategies to describe the processes involved with preserving upright posture. Synergies are understood to emerge as a component of postural strategies.

A model put forward by Nashner and McCollum (1985) stated the regions in which an individual could move without falling over. They described this as the region of reversibility. Within the region of reversibility, these researchers proposed six strategies which may be employed to ensure that upright posture is preserved. The strategies are: forward hip, forward ankle, backward hip and backward ankle, as well as up and down suspensory movements. Gravitational laws play an integral part in the execution of strategies as does the form of perturbation displacing an individuals upright posture. If the center of mass falls beyond the region of reversibility, it was suggested that a change in strategy may be activated. For example, a stepping or stumbling strategy may be initiated which would move the center of mass to remain over the base of support.

Forward and backward hip and ankle strategies are most commonly addressed in the literature. The forward strategies involve the anterior muscles of the leg and trunk, for example the Abdominals, Quadriceps and Tibialis anterior. The Erector spinae, Hamstring group and Gastrocnemius are the posterior postural muscles usually found in backward strategies. An ankle strategy involves the distal to proximal activation of either anterior or posterior muscles for forward or backward movement respectively. Similar anterior and posterior muscles which activated for the ankle strategy, are activated for a hip strategy but in a proximal to distal order.

In an experiment carried out by Horak and Nashner (1986) subjects stood on support surfaces of different lengths. The supports ranged from longer than foot length (relative to the foot) to shorter than foot length (9cm). The experimental task required subjects to maintain an upright stance while the support surface was abruptly perturbed in either a forward or backward direction. Horak and Nashner (1986) found that different strategies were revealed. For the short surface, a hip strategy was used and for the longer support surface an ankle strategy was employed. Further, combinations of the two strategies were found with an intermediate length support surface. They argued that the support surface lengths and recent experience by subjects are important factors for organizing strategies for a motor task and they suggested that the combination of two or more synergies allowed the individual to respond quickly while dealing with different support surface lengths (Horack & Nashner, 1986). In addition to the support surface lenghths suggested Horack and Nashner, other important factors exist which contribute to the strategies and synergies executed. These may include initial stance adpoted by the subjects, for example the width between the feet alterting the base of support and the positioning of knees and hips at the start of a trial.

Summary - Strategies provide a means for classifying identified control methods employed for maintaining upright posture under different conditions.

Synergies

Definition

The precent investigation has adopted the definition of synergy used by Bernstein (1967) as the coordination of muscles into 'sets'. The result being that onset times of muscular activity are organized such that limbs are constrained to act as a single unit in order to achieve the intended task (Kelso, 1982; Tuller, et al., 1982; Goodman, 1985; Soechting & Lacquaniti, 1989; Turvey, 1990). Much of the research on synergies has concentrated on temporal and spatial patterning of muscles. This has been collectively referred to as the morphological properties of synergies (Lee, 1984). The term 'spatial' indicates that muscles are activated together in anatomical regions . The 'temporal' aspect refers to the onset sequence and timing of muscle activation. It is the combination of temporal and spatial properties of muscles which are controlled to form synergies (Lee, 1984). If a synergy is considered as a fixed unit of control, then the activation of muscles would occur with a fixed temporal pattern (MacPherson, 1991). However, as observed by Soechting and Lacquaniti (1989, cited by MacPherson, 1991), muscle activation patterns are not always found to exhibit consistent timing. While the control of synergies may be viewed as a complex phenomenon, the consistency of synergies may be considered as an integral issue to simplifying control.

Consistency of Synergies

The understanding of how synergies are triggered, composed and controlled has progressed over several decades. Belin'kii et al. (1967) thought that stereotypical patterns of control existed for a given condition. Nashner (1977) sought to find evidence that functionally related postural muscles in the legs are activated by fixed synergistic patterns. In his study, subjects were required to stand on a platform which induced forward and backward sway by translation. The platform was also rotated about the axis of the ankle first as a perturbation and then subjects were allowed to induce ankle rotation themselves. It was found that two forms of stimulation, anterior/posterior sway and ankle rotation, elicited the same fixed pattern of muscle activity among the leg and possibly the lower back, however, the effect on movement at the hip joints was different in each condition. Nashner concluded that the muscle activation linking body segments appeared to be preset by the system.

Conversely, Weeks and Wallace (1992) put forward an argument postulating that synergies appear to be flexible with no 'hard wiring'. They carried out a study that examined velocity effects on postural responses. A rapid elbow flexion in the horizontal plane was performed by subjects to a target (60°), while standing on a force plate. The subjects held a freely moving weighted (1 Kg) manipulandum, which was fixed to a wall, to allow elbow flexion in the horizontal plane. Focal movement was controlled in this task by establishing a spatial error bandwidth for the target location and a temporal error bandwidth for the movement time. Under these constraints, the order of onset and temporal latencies were found to be flexibly organized (Weeks & Wallace, 1992). The variety and flexibility of the sets, or coordinative patterns has led them to argue that control occurs through motor equivalence. Lee et al. (1987) also carried out a study in which they were interested in the organization of postural adjustments. Subjects were required to perform a shoulder flexion under a self-paced condition and under a visual stimulus reaction time paradigm. In their results, a scaling pattern was not found between Hamstring group and Erector spinae EMG amplitudes. However, a consistent distal to proximal order about the hip joint was observed for most subjects (Lee et al., 1987).

Based on the belief that synergies exit, once the order of onset has been determined by the system, fine tuning of synergies may provide the accuracy required for the completion of a task. However, it could also complicate control by increasing the number of degrees of freedom and therefore, increasing the number of parameters to be control. The total number of parameters to be controlled, however, would be less than the number of muscles activated (Nashner & McCollum, 1985; MacPherson, 1988).

MacPherson (1988) has also postulated that fine tuning allows refinement of control by variability of each muscles morphology and mechanical effectivness at a given joint position. In addition, tuning would be more flexible than a fixed synergy system in adapting to demands placed on the body. This is because the basic synergy could adapt through fine tuning rather than being restructured.

It has been found that a given task can influence both the preparation of the postural muscles and the strategy employed for postural maintenance (MacPherson, 1988) of synergistic the pattern executed. The experiment was carried out on cats, in which each animal had eleven EMG electrodes implanted in the left hindlimb and six in the left forelimb. The cats were trained to stand quietly on a force plate, which was composed of four independent triaxial sections, each paw stood on a different section. The plates were perturbed in four different directional translations during quiet stance. Results revealed that some postural muscles (Gluteus and Adductor femoris) were grouped together for varied perturbation conditions. In addition, timing of flexor and extensor leg muscle bursts and their duration's were found to be greatly influenced by the hip joint position. Thus, she suggested that fine tuning, stimulated by platform translation may occur according to limb position. It was concluded that muscles are controlled using a modified synergistic strategy where a synergy is not simply a fixed group of muscles, rather muscles are organized as task dependent mechanisms which are modified as needed with the addition or subtraction of other muscles (MacPherson, 1988).

Recently, it was put forward by Forssberg and Hirschfeld (1994) that the organization of posture by the central nervous system (CNS) could be simplified by the utilization of a few central pattern generators. The aim of the experiment carried out by Forssberg and Hirschfeld (1994) was to investigate which sensory information triggered postural responses (excluding the ankle) and also if muscle synergies act in a stereotypical or modified manner. In their experiment, subjects were seated with their legs supported almost to horizontal, then the base of support was perturbed in one of four directions (forward translation, legs up rotation, backward rotation of the pelvis and a backward sway of the lower trunk). They found that despite the four different movement conditions the muscle activation patterns were similar. Part of their findings revealed early and reliable detection of equilibrium disruption. They argued that the weak relationship found in their experiment between muscle stretch and muscle activity indicated that muscle activation patterns were probably not evoked by reflexes but from a central control mechanism (Forssberg & Hirschfeld, 1994). It was suggested that central pattern generators controlled at the lower level of the CNS would solve the control for rapid responses, due to the speed at which movements are made. They suggested that this contrasts with studies which have shown sensory information from the ankle as critical for maintaining posture in standing.

Based on the premise that postural muscles are synergistically organized (Horak & Nashner, 1986), it was suggested that if an interaction between synergistic components rose above a threshold, scaling properties would be exhibited, that is, where functions which characterize the behaviour of components of a given synergy are not significantly different (Lee, 1984). However, when Lee et al., (1987) compared fast and slow movements, the magnitude of muscle activity under a simple reaction time protocol failed to reveal a scaling pattern. That is, with an increase in movement velocity, the magnitude of the EMG amplitude did not increase in a corresponding fashion.

Preparatory issues

Brown and Frank (1987) stated that a precise interaction exists between the focal movement and anticipatory postural changes for the execution of a voluntary arm movement. Belin'kii et al. (1967) were the first to demonstrate that postural muscles are activated prior to the prime mover (Anterior deltoid). In their experiment, subjects were required to react to an auditory stimulus by either, performing an upward or a downward arm movement. Friedli et al. (1984) used a reaction time protocol in their experiment. Subjects were required to perform an elbow flexion in both a supported and unsupported condition. In the unsupported condition subjects were free standing, while the subjects were strapped firmly to a wall for the supported condition. Friedli et al. (1984) found that in the supported condition a distal to proximal sequence of EMG activity was observed in the postural muscles. The reverse was seen in the unsupported condition. Adjustments of the distal to proximal ordering were found to be brought about in two ways, firstly, through variation of the timing of bursts relative to each other and secondly, by variation of the burst magnitude. It was argued that the postural adjustments were preprogrammed as they began before the focal movement and were specific for the focal movement as well as the postural set. Bouisset and Zattara (1981) used a voluntary arm movement paradigm to show that postural muscles are activated prior to the prime mover. In this experiment subjects were required to make an arm movement from their side, to approximately 80° under fast, slow and self-paced conditions. Different muscle orderings were found under the slow as compared to fast condition. In the slow movement condition Anterior deltoid was found to be activated prior to the postural muscles, but in the fast movement condition postural muscles were generally activated prior to the prime mover (Bouisset and Zattara, 1981; Lee et al., 1987; Henstridge et al., 1993).

Woollacott et al. (1984) attempted to determine whether preparatory processes are controlled in a general manner or if they are controlled with respect to each individual movement. Their experiment was based on the assumption that the postural control system in standing humans is always activated at a certain time interval ahead of the voluntary movement. The task required subjects to pull or push a lever under a choice reaction time (CRT) protocol, while standing on a platform. The subjects controlled the start of the trial once they had balanced the platform to a zero point. The subjects ankles were subsequently rapidly dorsiflexed (3°), at three different time intervals (100, 300 and 500 m/s) before the response signal. The onset of the response signal was then given which necessitated subjects to push or pull on a lever. The purpose of the ankle rotations was to elicit a stretch reflex at the triceps surae muscle. A general preparatory effect of the postural muscles was noted where an equal regulation of reflex excitability in both the measured muscles, Gastrocnemius and Soleus, where the former was facilitated and the latter was inhibited. Thus, Woollacott et al. (1984) concluded that preparatory processes of postural and voluntary arm movement control are linked together and may have a common form of control. Their experimental results supported the hypothesis that the postural system is regulated by preparatory processes. They also proposed that general effects for postural control does exist but they should be considered along with task dependent control as part of a double control system (Woollacott et al., 1984)

The preparation of the postural muscles prior to the execution of the focal movement may influence the form of synergy executed. However, reports of premovement postural activity have failed to provide adequate evidence that postural activity is reliably time-locked to the onset of the task movement (Lee, 1980). That is, the onset of postural muscle activity may be a function of task execution. Thus, it has been proposed that central programs can control synergies through anticipation of external events thereby reducing the individuals need for feedback (Woollacott et al., 1984; McCollum, Horack and Nashner, 1985; Horack & Nashner, 1986). Similar conclusions of preprogrammed postural control were drawn by Bouisset and Zattara (1981). They found that anticipatory movements were present in the lower limbs, hips and trunk before the onset of the voluntary movement of the arms. They argued that postural changes triggered by anticipation are specific to forthcoming movements. These movements which contribute to the general dynamic organization of balance and reduce postural disturbances can therefore, only be preprogrammed (Bouisset & Zattara, 1981).

