Biomechanics of Rock Climbing Technique

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The candidate confirms that the work submitted is his/her own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

Rock climbing routes have become increasingly difficult over the last twenty years. In rock climbing manuals and articles, specific techniques for making arm movements on steep, overhanging routes are suggested as offering the climber noticeable performance benefits. The techniques recommended generally depend on the orientation of the ipsilateral foot. Decisions on technique are important, as the results are cumulative and can impact on the overall performance of the climber on the route.

The overall purpose of this research is to evaluate the impact of different ipsilateral foot orientations on reaching tasks in overhanging rock climbing situations.

As the research base for technique analysis is limited in rock climbing, a qualitative study was initially conducted to confirm the existence of the different techniques and to provide a base from which to ascertain the performance variables for technique comparison. Comparison Study 1 involved a 3D kinematic study, modelling the climber as a 14-segment rigid body model, comparing the techniques in terms of centre of mass displacement and velocity as well as joint angular changes. Comparison Study 2 compared the techniques in terms of the identified performance measures of postural demand, trajectory efficiency and work/power.

Statistically significant differences were found in centre of mass characteristics and body geometry, with differing orientations of the ipsilateral foot. Variations in complexity and in strategies of joint angular change were demonstrated, but the coordination in the reaching arm and the final arm posture were found to be invariant with technique. The postural demands within each technique varied significantly, however, in terms of trajectory efficiency and bio-energetics; differences between the techniques were small.

The overall conclusion was that, although reaching arm movements are not affected by foot orientation, the overall technique and performance of a reaching task is.

The study has practical and theoretical implications for rock climbing as well as for theories of grasping.

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Chapter 1. Introduction

> 'It is the essence of climbing. For an endless moment everything is concentrated on the outcome of one shift in body weight, one calculated decision to move, upon which the outcome of the entire climb – if not your life – is dependent.'
>
> Joe Simpson, *The Beckoning Silence* (2003, p226)

The sport of rock climbing has become increasingly popular as a recreational and leisure activity. The increased popularity is evidenced in the 40% rise in British Mountaineering Club (BMC) membership since 1990 and the explosion in indoor climbing walls (BMC, 2003). In addition to more participants, there has also been a marked growth in the number of instructors (BMC, 2001).

The rate of increase in difficulty of rock climbing routes, although slower than in the 1980s, continues to increase (Watts, 2004). Advances in safety equipment, along with the use of indoor walls as training venues throughout the year have allowed climbers to achieve ascents of extremely difficult terrain. Routes such as Realisation (9a+) at Ceuse, in France or Action Direkt (9a) at Frankenjura, in Germany are characterised by very steep overhanging walls with small holds.

Rock climbers have developed a number of subjective grading systems to rate the difficulty of pitches (sections) of a climbing route. In Europe, an established system is the French system. In this system, routes are graded using integers from 1 to a current high of 9. To further differentiate the degree of difficulty, the numbers from 6 upwards are given letter subdivisions of a, b and c, and the use of a + sign between the subdivisions.

In the late 1980's a new competitive element was introduced. The very first difficulty climbing competition was held in 1985 in Torino, Italy and in 1989 the first World Cup event was held in Leeds, UK (UIAA, 2004). Climbers now had the opportunity to test their skills directly against one another on the same route. Although the difficulty of the routes are not as high as the hardest routes performed outside, the routes are still of an extremely high level on overhanging walls.

The ultimate goal of the UIAA is for competition climbing to achieve Olympic status. At an international level, the UIAA holds an annual World Cup series, biannual World Championships and Continental Championships and there are five continental councils for competition climbing (UIAA, 2004). However, despite the rise in popularity of the sport, the ever- increasing standard of difficulty and the high level of structure of competition climbing both internationally and nationally, there has been relatively little scientific research into rock climbing (Grant et al. 2001).

Goddard & Neumann (1993) proposed a multi-factorial model for climbing performance (Figure 1-1). Any climbing performance will involve aspects of all six components, though the relative contribution will vary from route to route. Failure on a climbing route occurs when a climber falls off. This may be due to an inability to solve the actual movement problem confronting them, but failure is due more often to a build up of movement mistakes made earlier on in the route (Goddard & Neumann, 1993). In competition, the winner is the climber who can climb the route with the fewest movement errors.