An experiment by Brown and Frank (1987) proposed that "to preserve the integrity of the intended response, a precise coordination between anticipatory postural adjustments and the primary movement is required." (Brown & Frank, 1987, p645). The aim of their investigation was to resolve whether posture and focal task are both controlled through one command or if a separate process of motor control was used. Standing subjects with elbows at approximately 90° were required to pull or push on a stiff handle as quickly as possible under a precuing protocol. The preparatory set was manipulated in a two choice reaction time task through informing the subjects at the start of each trial of the probability (80, 50 or 20%) that a push or pull task would arise. Subjects were analyzed individually and it was found that only three out of six subjects showed an effect of preparatory set on their reaction time performance. The preparatory effect (for the three subjects whose performance was influenced by the probability information), was found by Brown and Frank (1987) to influence the timing of coordination between the prime mover and postural muscles. For the 80% and 50% conditions, the postural-focal latency remained fixed. This may be due to the influence of postural adjustments on the production of the arm movement. Brown and Frank (1987) suggested that the fixed latency may be to prevent a disruption of balance by early postural muscle activation. The low preparatory set (20% probability condition) revealed that the postural-latency increased. That is, when subjects were instructed to move opposite to the forewarned direction, it was found that reprogramming of the response required more time to stimulate the prime mover than if the correct response had been carried out. In addition, a very limited set of muscle synergies are required for anticipatory postural adjustments. Thus, it was suggested that a separate central command contributes to both postural and focal activation (Brown & Frank 1987).

Summary - Synergies provide a solution for movement by reducing the degrees of freedom to be controlled. Recently it has been argued that synergies are controlled in a flexible manner.

Reaction Time

A methodological approach pertinent to this investigation has been the use of the reaction time paradigm. A series of experiments was carried out by Klapp and Erwin (1976) to investigate the notion that the response duration was a reflection of the programming carried out for that response. The first experiment involved subjects repeating words, with the duration of response analyzed. The design of the second and third experiments were similar to each other. The task required subjects to move a handle along a freely moving track in a given direction. A button on the handle was included as part of the response for the second experiment but not the third. Simple and choice reaction time protocols were used in all three experiments. It was concluded that response programming should allow variation in timing of the response, while accommodating programming time which can increase as a function of response duration alone. Thus, CRT protocol would reveal a longer response time due to preparation than SRT protocol.

The SRT protocol informs the subject of the response prior to presentation of the stimulus, thus preparation can take place prior to the stimulus.

A simple reaction time protocol provides 100% certainty of the task to be carried out, whereas for example, a two choice CRT provides two or more choices of a task to be carried out. As the response is known in the SRT condition, postural preparation can be made prior to the stimulus. Whereas, under a CRT condition, the exact response is not known prior to the stimulus, so a general postural preparation may be made. In addition, when the stimulus has been presented under a CRT protocol, the time to prepare the postural muscles may then be longer than under an SRT protocol. Brown and Frank (1987) proposed a similar argument which was based on their results. They found that more time was required to 'reprogram' the response under a condition where there was low probability of the task occurring, where as the latency remained fixed when a high probability of the task occurred. They suggested that Hick's law could account for the reprogramming. Hick's law states that CRT is linearly related to the Log of the number of stimulus alternatives (Schmidt, 1988). CRT has been found to increase almost consistently every time the number of stimulus-responses are doubled.

A study by Lee (1980) using an SRT protocol, aimed to investigate the components of a premovement pattern. Subjects were required to perform a rapid voluntary unilateral arm movement while standing. The task required the subjects to react to a light stimulus on a board in front of them by raising the appropriate arm from by their side to a horizontal position. The reaction time was measured by a key release, which their hand rested on at the start of each trial. Similarly to Weeks and Wallace (1992), the reaction time of the subjects had to be within a predetermined bandwidth which was calibrated for each subject. EMG was measured from Biceps femoris and Anterior deltoid on both arms. The temporal characteristics of the patterns found, showed considerable variability, especially between the ipsilateral Biceps femoris and the Anterior deltoid. Percentages of onset times varied between and within subjects, although three out of the five subjects almost met the criterion of early onsets of muscle activation by the fourth day. The spatial pattern results showed almost no variance across all subjects. From the results, it was concluded simple, discrete responses may be elicited by complex neuromuscular patterns. It was argued therefore, that the temporal aspect of the response may be determined by central and peripheral sources rather than a single, centrally stored response. Specifically, it was also found that the premovement activity in the Biceps femoris may be considered as part of the voluntary response which probably controlled via a feedforward process similar to that operating for the prime mover (Lee, 1980).

An aim of a study carried out by Kasai and Taga (1992) was to asses EMG activity in order to establish if the timing in postural muscles is preprogrammed. Under an SRT protocol, standing subjects were required to raise their right arm to horizontal as quickly and accurately as possible when an auditory stimulus was given. An electromagnetic weight was attached to the wrist (approximately 7.5Kg). The weight could be switched on or off without the subjects' knowledge. The purpose was to investigate the effect of postural adjustments of subjects who had no prior knowledge of the absence or presence of a load. It was found that no knowledge of the load revealed similar onset times. Kasai and Taga (1992) argued that adjustments are in the higher centers of the CNS and are greatly influenced by an individuals' perception of their postural stability. Thus it appears that in situations when subjects are aware of the task to be carried out, varied EMG onset times are found. Whereas conditions which mask the response until a stimulus is presented reveal similar onset times across different conditions. Further, a range of different EMG onset sequences were also found by Weeks and Wallace (1992) under an SRT protocol.

Lee et al. (1987) tested postural control of subjects performing a voluntary arm movement. They found that recruitment of postural and focal muscles during flexion were sensitive to a number of factors in the experiment, including a difference between results of simple and choice reaction time conditions. They argued that a parallel process of control existed where each group of muscles was influenced differentially by various factors (Lee et al., 1987).

Summary - Reaction time protocol provides a useful methodological approach to investigate preparation of postural activity.

Purpose

It has been suggested that for a given task, a number of different synergies would be possible but in any given instance only one would manifest itself (Nashner, 1977; Nashner and McCollum, 1985). For constant initial conditions, there may be little choice in the patterns of muscle activation to meet the mechanical requirements (MacPherson, 1991). Given such conclusions and evidence previously discussed, in the present investigation it is proposed that under controlled conditions it is possible to illicit similar postural synergies for a specific task.

The aim of the first experiment is to use two spatially and temporally defined displacements to elucidate synergies employed for different control requirements. The two displacements involved a straight arm shoulder flexion to a short and long extent. Due to the different demands on the system to maintain upright posture, it is expected that a different pattern of EMG onset would emerge under each condition. The temporal constraint under a CRT protocol is expected to force the system to reveal more similar EMG onset patterns. The greater preparation time under the SRT condition would allow any of a number of synergies to be executed and also the RT is expected to be shorter than under the CRT condition.

The purpose of the second experiment was to clarify some of the findings from the first experiment. The target and reaction time bandwidth requirements imposed in the first experiment were changed so as to release this constraint and make each condition distinct. The aim of the experiment was to allow the system to reveal different synergistic patterns under each reaction time condition and movement extent.

Hypotheses

Experiment 1

The intention of the investigation was to investigate postural synergies. In particular, by incorporating two differing conditions of a simple arm raising task, it was anticipated that two differing postural strategies would be elicited. Each movement condition required subjects to move to an individually calibrated distance within a calibrated reaction time bandwidth. In the small perturbation condition (short arm movement) an 'ankle strategy' was expected to dominate while in the larger movement a 'hip strategy' was expected.

Research Hypotheses

1) The two separate movement conditions will give rise to different postural strategies.

Rationale

The task was a voluntary arm movement, thus, according to the literature a hip strategy would normally be employed. However, in studies which have used large scale, non-self paced arm movements, a hip strategy was found. Evidence of an 'ankle' strategy has been found when small perturbations have been applied to posture. Thus, it was thought that if a relatively small perturbation could be applied by means of an arm raising task, then an ankle strategy would predominate.

2) Synergistic patterns will exhibit more consistency under the CRT condition than the SRT condition.

Rationale

The time available to prepare for each movement is different for the SRT and CRT conditions. Under the SRT condition, the subject would know the task requirement before the stimulus was presented and therefore could prepare for the movement in the most appropriate and efficient manner. The CRT condition would impose a preparation constraint on the subject. While the subject would know the choice of tasks to be carried out, they would not know exactly which response would be required. This may result in a general form of preparation which would take place prior to presentation of the stimulus. Once the stimulus occurred, then the subject would be forced to detemine the synergy to be used prior to performing the task as rapidly as possible. Therefore, it is expected that the most easily viable and therefore similar synergies would be executed.

Experiment 2

The second experiment was a modified design of the first experiment. The use of targets with individually calaibrated accuracy bandwidths and bandwidths for reaction time used in experiment one, were altered in the second experiment. The extent condition was designed so that the short movement was under 20° and the long movement was over 80°. It was thought that the criterion movements in experiment one were not different enough, due to constraints of the bandwidths used. A clearer form of synergy was expected to be exhibited in the second experiment when a more extreme range of movement conditions was presented to subjects

Research Hypotheses

The research hypotheses were the same as for experiment one.

Chapter III

EXPERIMENT 1

Methodology

Subjects

Eight males from the student population served as volunteer subjects (age range 19 to 29 years). The subjects were given information regarding procedures of the experiment and signed a consent form (Appendix A). The procedure was then explained to the subjects. All subjects were paid $10.00 on completion of the experiment.

Data Collection

The subjects were tested individually. Each subject stood in front of the target panel with their toes placed against a line marked on the floor 58cm away from the panel. The stimulus and warning lights were mounted on the panel, which was angled away from the subjects. The long movement stimulus light was positioned above the warning light and the short stimulus light was positioned below. The lights were adjusted to an appropriate height on the panel for each subject. After each trial, the experimenter gave verbal quantitative feedback of reaction time.

Electromyographic information was obtained from muscles of the right side of the body which included Anterior deltoid (as the prime mover), Erector spinae (lumbar), Biceps femoris, Rectus femoris, medial head of Gastrocnemius and Anterior tibialis. Six channels were used from an eight channel EMG system. Pre-amplified, silver/chloride surface electrodes were attached on the six muscles (Delagi et al. 1975) after appropriate preparation of each site.