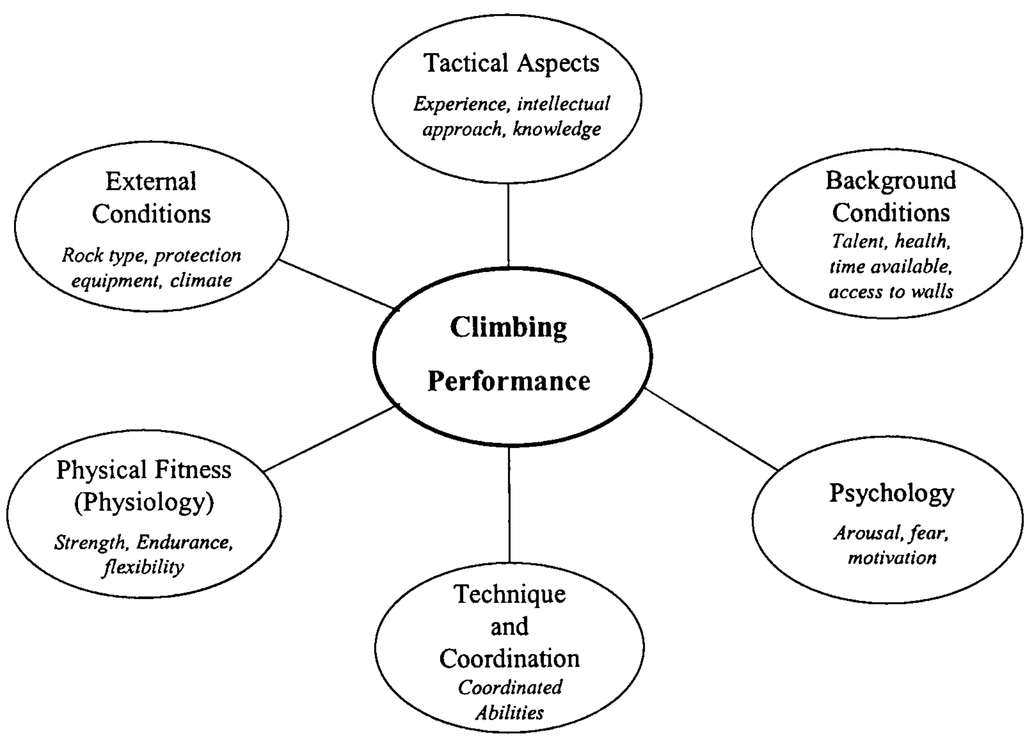


Figure 1-1 Goddard & Neumann (1993) multi-factorial model of climbing performance

Rock climbing is basically a movement-centred sport (Goddard & Neumann, 1993). The movements of the climber occur in an almost infinitely variable environment. The hands and feet provide the points of contact with which the climber can interact with the environment, though application of forces to maintain balance (Quaine et al., 1997a) and movement of limbs (Testa et al., 1999). The orientation of the hands and feet have to adapt to way the environment allows forces to be applied.

If the hand is initially taken as a single unit, the wrist can orientate the hand in essentially three ways. The hand can be positioned on top of the hold, in an overgrasp, underneath the hold, in an undergrasp or it can use the side of the hold, in a sideways-type grasp. The fingers can then be shaped to interact with a hold. The most common grips are the: crimp grip (Figure 1-2), open grip (Figure 1-3) and the pinch grip (Figure 1-4) (Richardson, 2001). A fourth grip, the cup grip, is a variant of the open grip which uses the whole hand over the top of a rounded hold.



Figure 1-2 Crimp grip (left photo)

Figure 1-3 Open grip (centre photo)

Figure 1-4 Pinch grip (right photo)

The feet can also apply forces on a hold: with the edge of the shoe, known as 'edging' (see figure 1-5 to 1-7), and with the sole, known as 'smearing', which relies on the frictional properties of the rubber sole on the shoe (Richardson, 2001). The edging technique is performed with the front portion of the foot (Richardson, 2001) and can be further categorized by the part of the foot used: the inside edge, i.e. the medial section of the forefoot (the big toe), the outside edge, the lateral section of the forefoot (the little toe), or the end of the foot with the foot pointing perpendicularly outwards from the wall (Richardson, 2001). However, it is not only the front of the foot that can be utilized by the climber. The heel of the foot can be used as a third hand, by hooking the heel onto a hold (Richardson, 2001).