A potentiometer was used to measure arm displacement and subsequently derive reaction time. It was aligned with the head of the humerus on the right side then attached with tape and velcro bands. Two strain-gauge goniometers (Penny and Giles) were used to measure change in position at the ankle and hip joints. The first was attached on the right side to the lateral side of the pelvis (proximally, parallel to the anterior superior iliac spine then across the head of the femur for the distal attachment). The second goniometer was attached to the posterior surface of the lower leg (distally to the posterior surface of the calcaneous then proximally, between the two heads of Gastronemius).

All analog signals were sampled at 1000Hz by means of a 10 channel A/D converter, which interacted with a personal computer (486 DOS compatible, Figure 1). Information was gathered from the potentiometer, goniometers, accelerometer and the EMG electrodes were displayed on the computer monitor after each trial, which was not visible to the subjects. Initiation of movement was displayed on the monitor by a marker perpendicular to the displacement trace. The subject's reaction time was also shown on the monitor but only to the experimenter.

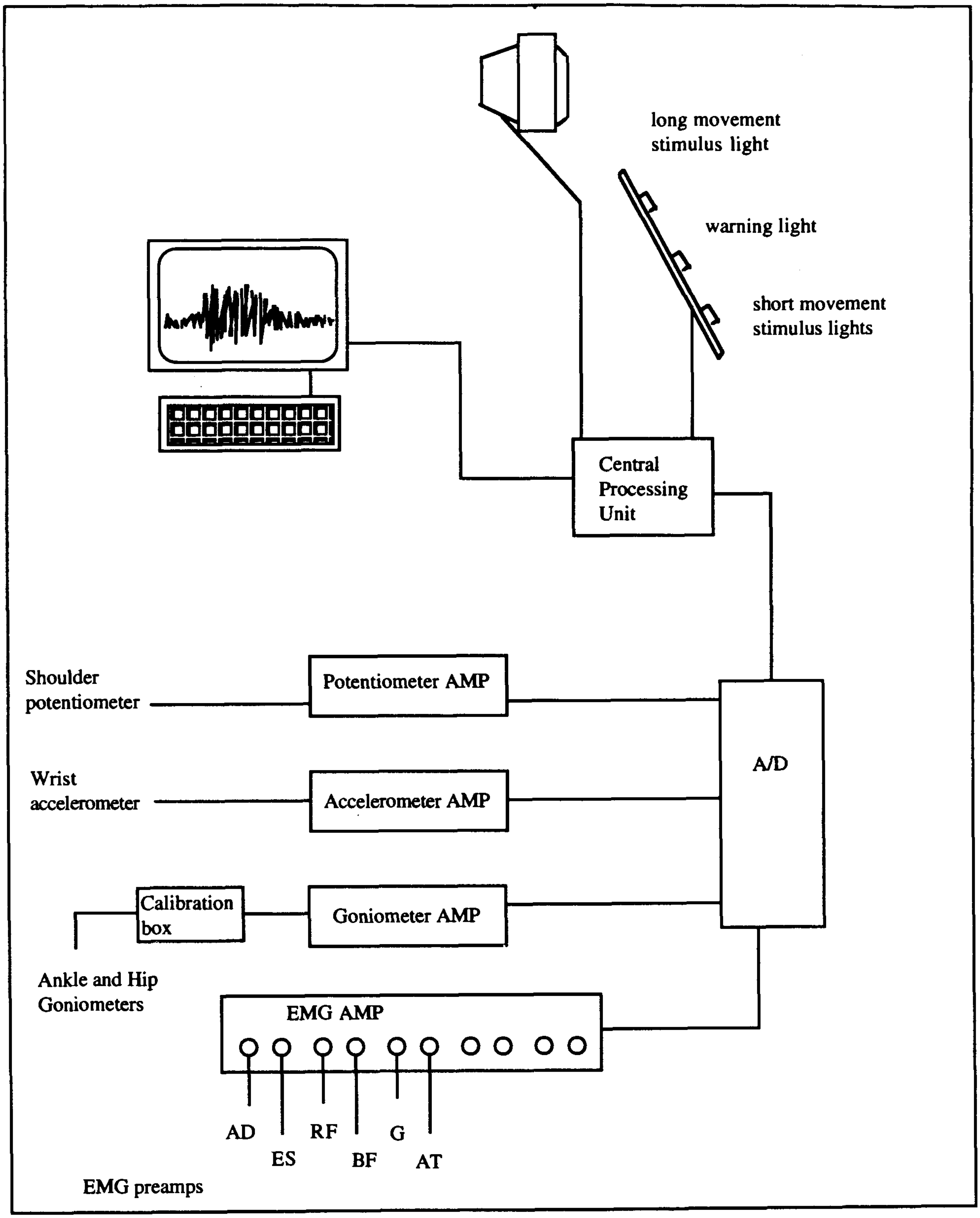

Figure 1. Schematic diagram of experimental design

Conditions

Two conditions were used: simple reaction time (SRT) and choice reaction time (CRT). From the five practice trials, a median RT was estimated and used as the criterion value. Trials were accepted if they fell within a ± 100 ms bandwidth of a median value estimated from practice trials. The conditions were calibrated for each individual for both the short and the long movements. Subjects were asked to move rapidly to a short distance which was calibrated as their target after replicating the movement to the same point five times. The zero degrees was calibrated as the point at which their arms were relaxed, while standing holding the weight. Therefore across subjects, zero was approximately between 5° and 15° from vertical. The same procedure was carried out for the long target ensuring both targets were in the subjects visual range. The targets ranged across subjects from 25° to 40° for the short target and 54° to 77° for the long target. A criterion was established so the accuracy of each trial could be monitored. The accuracy to target was accepted within a ±10° bandwidth of the subjects target value. A total of ten valid trials were collected for each condition. In the SRT condition a block of five trials for each movement extent was collected, with movement extent trials collected in a random manner in the CRT condition. Five practice trials of each movement extent were given at the start of the experiment. The conditions were presented in a random manner across subjects. Trials with errors of greater than ±10° accuracy of the target or with reaction time greater than ± 100 msec of the criterion RT established during their practice trials were not accepted as valid trials.

Task

While standing, each subject was required to perform a rapid shoulder flexion, while holding a single weighted bar with both hands in front of their hips (Figure 2). The weight of the bar was scaled by 1Kg (4.8Kg to 6.8Kg) for every change in 5Kg of grip strength (range 55Kg to 48Kg) scored from the grip dynamoneter. A median value was taken from three grip strength scores performed by each subject.

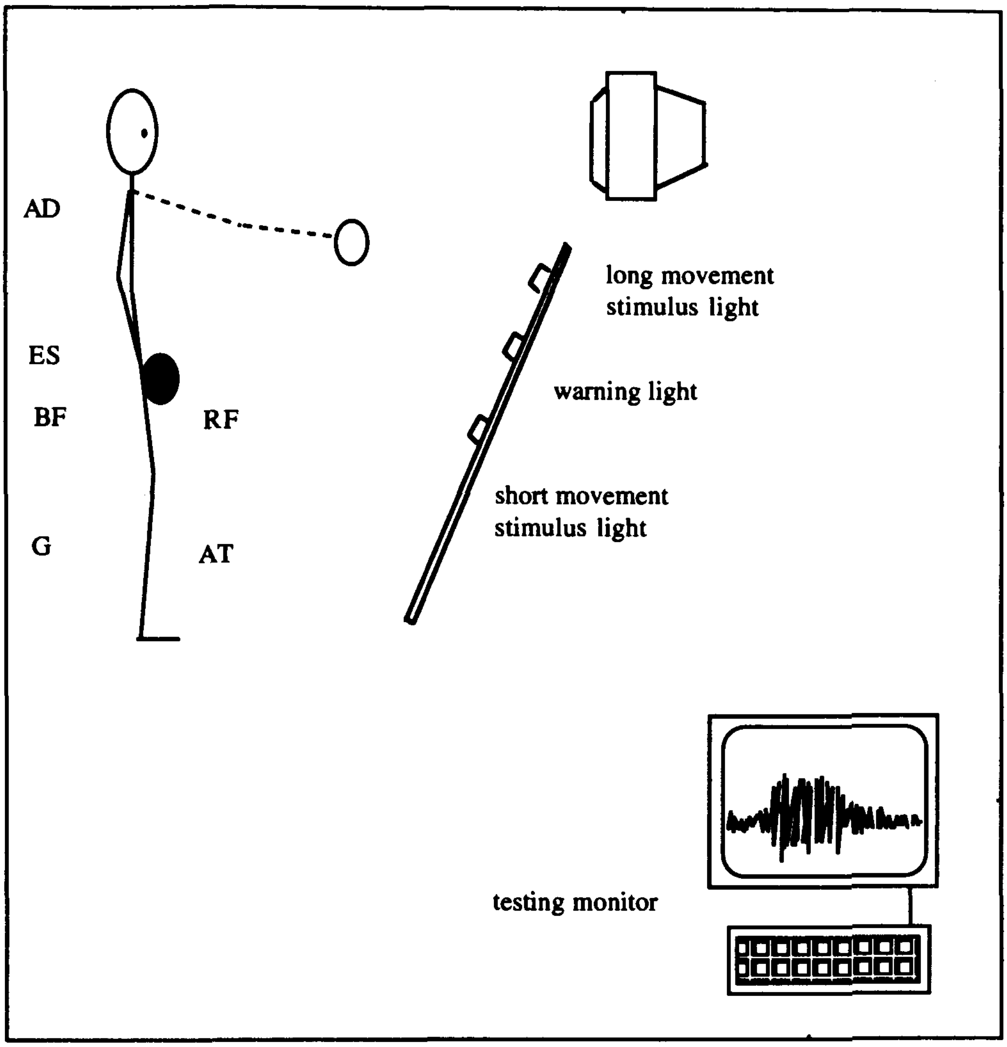

Figure 2. <u>Experimental set up</u>. Muscles measured include (AD - Anterior deltoid; ES - Erector spinae; BF - Biceps femoris; RF - Rectus femoris; G - Gastrocnemius; AT - Anterior tibialis). In addition, a potentiometer was attached to the right shoulder, an accelerometer attached to the right posterior side of the wrist and goniometers attached to the right hip and ankle.

Given that postural sway is inherent in upright humans (Marsden et al. 1981) the subject was asked to stand relaxed, while holding the weighted bar for 20 seconds in order to obtain a baseline of EMG data.

Procedure

An orange visual warning cue was given to the subject at the start of each trial. After a variable foreperiod (1400 - 2500 msec, with data collected for the last 500 msec; Figure 3), a red stimulus light was presented. Subjects were required to react as fast as possible moving their arms from a relaxed position in front of their hips to the required target position. Under the SRT condition, the movement magnitude was known prior to the start of the trial. Under the CRT condition, magnitude of movement was presented simultaneously with the stimulus.