Figure 1-5 Edging with the inside edge of the foot (left photo)

Figure 1-6 Edging with the outside edge of the foot (centre photo)

Figure 1-7 Edging with the front of the toe (right photo)

Feet can in fact be utilized by the climber by not placing them on a hold at all (Goddard & Neumann, 1993). The foot can be left to dangle in mid air while another limb moves. It can also be placed against the wall to provide torsional stability by counteracting the body's natural tendancy to rotate about the supporting hand and foot when the centre of mass lies laterally to those holds (Goddard & Neumann, 1993). This technique is known as 'flagging' (Goddard & Neumann, 1993; Richardson, 2001).

Competition routes are often steep, overhanging environments. It has been suggested that rock climbing activity is more strenuous in this environment, as the climber is off-balance, requiring the use of the upper body to maintain support (Berry, 2004).

In rock climbing manuals and articles, specific techniques for making arm movements on steep routes are suggested as offering the climber performance benefits. The techniques essentially depend on the orientation of the feet, in particular the ipsilateral foot. When the inside edge of the foot is used, the centre of mass is claimed to stay closer to the wall (Gresham, 2002a; Richardson, 2001) – something considered to be an attribute on overhanging rock (Richardson, 2001). Similarly, the use of the outside edge of the foot is claimed to offer superior balance (Richardson, 2001; Gresham, 2002b), through bringing the body closer to the wall, and to be less energetically demanding when making an arm reach (Gresham, 2002b, c). Goddard & Neumann (1993) claim the use of the outside edge of the foot while making an arm reach to have biomechanical advantages, but do not specify what they are. The authors nevertheless claim that the failure to use this technique was a key mistake made by less successful climbers in the 1991 World Championships.

In short, the choice of an incorrect technique for a single reaching movement can impact, possibly quite seriously, on the successful performance of the climber on the whole route. Therefore it is important for climbers to know the relative benefits of competing techniques. However, there seems to be ambiguity and vagueness in the advice from guidance manuals about the use of the outside or inside edge of the foot in reaching movements, and little research evidence is offered in support of specific claims. The question of arm movements is thus important to both the practice and theory of rock climbing and appears to be in need of empirically-based research.

The term 'technique' has been used in a non-specific manner up to this point. Technique is a term which is commonly used in biomechanics, but often not defined (Lees, 2002). In this study, technique will be defined as

> 'a specific sequence of movements or parts of movement in solving movement tasks in sports situations' *Dictionary of Sport Science* (1992)

This definition implies that technique has a degree of internal coherence, plus a functional and planning component, and thus avoids the circularity problem of technique simply being anything that a climber happens to do.

When studying technique, the issue of variability must be carefully considered. Variability in technique can exist both within and between individuals. Intra-individual variation would include the use of different techniques to achieve the same task goal. In fact this ability to vary the movement pattern to achieve a set goal gives the performer a flexible approach to adapt to the specific context of the environment (Davids et al., 2000). Intra-individual variability is also important when considering the consistency of movement responses by the participants and the number of trials required to be representative of the typical response (Mullineaux et al., 2001). Inter-individual differences in technique can exist even within a group of highly skilled performers. Temprado et al. (1997) found group differences between novices and experts in the pattern of joint pair coordination used to serve a volleyball, but also found that two of the six experts did not show the same pattern as the rest of the expert group. Although there may be intra and inter-individual variation in a particular technique, there must still exist a basic underlying movement pattern which is recognisable of that technique and identifiably distinct from an alternative technique that could be used to solve the given task. If interest lies in determining whether a particular set of movements constitute a distinctly different technique then the variability within and between the participants must be reduced so that the basic underlying movement pattern can be analysed.