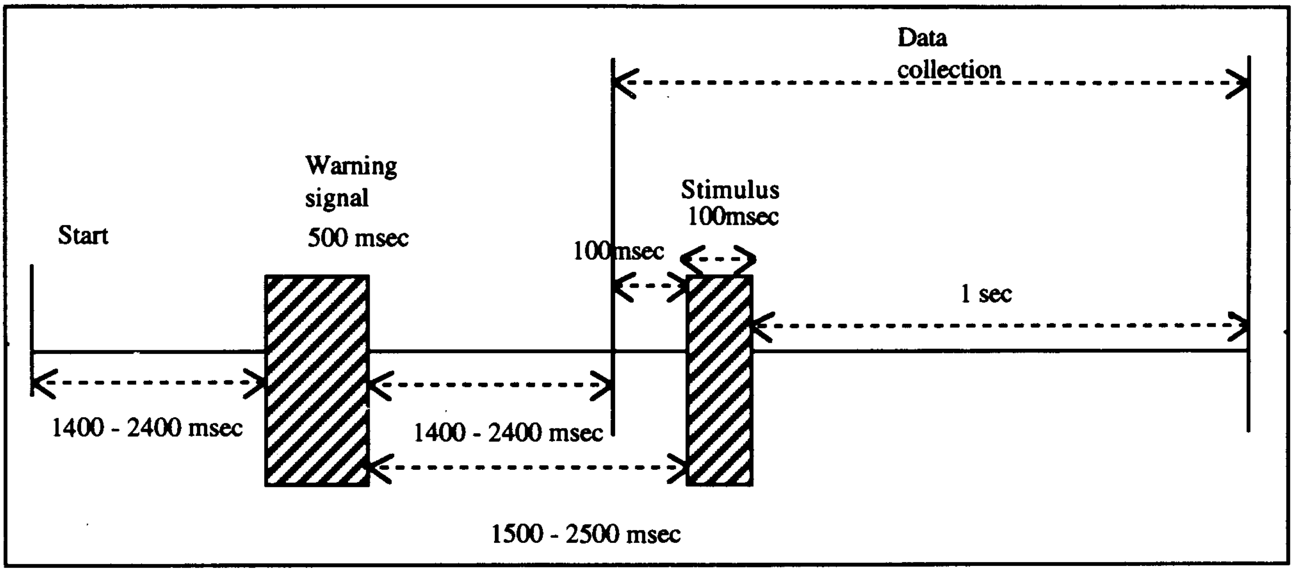

Figure 3. Data collection time series.

Data Analysis

The EMG signal was rectified and low pass filtered at 30Hz with a fourth order Butterworth filter (with zero lag) and compared simultaneously against the raw rectified signal. Three EMG traces were displayed on the monitor at one time to allow a clear resolution for accuracy of placing markers. An interactive in-house algorithm was used in order to identify the initiation of muscle activation. For each trial a cursor was placed at the start of each initial burst of muscle activation, which was adjusted manually when necessary[1]. The markers were placed to identify the initiation of muscle activation shown by the EMG trace. The reaction time was defined through manual placement of a marker at the first observable change in direction of the displacement trace after presentation of the stimulus. The trace was viewed on the monitor with Anterior deltoid EMG trace as a reference guide.

The kinematic data from the hip and ankle goniometers were analyzed by placement of a marker at the first change in movement after the stimulus had been presented. The information with respect to EMG and displacement data were imported to a spread sheet for further analyses.

Onset times of muscles for each trial were sorted according to onset times. A lower cut off point for onset was established[2] at 60 msec. The data were imported to a spread sheet (Microsoft Excel) for individual trial analysis.

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[1] The criterion for placing markers for EMG onset was at the start of a burst, when the trace did not fall back to the base line. For most muscles this was obvious, however with G, AT and sometimes RF, a continuous series of bursts were observed. It was not always possible to distinguish which, if any of the bursts were resultants from the stimulus.

[2] Any EMG activity below 60msec may not be as a result of reacting to the stimulus but possibly due to reflexes maintaining upright posture due to sway. Continuous bursts of G for example were observed before and after the stimulus was presented. While such a measure has not specifically been addressed in the literature (known to the author), EMG data displayed on a graph (Freidli, Hallett and Simon, 1984) showed minimum onset values at 60 msec. Other authors have mentioned taking values of minimum between 90 - 120 msec.

Statistical Analysis

Reaction time was obtained from the displacement trace. The median value for reaction time for each condition was calculated. A two way repeated measures ANOVA was calculated (condition (2) x extent (2) x subject (8) RM).

Each trial was ranked according to onset time of each muscle. Trials were categorized into either hip or ankle strategy, in order for synergies to be assessed within each strategy. A criterion was developed to categorize trials into a strategy by the first muscle onset. If the ES, BF or RF were onset first, then the trial was categorized as a hip strategy; if AT or G were onset first, then the trial was categorized as an ankle strategy. Percentage frequency for each strategy was calculated with conditions collapsed over subjects. Within each strategy consistency of synergies were determined. Consistency of synergistic patterns was defined as the onset of the first two or three muscles activated in the same order within trials (Friedli et al. 1984; Bouisset and Zattara, 1981). A further analysis only considering the activation order of ES and BF was also carried out in order to compare results with the finding of Friedli et al. (1984).

The median onset time of each muscle was calculated across trials for each condition within subjects relative to the stimulus and Anterior deltoid. A two way ANOVA with repeated measures was carried out (condition (2) x extent (2) x subject (8) RM). Initiation of muscle activation within conditions was normalized (M_N) to AD using equation 1. A median value was then calculated from the normalized values and a two way ANOVA with repeated measures was carried out for each muscle across conditions.

$$(M_N) = \frac{\text{AD - muscle}}{\text{AD}} \qquad \text{equation 1.}$$

Results

Reaction Time Data

An initial analysis was carried out on the reaction time data using a two way ANOVA with repeated measures (condition (2) x extent (2) x subjects (8) RM). Reaction time was taken from the displacement trace and defined as the first observable change in movement after presentation of the stimulus. A significant difference was found for reaction time condition between simple and choice reaction times ($F(1,7) = 21.76$; $p<0.002$), however no significant difference was found for extent between the short and long distances (Table 1; Appendix B). No interaction was found.

Table 1. Reaction time (msec) means across subjects for simple and choice reaction time conditions

	SRT		CRT	means
short	208	<	271	240
long	221	<	268	244
means	214	<	269	

Frequency of strategies and synergies activated

Trials were sorted into different strategies. For each trial, muscles were sorted by activation time (Table 2). The earliest onset muscle was used for categorization into either hip or ankle strategy. It was found that between 72 and 85 % of trials could be categorized as a hip strategy, with between 15 and 25 % of trials categorized as ankle strategy (Table 2).

Table 2. Percentage frequency of activation for hip and ankle strategy

		Hip	Ankle
SRT	short	85%	15%
	long	85%	15%
CRT	short	77.5%	22.5%.
	long	75%	25%

Table 3. Frequency of synergy patterns activated within trials for each subject (S1 - S8)

	SRT				CRT			
	short		long		short		long	
	activation order	frequency	activation order	frequency	activation order	frequency	activation order	frequency
S1	ES-RF-AT	60%	ES-RF	60%	RS-RF	80%	ES-RF	100%
S2	AT-RF-ES	60%	RF-ES	100%	RF-ES	60%	RF-ES	40%
S3	RF-ES	40%	AT-RF-ES	40%	AT-RF-ES	40%	RF-AT-ES	40%
	ES-RF	40%						
S4	RF-ES-BF	60%	RF-ES-G	40%	ES-G-BF	60%	RF-G-ES	40%
			G-ES-RF	40%				
S5	RF-ES	40%	RF-ES	60%	RF-ES	40%	ES-RF	40%
S6	AT-ES-RF	40%	RF-ES-AT	60%	RF-ES	40%	RF-AT-ES	40%
S7	RF-ES	60%	RF-ES-AT	40%	RF-ES	60%	ES-RF-AT	60%
S8	RF-ES-BF	40%	no	consistency	G-ES-BF	40%	no	consistency
					G-RF-BF	40%		

Table 4. Frequency of activation by Erector spinae and Biceps femoris within trials for each subject (S1 - S8)

	SRT				CRT			
	short		long		short		long	
	activation order	frequency	activation order	frequency	activation order	frequency	activation order	frequency
S1	ES-BF	80%	ES-BF	100%	ES-BF	60%	ES-BF	40%
	no BF	20%			no BF	40%	no BF	60%
S2	ES-BF	40%	ES-BF	60%	ES-BF	80%	ES-BF	80%
	no BF	60%	no BF	40%	no BF	20%	BF-ES	20%
S3	ES-BF	80%	ES-BF	100%	ES-BF	100%	ES-BF	100%
	no BF	20%						
S4	ES-BF	80%	ES-BF	100%	ES-BF	100%	ES-BF	100%
	BF-ES	20%						
S5	ES-BF	40%	ES-BF	100%	ES-BF	100%	ES-BF	100%
	no BF	60%						
S6	ES-BF	100%	ES-BF	100%	ES-BF	100%	ES-BF	100%
S7	ES-BF	100%	ES-BF	100%	ES-BF	100%	ES-BF	100%
S8	ES-BF	100%	ES-BF	100%	ES-BF	100%	ES-BF	100%

An analyses of synergistic patterns within the hip strategy revealed consistency of synergistic patterns within each condition. The most common order of muscle activation was ES-BF, however, two patterns were sometimes present in each condition (Table 3). Of the ankle strategies found consistent synergistic activation was also revealed. There were no trends for different patterns between reaction time or movement extent conditions (Table 3). When the activation order of only ES and BF was considered, it was found that the activation of ES prior to BF dominated every condition (Table 4).

Given that no difference was found between the reaction time and extent conditions, a more detailed analysis of individual muscles was made. The next stage in the analysis was to consider the latency of activation for each muscle. Analyses were carried out for muscles relative to the stimulus (absolute time) and by normalization of the onset times relative to AD.

Latencies between muscles relative to the stimulus

Reaction time condition

A two way ANOVA with repeated measures (condition (2) x extent (2) x subject (8) RM) was carried out on each muscle relative to the stimulus (Appendix B). A significant difference was found for all muscles except G, (AD ($F(1,7) = 55.27; p<.005$); ES ($F(1,7) = 30.63; p<.001$); BF ($F(1,7) = 28.99; p<.001$); RF ($F(1,7) = 10.12; p<.016$); AT ($F(1,6) = 14.06; p<0.01$). The activation times showed that muscles under SRT were onset quicker than muscles under the CRT condition (Table 5). No interaction was found.

Extent condition

The same ANOVA format was used to compare activation latencies of postural muscles with the prime mover activation time (Appendix B). No significant differences were found. A trend for AD, ES and BF revealed short movements to be activated quicker than the long movements, with the reverse trend for the lower leg muscles (AT and G; Table 5). No interaction was found.

Latencies between prime mover and postural muscles

Reaction time condition

The results from the two way ANOVA with RM, for muscle activation times relative to Anterior deltoid revealed a significant difference for G (F(1,6) = 7.764; p<.0317) with no significant difference for EF, BF, RF and AT (Appendix B). The activation times showed that CRT was activated quicker than SRT under G, while the non significant muscles demonstrated the reverse (Table 6). No interaction was found.

Extent condition

The ANOVA results showed a significant difference for G (F(1,6) = 7.76; p<.032) and AT (F(1,7) = 9.829; p<.017), with no significant difference for the trunk muscles (ES, BF and RF; Appendix B). The activation times demonstrated that the short movement was activated quicker relative to the long movement for all the muscles except RF where the long movement was activated prior to the short movement (Table 6). No interaction was found.

The catch trials included in the design were analyzed to check for AD activity. None of the subjects showed EMG activity of AD. For most subjects, continuous bursts of activation of G and sometimes AT were observed for the whole trial.

Table 5. Main effect and cell means for absolute onset times (msec) of each muscle

			Main	Effects		Main	Effects		Cell
Muscle	Condition	Trend	Mean	Extent	Trend	Mean	Condition	Extent	Mean
AD	SRT	S<C*	164	short	s<l	187	SRT	short	162
	CRT		211	long		188	SRT	long	166
							CRT	short	213
							CRT	long	210
ES	SRT	S<C*	152	short	s<l	171	SRT	short	144
	CRT		197	long		178	SRT	long	160
							CRT	short	198
							CRT	long	196
BF	SRT	S<C*	230	short	s<l	247	SRT	short	232
	CRT		298	long		280	SRT	long	229
							CRT	short	263
							CRT	long	332
RF	SRT	S<C*	140	short	s<l	155	SRT	short	143
	CRT		169	long		155	SRT	long	137
							CRT	short	166
							CRT	long	173
G	SRT	S<C	223	short	l<s	254	SRT	short	238
	CRT		271	long		240	SRT	long	207
							CRT	short	270
							CRT	long	273
AT	SRT	S<C*	200	short	l<s	251	SRT	short	201
	CRT		273	long		222	SRT	long	198
							CRT	short	301
							CRT	long	245

* significant p<.05

Table 6. Main effect and cell means for onset times (msec) of each muscle relative to Anterior deltoid

		Main	Effects			Main	Effects		Cell
	Condition	Trend	Mean	Extent	Trend	Mean	Condition	Extent	Mean
ES	SRT	S<C	0.107	short	s<l	0.109	SRT	short	0.117
	CRT		0.148	long		0.147	SRT	long	0.098
							CRT	short	0.101
							CRT	long	0.196
BF	SRT	S<C	-0.431	short	s<l	-0.410	SRT	short	-0.667
	CRT		-0.176	long		-0.197	SRT	long	-0.195
							CRT	short	-0.152
							CRT	long	-0.199
RF	SRT	S<C	0.182	short	l<s	0.182	SRT	short	0.210
	CRT		0.157	long		0.157	SRT	long	0.154
							CRT	short	0.219
							CRT	long	0.096
G	SRT	C<S*	-0.540	short	s<l*	-0.515	SRT	short	-0.732
	CRT		-0.176	long		-0.201	SRT	long	-0.347
							CRT	short	-0.298
							CRT	long	-0.054
AT	SRT	S<C	-0.056	short	s<l*	-0.246	SRT	short	-0.185
	CRT		-0.229	long		-0.039	SRT	long	0.073
							CRT	short	-0.306
	* significant	p<.05					CRT	long	-0.152

Discussion

A significant difference was found between the SRT and CRT conditions. This finding complies with Hick's Law, where the increased choice response resulted in an increased RT. Comparison of the RT for extent conditions revealed no significant difference between the short and long movements.

Choice of postural strategies

Of particular interest to this study were the strategies and synergistic patterns within those strategies used to perform the arm movements. It was hypothesized that a different strategy would be used in each movement extent. That is, that an ankle strategy would be utilized in the short movement condition and a hip strategy would be used in the long movement. Studies in the literature have investigated large arm movements and found the hip strategy to be employed but, at present, none has utilized a short arm movement. Studies which have investigated small movements due to sway found that ankle strategies were used, and larger movements elicited the use of the hip strategy. While a hip strategy was found to be dominant in both movement conditions for this experiment, ankle strategies were also observed. Thus the hypothesis cannot be upheld.

Consistency of synergistic patterns

It was hypothesized that synergistic patterns would be more consistent under the CRT condition than the SRT condition. It was found that there was no difference in consistency of synergistic patterns between reaction time conditions. The synergies which were revealed demonstrated a variety of onset patterns within conditions and subjects. The implication of this finding is that while some consistency exists, synergies may be controlled in a flexible fashion.

Activity of the postural muscles was found to be activated in a distal to proximal order (RF - ES). The order of activation occurred almost twice as many times as the second dominant synergy which had a proximal to distal order of activation (ES-RF).

The different methods of analysis which have been used in the literature which makes comparison of the data difficult. Friedli et al. (1984) reported a consistent distal to proximal ordering of muscle activation for ES and BF. When these two muscles alone were analyzed in the present experiment the same order of activation was dominant. Further, it was RF and not ES or BF muscles which was activated initially in the full analysis.

Latencies between postural muscles relative to the stimulus

SRT versus CRT

The activation time for the majority of muscles was found to be significantly shorter for the SRT than the CRT condition. The results support the assumption that since the response in the SRT condition was known, the movement can be prepared for *a priori* to the stimulus. Such a preparation cannot be completed for the CRT condition as the required response is not known until presentation of the stimulus occurs.

Long versus short movement

No significant difference in muscle activation latency was found between the short and long movements for all muscles although the trend was for the short movements to be activated earlier than the long movements. Friedli et al. (1984) carried out an experiment where subjects were required to perform an elbow flexion at 50°, 70° and 90°. From their results they too observed a tendency for postural muscles to be activated earlier in the smaller movements.

Latencies between prime mover and postural muscles

SRT versus CRT

It was found that the activation time of the prime mover relative to the postural muscles was not significantly different between SRT and CRT conditions, except for G. A tendency was apparent for the latency between the prime mover and the postural muscles to be greater under the SRT than the CRT condition. Brown and Frank (1987) used three different precues (subjects were provided with a probability of 20%, 50% or 80% chance that a particular response would be required prior to onset of the stimulus). They found no significant difference in reaction time between the 50 and 80% conditions. In the present experiment, those conditions may be compared with the CRT condition (50%) and the SRT condition (100%), respectively. The non significant findings may be due to coupling of postural muscles with the prime mover. The postural muscles were found to be activated about the time when Anterior deltoid was activated.

Long versus short movement extent

It was found that the latency between the prime mover and the lower leg muscles (G and AT) were significantly different between the short and long movements. The non significant difference of the other postural muscles may be the result of task dependency. The activation of those muscles may occur at a latency coupled with the prime mover in order for posture to be maintained due to the response.

Conclusion

Experiment one revealed that different preparation times of movement occur under SRT and CRT conditions, prior to execution of the task. It was also shown that a hip strategy was dominant for both the short and long movement extents. Consistent synergistic strategies within the hip strategy were demonstrated across conditions.

Chapter IV

EXPERIMENT 2

The results from the first experiment demonstrated that a hip strategy was the dominant consistent synergistic pattern across conditions. A non significant difference was found for reaction time between the short and long movements. Thus it was concluded that the movement conditions were not different enough from each other. In order to further elucidate the findings in the first experiment, modifications were made in the second experiment to the task protocol. The short movement condition was a minimal movement (under 20°) with the long movement being kept above 80°. In addition, the specific targets and reaction time bandwidth were removed. Further, subjects were required to hold a dumbbell in each hand by their side rather than holding a single bar with both hands in front of their hips as in experiment one.

Methodology

Subjects

Six males from the undergraduate and graduate students served as volunteer subjects (age range 27-34yrs). These subjects were first given information regarding procedures of the experiment and then signed a consent form (Appendix A). The procedure was then explained to the subjects. All subjects were paid $15.00 upon completion of the experiment.

Data Collection

Subjects stood in front of the target panel. Toes were placed against a line marked on the floor 58cm away from the panel. Stimulus and warning lights were mounted on the panel, angled away from the subjects. Stimulus lights were arranged in a longitudinal axis, the warning light in the middle with the short and long lights above and below, respectively, each approximately 2cm apart. After each trial, the experimenter gave verbal quantitative feedback of reaction time. As with experiment one, the EMG and kinematic data were collected in the same manner, although an accelerometer was not used.

Conditions

As with the first experiment, two conditions were used, SRT and CRT. Subjects performed a minimum of five practice trials to learn to move to a short distance, (under 20°) and a long movement (over 80°). A reading of the degree to which the right arm moved was given by the computer, from information obtained from the potentiometer attached to the right arm of the subject. Ten valid trials were collected for each condition. In the SRT condition a block of five trials for each movement extent was collected, with movement extent trials collected in a random manner in the CRT condition. Five practice trials of each movement extent were given at the start of the experiment. The conditions were presented in a random manner across subjects. Trials were rejected if they were above 20° for a short movement and under 80° for a long movement.

Task

While standing, the subject was required to perform a rapid shoulder flexion with a straight arm while holding a lightly weighted dumbbell (.8Kg each) in each hand.

The procedure, data analysis and statistical analyses were similar to that carried out in experiment one.

Results

Reaction Time Data

An analysis was carried out on the reaction times using a two way ANOVA with repeated measures (condition (2) x extent (2) x subjects (8) RM). A significant difference was found for condition between simple and choice reaction time ($F(1,5) = 354.83; p<.05$) with no significant difference found for extent between the short and long distances (Table 7; Appendix B).

Table 7. Reaction time (msec) means across subjects for simple and choice reaction time conditions

	SRT		CRT	means
short	244	<	299	272
long	229	<	304	266
means	237	<	301	

Frequency of strategies and synergies activated

Sorted trials by onset time were categorized into either hip or ankle strategy (Table 8; Appendix B). It was found that between 85% and 93% of trials revealed the hip strategy, with between 6% and 15 % of trials could be categorized as ankle strategy.

Table 8. Percentage frequency of hip and ankle strategy

		Hip	Ankle
SRT	short	93%	6.67%
	long	85%	15%
CRT	short	86%	13.3%
	long	85%	15%

Table 9. Frequency of synergistic patterns activated within trials for each subject (S1 - S6)

	SRT				CRT			
	short		long		short		long	
	activation order	frequency	activation order	frequency	activation order	frequency	activation order	frequency
S1	ES-BF	60%	ES-BF	90%	ES-G-BF	30%	ES-BF	60%
S2	ES-BF	60%	ES-BF	30%	ES-BF	40%	ES-BF	30%
	BF-ES	40%	BF-ES	70%	BF-ES	50%	BF-ES	60%
S3	BF-ES	40%	G-ES-BF	50%	RF-BF	60%	G-ES-BF	30%
			G-BF-ES	20%	AT-RF-BF	20%	BF-ES	30%
S4	ES-BF	60%	ES-BF	50%	BF-ES	70%	ES-BF	60%
	BF-ES	40%	BF-ES	40%			BF-ES	30%
S5	ES-BF	60%	ES-BF	90%	ES-BF	50%	ES-BF	70%
							G-ES-BF	20%
S6	ES-BF	60%	ES-BF	50%	ES-BF	60%	ES-BF	90%
			BF-ES	20%	BF-ES	30%		

Consistency of synergistic patterns within each trial was found with the most common order being ES-BF, however, two different patterns were usually present within conditions (Table 9). There were no trends for different patterns within reaction time or movement extent conditions (Table 9). When only ES and BF were considered for activation order, it was found that both patterns were almost evenly dominant across conditions, but no trend for onset of a particular pattern within conditions (Table 10).