The overall purpose of this research programme is to evaluate the impact of different ipsilateral foot orientations on reaching tasks in overhanging rock climbing situations. The knowledge gained through this study will be of benefit to practitioners, instructors and coaches of competition and high-level rock climbing.

In order to achieve this evaluation, the specific objectives are:

1. To establish that the ways in which climbers in an overhanging rock environment solve a reaching-movement task, using different orientations of the ipsilateral foot, constitute separate techniques.
2. To establish a robust methodology for detailed quantitative analysis of the position and orientation of the climber using any of these techniques on an overhanging wall
3. To establish the effect of ipsilateral foot orientation on the performance of the reaching task on an overhanging wall.

Objective 1 will be addressed initially by developing a notation analysis identifying the types of foot orientation involved in reaching movements employed by climbers on an overhanging competition route (Pilot study 1). A second pilot study (Pilot study 2) using elite climbers will be carried out to establish whether predicted sequences of movement are used. A controlled comparative study of the different foot orientations will then be undertaken, which breaks down the reaching task into separate phases. In each phase, the sequences of movement associated with each foot orientation will be compared and contrasted. A descriptive analysis of the sequence of changes in joint angular rotations will explain the way the movements are made in relation to the whole-body centre of mass motion. Differences in body geometry will be compared at the end of each phase. Attempts will be made to characterise the resulting techniques in terms of proximal-distal sequencing in the legs prior to the reaching movement phase of the task. A measure of coordination complexity will be derived through analysis of joint angular reversals.

Objective 2 will be achieved using the results of the notation analysis study and contemporary three-dimensional kinematic techniques drawn from the literature. Emphasis will be placed on minimising errors. The techniques to be used will be validated through a series of small tests to establish the relative contribution of error. Pilot study 2 (above) will be constructed so that the participants are freely allowed to choose the starting position and technique with which to accomplish the climbing task. It will allow testing of the experimental protocol, in terms of marker placement and reconstruction of anatomical landmarks, and also allow the complete data processing chain to be established.

Objective 3 will establish the effectiveness of each technique in the performance of a rock climbing hand-reach task. Performance will be measured in terms of energetic and postural demand and a measure of whole-body centre of mass trajectory efficiency, based on existing theoretical principles determined though the literature review. A subjective ranking of the techniques by the participants will be undertaken using a post-test questionnaire.

The thesis begins with a survey of the literature in Chapter 2. The two pilot studies are in Chapters 3 and 4 and the two main 'Comparative Studies' are in Chapters 5 and 6. The results of these four chapters are brought together in Chapter 7 and an overall evaluation of the techniques is given. It is expected that different foot orientations will produce recognisably different techniques in solving the reaching task. It is also hoped that it will be possible to show differences in performance of the reaching task though use of the different techniques.

Chapter 2. Literature Review

2.1. Introduction

The literature review has a number of purposes. The primary purpose is to evaluate to what extent previous work has already contributed to the research question. The review will begin with an analysis of research into rock climbing activity in general and then focus on work which has looked at reaching movements. The review will also summarise theoretical ideas involved in the use of three-dimensional kinematics, the ideas of which will be validated in Chapter 3. The review will finish by addressing the topics of co-ordination and work models.

If Goddard & Neumann's (1993) six component model of climbing performance is considered, research has focused on the three major strands of physiological factors, psychological factors and technique. Technique is used as an umbrella term in Goddard & Neumann's (1993) model and encompasses biomechanical research.

2.2. Physiological Research into Rock Climbing

Studies related to physiological aspects of climbing have had a broad focus. Research has looked at climbers' anthropometry (Watts et al., 2003; Grant et al., 2001; Mermier et al., 2000), their injuries (Wright et al., 2001; Quaine et al., 2003; Wyatt et al., 1996; Schweizer, 2001) and the physiological responses associated with rock climbing activity (Booth et al., 1999; Watts & Drobish, 1998; Mermier et al., 1997; Sheel et al., 2003; Grant et al., 2003).