Table 10. Frequency of activation by ES and BF within trials for each subject (S1- S6)

	SRT				CRT			
	short		long		short		long	
	activation order	frequency	activation order	frequency	activation order	frequency	activation order	frequency
S1	ES-BF	90%	ES-BF	90%	ES-BF	70%	ES-BF	90%
	BF-ES	10%	BF-ES	10%	BF-ES	10%	BF-ES	10%
S2	ES-BF	60%	ES-BF	40%	ES-BF	50%	ES-BF	40%
	BF-ES	40%	BF-ES	60%	BF-ES	50%	BF-ES	60%
S3	ES-BF	30%	ES-BF	70%	ES-BF	10%	ES-BF	40%
	BF-ES	70%	BF-ES	30%	BF-ES	90%	BF-ES	60%
S4	ES-BF	60%	ES-BF	40%	ES-BF	20%	ES-BF	40%
	BF-ES	40%	BF-ES	70%	BF-ES	80%	BF-ES	60%
S5	ES-BF	50%	ES-BF	90%	ES-BF	50%	ES-BF	90%
	BF-ES	50%	BF-ES	10%	BF-ES	30%	BF-ES	10%
S6	ES-BF	80%	ES-BF	60%	ES-BF	60%	ES-BF	100%
	BF-ES	10%	BF-ES	10%	BF-ES	30%	BF-ES	

No differences were found within the reaction time or extent conditions. Therefore, as with the first experiment the next stage in the analysis considered individual muscles, analyzing the latency of activation for each muscle. Analyses were carried out for muscles relative to the stimulus and normalized relative to AD. Insufficient data was available to analyze AT for both analyses.

Latencies between muscles relative to the stimulus

Reaction time condition

A two way ANOVA with repeated measures (condition (2) x extent (2) x subject (8) RM) was carried out on each muscle relative to the stimulus (Appendix B). A significant difference was found for AD ($F(1,5) = 82.27$; $p<.001$) and ES ($F(1,5) = 89.88$; $p<.001$) with no significant difference for BF, RF or G (Table 9). The onset times showed initiation of all muscles to be quicker under the SRT condition than the CRT condition. No interaction was found.

Extent condition

The same ANOVA format was used to compare activation latencies of postural muscles with the prime mover activation time (Appendix B). Similarly to experiment one, no significant difference was found for the activation time of every muscle relative to the stimulus (Table 11). It was revealed that ES, BF and RF were activated quicker in the long condition relative to the short condition and the opposite trend was found for G. No interaction was found.

Latencies between prime mover and postural muscles

Reaction time condition

The results from the two way ANOVA for muscle activation times relative to Anterior deltoid, did not show a significant difference for ES, RF or G, however a significant difference was found for BF (F(1,5) = 10.85; p<.006) (Table 12; Appendix B). Theactivation times revealed all muscles to be activated quicker under the SRT condition relative to the CRT condition. An interaction was found for BF only.

Extent condition

The ANOVA results showed that there was no significant difference for the activation time relative to AD for all muscles (ES, BF, RF and G; Table 12; Appendix B). The trend however, demonstrated mean activation time for ES, BF and RF to be quicker for the long relative to the short movement. The opposite was found for G, where the onset time under the short movement extent was activated quicker relative to the long movement. No interaction was found.

The catch trials included in the design were analyzed to check for AD activity. None of the subjects showed EMG activity of AD. For most subjects, continuous bursts of activation of G and sometimes AT and/or ES were observed for the whole trial.

Table 11. Main effect and cell means for absolute onset times (msec) of each muscle

		Main	Effects		Main	Effects			Cell
	Condition	Trend	Mean	Extent	Trend	Mean	Condition x	Extent	Mean
AD	SRT	s< c*	171	short	s<l	205	SRT	short	169
	CRT		240	long		206	SRT	long	172
							CRT	short	240
							CRT	long	239
ES	SRT	s< c*	158	short	s<l	191	SRT	short	158
	CRT		225	long		193	SRT	long	158
							CRT	short	224
							CRT	long	227
BF	SRT	s< c	187	short	l<s	201	SRT	short	181
	CRT		209	long		195	SRT	long	193
							CRT	short	220
							CRT	long	198
RF	SRT	s< c	185	short	s<l	197	SRT	short	170
	CRT		280	long		268	SRT	long	200
							CRT	short	224
							CRT	long	335
G	SRT	s< c	203	short	s<l	225	SRT	short	240
	CRT		252	long		230	SRT	long	167
							CRT	short	211
	*significant p<.05						CRT	long	293

Table 12. Main effect and cell means for onset times (msec) of each muscle relative to Anterior deltoid

	Main Effects			Main Effects					Cell
	Condition	Trend	Mean	Extent	Trend	Mean	Condition x Extent		Mean
ES	SRT	s<c	0.126	short	l<s	0.401	SRT	short	0.134
	CRT		0.655	long		0.379	SRT	long	0.116
							CRT	short	0.668
							CRT	long	0.642
BF	SRT	s<c*	-0.003	short	l<s	0.059	SRT	short	-0.059
	CRT		0.116	long		0.054	SRT	long	0.053
							CRT	short	0.176
							CRT	long	0.056
RF	SRT	s<c*	-0.106	short	l<s	0.079	SRT	short	-0.047
	CRT		-0.097	long		-0.282	SRT	long	-0.166
							CRT	short	0.205
							CRT	long	-0.398
G	SRT	s<c*	-0.187	short	s<l	-0.092	SRT	short	-0.397
	CRT		0.027	long		-0.069	SRT	long	0.023
							CRT	short	0.214
							CRT	long	-0.161

* significant p<.05

Discussion

Similar to experiment one, reaction times were found to be significantly different between the SRT and CRT conditions. This complied with Hick's Law. It was expected at the outset of the experiment that a difference in reaction time activation patterns between the movement extents would be found however, this was not the case.

Choice of postural strategies

Both conditions revealed that a hip strategy was used in the majority of activation patterns. It was hypothesized that different strategies would emerge between short and long movement conditions, however, similar strategies were found for both movement extent conditions.

Consistency of synergistic patterns

It was also hypothesized that synergistic patterns would be more consistent under the CRT than the SRT conditions. It was found that a variety of synergistic patterns were demonstrated across conditions with consistency of patterns between 30% and 90% of trials (Table 9) within conditions. It was often observed that two patterns were demonstrated within one condition which may account for some of the low consistency percentages.

Latencies between postural muscles relative to the stimulus

SRT versus CRT

The activation time for AD and ES muscles was found to be significantly shorter for the SRT condition relative to the CRT condition. The assumption that the movement is prepared for prior to onset of the stimulus can only be supported by the significance found for these two muscles. The significant difference also implies that preparation may be influenced by the required response, that is, the muscles are linked to the prime mover. Therefore, the latency of the muscles would be more tightly coupled with AD than the stimulus

Long versus short movement

As with the first experiment there was no significant difference in muscle activation between short and long movements, although the trend was for short movements to be activated earlier than the long movements. These findings are in agreement with the observations of Friedli et al. (1984) who also found no significant difference between conditions of arm flexion, although they observed a tendency for postural muscles to be activated earlier in the smaller movements.

Latencies between prime mover and postural muscles

SRT versus CRT

A non significant difference was revealed for activation time of muscles between the SRT and CRT conditions, except for BF. A tendency was found for the latency between the prime mover and postural muscles to be greater under the SRT condition relative to the CRT condition. As with the first experiment, these results are supported by the findings of Brown and Frank (1987).

Long versus short movement extent

The latency between the prime mover and postural muscles was not found to be significantly different between the short and long movements. The non-significant findings in this experiment may be favorably compared to the findings of Friedli et al. (1984). They argued for interdependence between the focal movement and the postural muscles since the focal movement creates momentum for which the body has to compensate if it is to remain upright. A link may therefore be found between the activation of appropriate postural muscles and activation of the prime mover.

Conclusion

In conclusion, this experiment has demonstrated that preparation for the response occurred prior to activation of a movement under both SRT and CRT conditions. It was also found that the dominant strategy employed was the hip strategy. Within the hip strategy two consistent synergistic patterns were revealed under both conditions. Finally, control of synergies appeared to be in a flexible manner.

Chapter V

GENERAL DISCUSSION

In the present investigation reaction time was found to be significantly different between SRT and CRT conditions in both experiments. This supports the results of Cordo and Nashner (1982), who found a later RT activation latency under the CRT compared to the SRT condition for voluntary arm movements. It was expected that a difference in RT would be found for the extent condition, but no significant difference was revealed. The use of a target constrained the movement extents to within the subjects visual range, thus *post hoc* the movements were considered to not be different enough. In the second experiment the lack of difference in RT between the two movement extents was attributed to the weights not being heavy enough. In a review by Marteniuk and MacKenzie (1980) they cited a number of studies which have investigated the effect of RT by manipulation of response factors. A number of studies they reviewed did not find a time factor involved in the production of force or resistance in a task. However, they highlighted an article by Klemmer (1957) who stressed that an increase in RT would occur when a considerable displacement was required (Klemmer, 1957). The second experiment in the present investigation used movement extents which were extreme, yet a difference in RT was not found.

In addition to the effects of the task on RT, of interest was the principle strategy used and synergistic patterns within that strategy. Previously, studies have demonstrated strategies to be task dependent. That is, postural muscles are activated to counteract inertial forces to the body, depending on the task carried out in order to maintain upright posture. Studies which have used free voluntary arm movements whether from the elbow (Weeks and Wallace, 1992), or shoulder (Belen'kii et al., 1967; Bouisset and Zattara, 1981; Lee et al., 1984; Kasai and Taga, 1992) have used large movement extents and shown that hip strategies were dominant. Alternatively, ankle strategies have been seen where full foot support surfaces were perturbed (Nashner and Cordo, 1981; Cordo and Nashner, 1982; Nashner, 1977; Diener et al., 1984; Horak and Nashner, 1986;

Dietz et al., 1993). Ankle strategies were also observed while the subject held onto or was fixed to a rigid structure under small and large perturbations (Brown and Frank, 1987; Frank and Earl, 1990; Stephens, Frank, Burleigh and Winter, 1992). In the present experiments it was expected that a short arm movement, which has not been used in previous studies, would demonstrate the employment of an ankle strategy and the long movement extent would show that a hip strategy was used. Both conditions however, revealed that the majority of onset patterns followed a hip strategy, with very few following an ankle strategy.

Consistency of synergistic patterns

Within the hip strategy the order of muscle activation was analyzed to assess the consistency of synergies. No difference was found in consistency between the reaction time conditions for both experiments. More consistency of frequency of synergistic patterns was found in the second experiment compared to the first.

There were some differences found between the experiments. Activity at the trunk and leg muscles was found to be in a different order for each experiment. In the first experiment the dominant synergy was activated in a distal to proximal order (RF-ES), which occurred almost twice as many times as the second dominant synergy which had a proximal to distal order of activation (ES-RF). The direction of activation of each synergy occurred randomly across conditions. RF was not activated first in the second experiment but in comparison with BF and ES a proximal to distal order of activation was found to be used (ES - BF) more frequently than the distal to proximal order (BF to ES). In addition to flexible control of activation, it is speculated that the differences in direction of activation may be partly accounted for by the starting positions and weight held by the subjects. In the first experiment the subject held a heavily weighted bar in front of them with both hands, with arms held comfortably shoulder width apart. In the second experiment a light weight was held in each hand by their side.

The counter order of muscle activation was found by dominant synergy patterns to be relatively equal for both experiments. No previous studies have reported this. The majority of investigations have discussed distal to proximal order of activation about the hip joint for large voluntary arm movements. When the data were analyzed using the same method as Friedli et al. (1984) who reported a distal to proximal ordering (BF-ES), results in the present investigation were found to be different between experiments and compared to the results of Friedli et al. (1984). In the first experiment, ES was activated prior to BF for the majority of trials where as a relatively equal distribution of activation orders (ES-BF and BF-ES) was found in the second experiment. Friedli et al. (1984) chose to analyze only the BF and ES muscles as they found AT and G were not always activated. Similar lack of activation by these muscles was found in the present investigation, most notably in experiment two.

Consistency of synergistic patterns for a simple discrete movement has been reported previously in the literature. Belin'kii et al (1967) and Pal'tesev and El'ner (1967) were the first to demonstrate stable synergistic patterns for a voluntary movement task. Others (Nashner, 1979; Bouisset and Zattara, 1981; Lee et al., 1984) have also shown synergistic patterns to be consistent. However, recent investigators have argued that synergies are flexible (Goodman, 1985; Lee et al., 1987; Weeks and Wallace, 1992; MacPherson, 1991) rather than 'hardwired' and always the same, in that synergies are reformed for each movement executed. Results from the present experiments supports this argument; When all muscles measured were considered in the full analysis, flexibility was found in the RT and extent conditions. However, consistent onset patterns of the first two or three muscles activated were found with the other muscles appeared to be activated in a random order. While flexibility in recruitment order was demonstrated, association of postural muscles with the focal muscle in both conditions supports the premise that muscles are temporally linked, forming synergies. These synergies allow the system to reduce the degrees of freedom by simplifying the control of posture, with the flexibility the appropriate muscles activated for the most efficient response.

The functional consequence of postural activation patterns is not entirely clear (Frank and Earl, 1990). Bouisset and Zattara (1987) argued that early postural muscle activity does not consist of a simple rigidification of some joints, rather, it displaces the body segments center of gravity in the direction that opposes the reaction forces which resulted from activation by the focal movement. Frank and Earl (1990) found that for voluntary movement of a handle, postural muscle activity displaced the center of mass in a direction which opposed reactive forces. These reactive forces would be produced at the trunk by inertia from the handle. Nashner and McCollum (1985) suggested that upright stance was regulated by a limited set of prestructured postural synergies, with early activation of trunk and hip muscles to move the body's center of mass over the base of support to maintain upright stance.

Lee et al. (1987) compared their findings favorably to Belin'kii (1967) showing the relationship between quantitative EMG characteristics of Hamstring (HM) and ES muscles to demonstrate a consistent recruitment order over a range of arm accelerations tested, with muscles activated in a distal to proximal order (HM - ES). Lee et al. (1987) further suggested that differences in temporal predictably cannot resolve every discrepant report on recruitment order. Their results showed that the timing of anticipatory postural adjustments can be altered by cognitive as well as mechanical factors, where recruitment of postural and focal muscles were sensitive to self-paced versus visually guided tasks. It was suggested that a parallel form of control may be used as each group of muscles was influenced in a different way by various factors (Lee et al., 1987).

Evidence for postural maintenance due to inherent sway was eluded through background activity shown in trials by G and AT for most subjects. Cordo and Nashner (1982) found G to be continuously active, indeed in the present experiments analysis of catch trials for all subjects in both conditions revealed that continuous bursts of G and occasionally AT were found while the other muscles were quiet for the majority of trials. Further, other inconsistent patterns which could not be categorized may have occurred due the possibility of interacting synergies (Lee, 1980). As was also found by Friedli et al. (1984) the activation of G and AT within trials was erratic. The significant difference between activation time of lower leg muscles in experiment one and the stimulus suggests that the system needs to overcome any sway and would be relatively stable prior to execution of the movement. These findings may be supported by Friedli et al.

(1984) who argued that a link has to exist between the prime mover and postural muscles since the prime mover exerts force on the system and the postural muscles ensure an upright stance is maintained. Based on the finding that postural activity was linked with voluntary movement Friedli et al. (1987) suggested that during movement preparation, the appropriate postural pattern is organized in a feedforward manner in parallel with the activation of the focal movement. Therefore the link between the voluntary movement and postural adjustments maybe at a low level of the CNS. The evidence found in the present investigation implies that the activation latency of postural muscles is related to the focal movement and thus the non significant finding for muscle activation between muscles and the stimulus could be expected.

One variable which could not be controlled in these experiments was the initial state of the subject. That is, the influence of inherent sway at the time of stimulus presentation. The effect of sway may be the factor which influenced the muscles which were activated after the first two or three, for the general maintenance of upright stance. Further investigations may be able to control this by using a force plate to correlate the center of pressure with the type of synergy exposed. While the present thesis investigated a simple, discrete voluntary movement, it is worth recognizing the effects of studying a more complex and dynamic movement. Some studies have found that for multidirectional movements, synergies become complex (Michaels, Lee and Pai, 1993). Thus, a major advantage of the present investigation was that the simple nature of the task allowed synergies to be revealed and provided some evidence that synergistic mechanisms support the argument as a means to simplify coordination of posture (Bernstein 1967; Kelso, 1982; Goodman, 1985; Turvey, 1990).

Latencies between postural muscles relative to the stimulus

Both experiments demonstrated no significant difference of muscle activation latencies between short and long movements, with a trend for short movements to be activated earlier than long movements. Nashner and McCollum (1985) designated an area about the body called the region of reversibility which defined a range in which sway could occur prior to the individual falling over. In the present experiment, the fact that no significant difference was found between the two extent conditions may be explained by the body's ability to compensate for extreme conditions prior to falling over. Although the findings of Friedli et al. (1984) alluded to a difference between conditions, the present experiments did not find a significant difference under extreme conditions. In the second experiment, subjects commented that they found the shorter movement more difficult to execute than the long movement. This may be a result of the braking required to ensure the movement carried out was under the required extent of 20°.

Latencies between prime mover and postural muscles

In both experiments it was found that activation time relative to postural muscles was non significantly different between SRT and CRT conditions, except for G in the first experiment and BF in the second. These findings may be compared with Brown and Frank (1987) who found no significant difference of latency between the 50% and 80% precue conditions for postural muscles and the prime mover. The present experiments revealed a similar finding, where the CRT condition (50%) and the SRT condition (100%), respectively showed no significant difference. In addition, they argued for interdependence between the focal movement and the postural muscles since the focal movement creates inertia for which the body has to compensate if it is to remain upright. A link may therefore be found between the activation of appropriate postural muscles and activation of the prime mover. While the majority of muscles showed non-significant main effects for the RT condition, the tendency was for the latency between the prime mover and postural muscles to be greater under the SRT than the CRT condition. The findings of the trend in the present investigation may be supported by an argument proposed by Brown and Frank (1987) who suggested that separate commands are used for preparation of postural and focal activation.

Conclusions

The present investigation revealed that for a simple discrete voluntary arm movement a hip strategy is employed for both short and long movement extents to maintain upright posture. Within the hip strategy, consistent synergistic patterns were found under both conditions. The results of the present experiments were similar to those of previous studies when the first two muscles were analyzed. However, when all the muscles activated were considered the consistency in activation order was reduced. Part of the inconsistency may be accounted for by the fact that five postural muscles were measured in the present investigation whereas many previous studies have only measured two postural muscles. Further, this flexibility of synergistic activation reflects the control exercised to achieve the correct response. Future studies should perhaps consider using more than two muscles to evaluate synergistic patterning. Finally, it can be concluded that the system appears to utilized a hip strategy for voluntary arm movements and to constrain muscles in a flexible manner for maintenance of upright posture.

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Appendix A

Simon Fraser University Form #2

INFORMED CONSENT BY SUBJECTS TO PARTICIPATE IN A RESEARCH PROJECT 0R EXPERIMENT

Note: The University and those conducting this project subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort and safety of subjects. This form and the information it contains are given to you for your own protection and full understanding of the procedures, risks and benefits involved. Your signature on this form will signify that you have received the document described below regarding this project, that you have received an adequate opportunity to consider the information in the document and that you voluntarily agree to participate in the project.

Having been asked by **Lucy Henstridge** of the **Kinesiology School** of Simon Fraser University to participate in a research project experiment, I have read the procedures specified in the document entitled :

An Examination of Postural Synergies, I

I understand the procedures to be used on this experiment and the personal risks to me in taking part. I understand that I may withdraw my participation in this experiment at any time. I also understand that I may register any complaint I might have about the experiment with the chief researcher named above, or with **Dr A. Hoffer, Director of School of Kinesiology,** Simon Fraser University. Copies of the results of this study, upon its completion, may be obtained by contacting: Lucy Henstridge. I agree to participate by allowing surface electrodes and potentiometers to be place on me. Also by carrying out the required task of moving my arms forward as instructed under the given conditions, as described in the document referred to above, during the period of November 1993 - April 1994. at Department of Human Kinetic, University of British Columbia.

NAME (please print):________________________________
ADDRESS: __________________________________
____
SIGNATURE: __________________ WITNESS: __________________
DATE: __________________

Once signed, a copy of this consent form and a subject feedback form should be provided for you.

Simon Fraser University Form #2

INFORMED CONSENT BY SUBJECTS TO PARTICIPATE IN A RESEARCH PROJECT 0R EXPERIMENT

Note: The University and those conducting this project subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort and safety of subjects. This form and the information it contains are given to you for your own protection and full understanding of the procedures, risks and benefits involved. Your signature on this form will signify that you have received the document described below regarding this project, that you have received an adequate opportunity to consider the information in the document and that you voluntarily agree to participate in the project.

Having been asked by **Lucy Henstridge** of the **Kinesiology School** of Simon Fraser University to participate in a research project experiment, I have read the procedures specified in the document entitled :

An Examination of Postural Synergies, II

I understand the procedures to be used on this experiment and the personal risks to me in taking part. I understand that I may withdraw my participation in this experiment at any time. I also understand that I may register any complaint I might have about the experiment with the chief researcher named above, or with **Dr A. Hoffer, Director of School of Kinesiology,** Simon Fraser University. Copies of the results of this study, upon its completion, may be obtained by contacting: Lucy Henstridge. I agree to participate by allowing surface electrodes and potentiometers to be place on me. Also by carrying out the required task of moving my arms forward or backward as instructed under the given conditions, as described in the document referred to above, during the period of 1994. at Department of Human Kinetics, University of British Columbia.

NAME (please print):______________________________
ADDRESS ______________________________
____
SIGNATURE: ________________ WITNESS: ________________
DATE: ________________

Once signed, a copy of this consent form and a subject feedback form should be provided for you.