2.2.1. Anthropometry

In a recent review of physiologically-based research into difficult rock climbing, defined as performances of an F6c level and above, Watts (2004) showed that climbers tended to be of small stature with low body mass and a low percentage body fat. Elite climbers had a high upper body strength to weight ratio with high upper body power, moderate to high aerobic power and high dynamic and isometric muscular endurance (Watts, 2004). To date, only two studies, both by the Watts group, have undertaken anthropometric measures of large groups of climbers. The first study, Watts et al. (1993), found elite international competition climbers to have a mean (standard deviation) height of 1.778 (±0.065)m and 1.654 (±0.040)m, with weights of 66 (±5.5)kg and 51.1 (±5.1)kg for males and females respectively. Ponderal indices, 43.8 (±4.8) for males and 44.4 (±0.9) for females, were similar to those of ballet dancers and distance runners. The percentage of body fat reported was very low, with mean values of 4.7 (±1.3)% and 10.7 (±1.7)% for males and females respectively. These values have found support from studies by Mermier et al. (1997), Booth et al. (1999) and Watts et al. (1996). A study by Grant et al. (1996) found their group of elite male rock climbers to be of similar height to that of Watts et al. (1993), but to have higher body mass, 74.5 (±9.6)kg, and body fat, 14 (±3.7)%. Grant et al. (1996) also found no significant differences between the non-climbers and 'elite' rock climbers.

However, the climbers were of a performance level of F6a, which could be regarded as intermediate rather than elite by modern competition standards (Watts, 2004). The second large-scale study by the Watts group investigated the anthropometry of young competitive climbers. These climbers showed similar characteristics to adult climbers but without the reduced body fat percentages, in comparison with age- matched non-climbing athletes (Watts et al., 2003).

Hand-grip strength has been shown to be only weakly related to climbing performance (Watts et al., 1993; Grant et al., 1996); however, when represented as a strength-to-mass ratio, climbers score much higher than age-matched norms (Watts, 2004). The reason behind these findings could be due to the methodology employed. The majority of studies have used hand-grip dynamometry, which involves an isometric contraction of the fingers opposing the thumb or base of the hand. Apart from a pinch grip, climbers do not use this type of action when climbing. Rather, climbers try to orientate the hand on the hold in such a way as to oppose the effect of gravity on the body (Watts, 2004) and, as will be shown later in this review, to keep the body in a balanced position (Quaine et al., 1997a). Grant et al. (1996, 2001) have used more climbing-specific methodologies to measure finger forces. The apparatus positions the hand so that all four fingers are flat against the measuring plate, the palm is positioned against the vertical plate and the elbow is supported directly under the hand. The participants then make maximal contractions, pulling down on the plate. Using this methodology, Grant et al. (1996) showed climbers to produce higher forces than non-climbers, but could not find significant differences between elite and recreational climbers, though this may again be due to the researchers' definition of elite level.

The way climbing holds are utilised by the fingers suggests that, rather than the amount of force generation, the muscular endurance, and in particular isometric endurance, may be more important. Very few climbing studies have measured muscular endurance (Watts, 2004). Grant et al. (1996) found that climbers could hold a bent arm hang longer and perform more pull ups than non-climbers. In a later study by the Grant group, it was demonstrated that maximum voluntary contraction endurance was significantly greater for climbers, compared with rowers and 'aerobically leg trained athletes'(Grant et al., 2003). Ferguson & Brown (1997), however, could not find significant differences between elite climbers and sedentary individuals in terms of sustained isometric endurance times, but for mean rhythmic isometric time, climbers recorded scores of almost double that of the sedentary individuals, indicating an increased vasodilator capacity allowing greater recovery in the climbers between contractions.

2.2.2. Physiological Responses

The physiological responses to a bout of climbing can be summarised as follows. VO_2 averages around 20 to 25 $ml.kg^{-1}.min^{-1}$ with peaks of over 30 $ml.kg^{-1}.min^{-1}$, giving equivalent energy rates of about 10 $kcalmin^{-1}$ (Watts, 2004). Interestingly, Watts & Drobish (1998) found that increased climbing angle had little effect on VO_2, but did increase heart rate. The VO_2 levels in this study were less than 60% of the aerobic power of a maximal running VO_2 test. The authors indicated that mechanical efficiency dropped from 11% at angles of 80° to the horizontal, to 3.3% at angles 102° to horizontal. VO_2 has also been shown to plateau in climbs of duration greater than two minutes (Watts et al., 2000; Booth et al., 1999).