Appendix B

Experiment 1

Median values of reaction time (msec) across condition and extent for subjects

	SRT		CRT	
	short	long	short	long
S1	224	240	221	245
S2	198	215	248	278
S3	259	240	361	316
S4	214	320	344	323
S5	200	188	250	228
S6	202	189	221	238
S7	156	202	254	257
S8	214	176	276	259

ANOVA summary table for reaction time (condition (2) x extent (2) x subjects (8)RM)

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	7	33949.500	4849.929			
Condition	1	24310.125	24310.125	30.851	0.0009	
Error	7	5515.875	787.982			1.00
Extent	1	162.000	162.000	0.215	0.6568	
Error	7	5270.000	752.857			1.00
CxE	1	561.125	561.125	0.869	0.3823	
Error	7	4520.875	645.839			1.00

ANOVA summary table of onset time, absolute value (condition (2) x extent (2) x subjects (8) RM).

1. Anterior deltiod

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	7	52547.969	7506.853			
Condition	1	17907.781	17907.781	55.272	0.000	
Error	7	2267.969	323.996			1.000
Extent	1	5.281	5.281	0.006	0.940	
Error	7	6042.469	863.210			1.000
CxE	1	108.781	108.781	0.137	0.722	
Error	7	5539.969	791.424			1.000

2. Erector spinae

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	7	44662.969	6380.424			
Condition	1	16516.531	16516.531	30.629	0.001	
Error	7	3774.719	539.246			1.000
Extent	1	399.031	399.031	0.367	0.564	
Error	7	7617.219	1088.174			1.000
CxE	1	586.531	586.531	0.631	0.453	
Error	7	6505.719	929.388			1.000

3. Biceps femoris

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	7	70973.875	10139.125			
Condition	1	36585.125	36585.125	28.993	0.001	
Error	7	8832.875	1261.839			1.000
Extent	1	8646.125	8646.125	1.715	0.232	
Error	7	35297.875	5042.554			1.000
CxE	1	10296.125	10296.125	1.571	0.250	
Error	7	45878.875	6554.125			1.000

4. Rectus femoris

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	7	42371.367	6053.052			
Condition	1	6888.445	6888.445	10.124	0.016	
Error	7	4762.867	680.410			1.000
Extent	1	0.008	0.008	0.000	1.000	
Error	7	12057.805	1722.544			1.000
CxE	1	328.320	328.320	0.099	0.762	
Error	7	23234.492	3319.213			1.000

5. Gastrocnemius

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	6	102046.304	17007.717			
Condition	1	16514.286	16514.286	1.683	0.242	
Error	6	58877.589	9812.932			1.000
Extent	1	1457.286	1457.286	1.039	0.347	
Error	6	8416.089	1402.682			1.000
CxE	1	2057.143	2057.143	2.056	0.202	
Error	6	6004.232	1000.705			1.000

6. Anterior tibialis

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	6	81077.625	13512.938			
Condition	1	37705.580	37705.580	14.060	0.010	
Error	6	16090.232	2681.705			1.000
Extent	1	6047.580	6047.580	3.063	0.131	
Error	6	11847.232	1974.539			1.000
CxE	1	4902.509	4902.509	3.458	0.112	
Error	6	8505.554	1417.592			1.000

ANOVA summary table for each muscle relative to Anterior deltoid (condition (2) x extent (2) x subjects (8) RM).

1. Erector Spinae

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	7	0.417	0.06			
Condition	1	0.013	0.013	1.081	0.333	
Error	7	0.087	0.012			1.00
Extent	1	0.011	0.011	0.546	0.484	
Error	7	0.147	0.021			1.00
CxE	1	0.026	0.026	0.831	0.392	
Error	7	0.223	0.032			1.00

2. Biceps femoris

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	7	1.173	0.168			
Condition	1	0.521	0.521	1.472	0.264	
Error	7	2.479	0.354			1.00
Extent	1	0.363	0.363	1.152	0.319	
Error	7	2.203	0.315			1.00
CxE	1	0.538	0.538	1.59	0.248	
Error	7	2.367	0.338			1.00

3. Rectus femoris

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	7	0.513	0.073			
Condition	1	0.005	0.005	0.281	0.613	
Error	7	0.117	0.017			1.00
Extent	1	0.065	0.065	1.225	0.305	
Error	7	0.369	0.053			1.00
CxE	1	0.009	0.009	0.242	0.638	
Error	7	0.265	0.038			1.00

4. Gastrocnemius

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	6	6.535	1.089			
Condition	1	0.925	0.925	6.067	0.049	
Error	6	0.914	0.152			1.00
Extent	1	0.691	0.691	7.764	0.032	
Error	6	0.534	0.089			1.00
CxE	1	0.034	0.034	0.182	0.685	
Error	6	1.136	0.189			1.00

5. Anterior tibialis

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	7	1.919	0.274			
Condition	1	0.238	0.238	0.56	0.479	
Error	7	2.972	0.425			1.00
Extent	1	0.34	0.34	9.829	0.017	
Error	7	0.242	0.035			1.00
CxE	1	0.022	0.022	0.29	0.607	
Error	7	0.524	0.075			1.00

Percentage frequency of activation times(msec) in hip and ankle strategies for each condition, across subjects

	Hip Strategy				Ankle Strategy			
	SRT		CRT		SRT		CRT	
	short	long	short	long	short	long	short	long
S1	100	100	100	80	0	0	0	20
S2	40	100	80	60	60	0	20	40
S3	80	40	60	60	20	60	40	40
S4	100	60	80	80	0	40	20	20
S5	100	100	100	80	0	0	0	20
S6	100	100	100	100	0	0	0	0
S7	80	80	20	60	20	20	80	40
S8	80	100	80	60	40	0	20	20
Total	680	680	620	580	140	120	180	200

Experiment 2

ANOVA summary table for reaction time (msec) (condition (2) x extent (2) x subjects (6)RM)

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	5	13226.844	2645.369			
Condition	1	25187.76	25187.76	354.83	0.00	
Error	5	354.927	70.985			1.00
Extent	1	162.76	162.76	0.135	0.7288	
Error	5	6048.927	1209.785			1.00
CxE	1	555.844	555.844	0.715	0.4365	
Error	5	3888.594	777.719			1.00

Median values from reaction time (msec) across condition and extent for subjects

	SRT		CRT	
	short	long	short	long
S1	210.5	183.5	245.5	271.0
S2	219.0	232.0	309.5	247.5
S3	260.5	247.5	304.0	323.5
S4	255.5	262.0	328.0	334.5
S5	304.0	199.0	334.5	319.5
S6	218.0	254.5	277.0	329.0

ANOVA summary table of activation time absolute value (condition (2) x extent (2) x subjects (8) RM).

1.Anterior deltoid

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correctio
Subjects	5	10749.500	2149.900			
Condition	1	28428.167	28428.167	82.271	0.000	
Error	5	1727.708	345.542			1.000
Extent	1	3.375	3.375	0.010	0.923	
Error	5	1641.500	328.300			1.000
CxE	1	32.667	32.667	0.067	0.806	
Error	5	2425.708	485.142			1.000

2. Erector spinae

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	5	12881.875	2576.375			
Condition	1	27202.667	27202.667	89.884	0.000	
Error	5	1513.208	302.642			1.000
Extent	1	20.167	20.167	0.063	0.812	
Error	5	1605.208	321.042			1.000
CxE	1	13.500	13.500	0.029	0.873	
Error	5	2366.875	473.375			1.000

3. Biceps femoris

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	4	6024.375	1506.094			
Condition	1	2376.200	2376.200	2.532	0.187	
Error	4	3754.425	938.606			1.000
Extent	1	151.250	151.250	0.340	0.591	
Error	4	1779.125	444.781			1.000
CxE	1	1428.050	1428.050	0.737	0.439	
Error	4	7746.575	1936.644			1.000

4. Rectus femoris

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	3	16414.547	5471.516			
Condition	1	35957.641	35957.641	9.300	0.055	
Error	3	11599.547	3866.516			1.000
Extent	1	20057.641	20057.641	1.750	0.278	
Error	3	34379.047	11459.682			1.000
CxE	1	6662.641	6662.641	0.732	0.455	
Error	3	27322.297	9107.432			1.000

5. Gastrocnemius

Source of Variation	df	Sum of Squares	Mean Square	F	p	Epsiolon Correction
Subjects	3	23613.563	7871.188			
Condition	1	9457.563	9457.563	5.680	0.097	
Error	3	4995.563	1665.188			1.000
Extent	1	90.250	90.250	0.127	0.745	
Error	3	2135.375	711.792			1.000
CxE	1	23870.250	23870.250	3.737	0.149	
Error	3	19160.375	6386.792			1.000

ANOVA summary table for each muscle relative to Anterior deltoid (condition (2) x extent (2) x subjects (6) RM).

1. Erector spinae

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	5	2.364	0.473			
Condition	1	1.679	1.679	2.165	0.201	
Error	5	3.878	0.776			1.00
Extent	1	0.003	0.003	0.184	0.686	
Error	5	0.081	0.016			1.00
CxE	1	0	0	0.005	0.947	
Error	5	0.078	0.016			1.00

2. Biceps femoris

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	5	0.286	0.057			
Condition	1	0.085	0.085	20.85	0.006	
Error	5	0.02	0.004			1.00
Extent	1	0	0	0.003	0.958	
Error	5	0.195	0.039			1.00
CxE	1	0.08	0.08	11.23	0.02	
Error	5	0.036	0.007			1.00

3. Rectus femoris

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	4	0.366	0.091			
Condition	1	0	0	0.004	0.953	
Error	4	0.472	0.118			1.00
Extent	1	0.651	0.651	7.249	0.055	
Error	4	0.359	0.09			1.00
CxE	1	0.293	0.293	2.317	0.203	
Error	4	0.506	0.127			1.00

4. Gastrocnemius

Source of Variation	df	Sum of Squares	Mean Square	F	P	Epsiolon Correction
Subjects	3	1.301	0.434			
Condition	1	0.182	0.182	3.096	0.177	
Error	3	0.177	0.059			1.00
Extent	1	0.002	0.002	0.02	0.896	
Error	3	0.315	0.105			1.00
CxE	1	0.631	0.631	3.317	0.166	
Error	3	0.571	0.19			1.00

Percentage frequency of activation times (msec) in hip and ankle strategies for each condition, across subjects

	Hip Strategy				Ankle Strategy			
	SRT		CRT		SRT		CRT	
	short	long	short	long	short	long	short	long
S1	90	100	70	90	10	0	30	10
S2	100	100	100	90	0	0	0	10
S3	70	30	80	50	30	70	20	50
S4	100	90	90	100	0	10	10	0
S5	100	100	80	80	0	0	20	20
S6	100	90	100	100	0	10	0	0
Total	560	510	520	510	40	90	80	90

Frequency of consistency of a synergistic pattern within the hip strategy[‡].

	SRT		CRT	
	Short	Long	Short	Long
S1	80%	40%	30%	70%
S2	100%	100%	100%*	60%
S3	50%	30%	60%	40%
S4	100%*	100%*	90%	100%*
S5	no data	90%	60%	60%
S6	60%	60%	70%	90%

* Two consistent patterns found

[†] The percentage may not represent the number of hip strategies found