Blood lactate levels increase to two to seven times resting levels during climbing (Watts, 2004) and remain elevated for over twenty minutes in resting recovery (Watts et al., 1996). These levels are, however, relatively low compared with maximal treadmill and cycling tests, due to the much smaller muscle mass in the upper arms (Watts, 2004). Increases in the blood lactate have been shown to relate to decreases in hand- grip endurance but not hand-grip strength (Watts et al., 1996).

The nature of the increases in VO_2 and heart rate has caused some debate. Mermier et al. (1997) found that the linear relationship between heart rate and oxygen uptake of treadmill and cycle ergometry tests was not shown in rock climbing, suggesting that VO_2 may not be an important indicator of climbing performance (Mermier et al., 2000). This view is also supported by Billat et al. (1995) and Watts & Drobish (1998). However, more recent studies such as Sheel et al. (2003) and Booth et al. (1999), have suggested that climbing performance has a significant aerobic contribution. Sheel et al. (2003) demonstrated that when climbers were assigned hard routes, scaled to the individuals' abilities, a VO_2 of about 50% of maximal cycling VO_2 was achieved. Booth et al. (1999) used a climbing specific test for maximal VO_2, as opposed to a cycling or upper arm test. Using a vertical climbing ergometer Booth et al. (1999) studied the effect of speed of climbing on heart rate and VO_2. The climbers were then tested on an outdoor route, where the speed was much lower. The outdoor route required 75% of the VO_2 climbing specific maximum, suggesting that climbing performance has a significant aerobic requirement. A disproportional rise in heart rate relative to oxygen uptake has been consistently reported (Mermier et al., 1997; Booth et al., 1999; Sheel et al., 2003). While Mermier suggests that this indicates a low aerobic requirement, the latter studies suggest that the cause is the intermittent isometric contractions of, in particular, the upper arms. Isometric contraction time can constitute up to a third of the total ascent time (Billat et al.,1995). When there is an isometric contraction, the local blood supply to the working musculature is reduced (Booth et al., 1999). There is also activation of the arterial baroreflex (Sheel et al., 2003). A powerful sympathetically- mediated pressor response due to accumulation of metabolites in the muscle tissue occurs, which has the effect of increasing heart rate as well as ventricular performance and increased systemic arterial pressure (Sheel et al., 2003). Heart rate can increase independently of oxygen uptake due to psychological stress, but both Sheel et al. (2003) and Booth et al. (1999) feel that the methodologies used in the studies mediate against this.

2.2.3. Injury

In a study of rock climbing related injuries reported to an Accident & Emergency department, a rate of one rock climbing-related injury per 2774 injuries per annum was recorded (Wyatt et al., 1996). The majority of these were on outdoor routes and involved hitting the floor after falling off the rock face. However, the majority of research has focused more on soft tissue overuse injuries. Overuse injuries are said to account for over 80% of injuries occurring at indoor walls (Rooks et al., 1995). The most common climbing specific injury is to the A2 pulley tendon; 69% of injuries to the hand occur in the region of the A2 pulley tendon on the ring or middle finger (Bollen, 1988). The A2 pulley tendon ensures that when a load is applied, the flexor tendons do not bowstring (Wright et al., 2001). Schweizer (2001) investigated bowstringing and forces in climbers using a crimp grip. In this position the proximal interphalangeal joints are flexed to approximately 90° and the distal interphalangeal joints maximally hyperextend. The flexion of the proximal interphalangeal joints increases the holding force by increasing the moment arm of the flexor tendons (Mester et al., 1995). However, the bowstringing of the flexor tendons apply high loads to the flexor tendon pulleys, which can cause injuries (Schweizer, 2001). Schweizer (2001) found that the distance of bowstringing over the distal edge of the A2 pulley increased by 30% during a warm up of about a hundred moves, about fifty cyclic moves on each hand. After warm up, peak forces to points on the flexor tendon sheath are prevented by the course of the tendon becoming more regular (Schweizer, 2001). Schweizer (2001) also showed that the distal edge of the A2 had three times the load compared with the force applied by the finger tips on the hold. In a recreational climber, a theoretical load of nearly 400 Newton could be applied to the A2 pulley – the maximal strength of the A2 pulley is 375 to 407 Newton (Tang, 1995; Lin et al., 1990).

2.3. Motor Control Research into Rock Climbing

2.3.1. Affordances

In 1979, Gibson put forward the concept of 'affordances', which is the reciprocal relationship between the organism and the environment needed to perform activities. Organisms perceive these relations through sensing information from the environment and within themselves. So, invariant properties of the environment act as information, to guide the exploration of the perceptual-motor workspace (Newell, 1991). Gibson (1979) stated that a surface will afford support, providing it is nearly horizontal, flat and sufficiently extended. Boschker et al. (2002) argue that the upper surface of a climbing hold affords support if the hold is sufficiently concave or convex and extended relative to the climber's grip and grasping abilities.

There is evidence that climbers perceive the possibilities a climbing wall affords differently: expert climbers focus on the functional aspects of a climbing wall, whereas non-experts attend to the structural aspects (Boschker et al., 2002). The expert climbers immediately and accurately pick up the functional (meaningful) information for action in that environment (Boschker et al., 1999). The authors also suggest that the experts pick up different scales, or 'grain' (Boschker et al., 2002), of affordances. Fine-grain affordances would be the opportunities of using individual holds, whereas coarse-grained affordances consist of a cluster of information about a series of holds. It is presumed that the coarse-grained affordances emerge from and are constrained by the finer-grain affordances (Boschker & Bakker, 2001). Relative to the climbing opportunities, the structural aspects are more arbitrary properties of an environment, which are independent from the observer and from action (Boschker et al., 1999, 2001). Thus for the expert climber, the same environment will afford more ways of interacting with it than for the non-expert.

2.3.2. Trajectory Complexity

Cordier et al. (1993, 1994) studied the complexity of climbers' trajectories using the concept of entropy. A straight line is connected from the bottom of the route to the top and the curve of the trajectory around that straight line is recorded, through videoing the path of an LED connected to the waist of the climber. The authors treated the trajectory as an object and used the curve's entropy as an index of its complexity. The greater the deviation of the trajectory curve from the straight line the more complex the trajectory, and thus the greater the entropy. The entropy of the curve is defined by the equation $H = \log_n 2L/c$ (Mendès France, 1981), where H is entropy, L is the length of curve and c is the curve's perimeter. The authors suggested that the trajectory is constrained by the route difficulty (external) and the climber's level of expertise (internal). So, the higher the entropy of the trajectory, the more constraining the environment and the fewer degrees of freedom available to the climber. The entropy curve shape was found to be an index of the climber's level of expertise, which was taken as the capacity of the climber to produce stable motor patterns (Cordier et al., 1993). More fluent trajectories and lower entropy values were associated with increased skill in the climbers. So, in a similar way that the spatial-temporal trajectory may be assessed by means of its dimensionality, entropy can be used to measure the complexity of a spatial trajectory (Cordier et al., 1993, 1994). The authors found that entropy of the trajectory decreased as the number of climbs increased, i.e. the entropy decreased with learning, which is consistent with the decrease in dimension of spatiotemporal trajectories in intermediate learning (Pijpers et al., 2003).

There are a number of criticisms which can be levelled at Cordier et al.'s (1993, 1994) research. The first is that the authors assume that the trajectory of the climber will be optimised when the trajectory becomes a straight line. This may not, however, be the case; for example, Long (2000) describes how the most elegant solution to moving leftwards around an overhang was to use holds to the right and ignore the holds to the left. Cordier et al. (1993) suggest that trajectories with more complex nodes indicate a searching process by the climber. These nodes could simply be due to the climber clipping the rope into a quickdraw, chalking up his hands or resting – not necessarily working out the best sequence to be performed. A more thorough understanding of the nature of the complex nodes could have been achieved, for instance, by asking the climbers to verbalise their thought patterns up the route.

The methodology also has several flaws. The trajectory of the climber was traced by an LED on the back at waist level. There was no validation that this was a valid representation of the climbers' centre of mass trajectory. If the movement is to be defined as a single point then the Centre of Mass is the most appropriate (Dewar, 1977). The climbers were asked to perform the route ten successive times with a one-minute rest between attempts. The route was graded at 6a. The average climbers had a skill level of 6b-6c, whereas the skilled group had a level of 7a-7b. Thus, the route was much closer to the limit of performance for the average climbers than for the skilled ones. As a percentage of their maximum, the average climbers were working at a much higher level than the expert climbers. Fatigue may therefore have had an impact upon the results, especially as the expert climbers may also have been physiologically better athletes. There is also a question of limb length bias; as the authors acknowledge, the results may simply be due to the expert group having longer limbs. There was no indication of errors within the study, for instance the errors associated with the digitisation of the film footage. The groups of subjects are also too small (three climbers for the average group, four for the expert) for any statistical significance to be applied to the results.

2.4. Biomechanical Research into Rock Climbing

Biomechanical research into rock climbing has studied both the kinetic and kinematic aspects of the sport, to varying degrees. The kinetic analyses have mostly focused upon balance maintenance in both vertical and overhanging environments, through studying the re-organisation of support forces.

2.4.1. Maintenance of Balance

2.4.1.1. Horizontal Environment

Gray (1944) provides a mechanical argument for the maintenance of equilibrium of a static tetrapod with respect to external forces in the horizontal environment. If a tetrapod has four limbs supporting body weight, then to be in a state of static equilibrium, the vertical reaction forces from the limbs must be equal and opposite to the weight of the tetrapod (Gray, 1944). The centre of mass must therefore lie within a triangle defined by the centre of pressure of three of the limbs and, if there are four limbs supporting the body, then there must be two triangles, either of which provide stable support for the animal. Depending on the orientation of the limbs with respect to the centre of mass, the animal will be able to move either of two limbs but neither of the other two (Gray, 1944). If the animal is to be in static equilibrium, then the sum of the moments about each axis through the centre of mass must equal zero, or the animal would pitch forwards or backwards or roll to one side. Therefore a system of diagonal coordination must exist, where changes in forces applied by one limb are reflected by a similar change in the diagonally opposite limb, which coincides with an opposite change in activity of the limbs on the opposite diagonal (Gray, 1944).

Experimentally, this pattern of diagonal support posture has been observed in limb flexions of cats, where centre of mass shift is small (Dufosse et al., 1982). Diagonal support posture accompanying unweighting of a limb has also been demonstrated in humans (Quaine et al., 1996). Quaine et al. (1996) demonstrated that the force re-organisation in the horizontal plane was fundamentally different from when a limb was unweighted in the vertical plane. In the vertical plane, the climbers showed a strongly non-diagonal stance. The authors attribute the differences to the specific gravitational environment in the two conditions.

2.4.1.2. Vertical Environment

In a vertical environment, the vertical projection of the centre of mass lies outside of a base of support. Gray (1944) demonstrated, using a model of a lizard, that balance equilibrium can be maintained, through the use of horizontal forces. When climbers are in equilibrium on a vertical surface they are subjected to two couples:

i. the weight of the climber and the vertical tangential forces acting at the hand and footholds,
ii. the normal forces acting at the hand and footholds (Gray, 1944).

If a climber is viewed sagittally on a wall facing left, then the first couple is tending to rotate the body clockwise, as gravity is acting downwards. In order for the climber to be in equilibrium, the second couple, due to the forces acting normally to the hand and footholds, must be trying to rotate the climber anticlockwise. Gray (1944) showed that resultant forces equal and opposite to the weight of the climber can be produced by the hands pulling downwards and outwards and the feet pushing downwards and inwards.

The theoretical model has been supported by a number of experimental studies (e.g. Quaine et al., 1997a; Quaine & Martin, 1999; Noé et al., 2001). Quaine et al. (1997a) looked at two body positions on the same layout of holds: one imposed and the other an optimised position the climber was free to choose. It was found that the climbers in the optimised position had their trunk closer to the wall, thus reducing the couple due to body weight, meaning that in the optimised position climbers can apply lower contact forces (Quaine et al, 1997a). Thus Quaine et al. (1997a) concluded that the role of the arms was to oppose backward imbalance and control the distance of the body from the wall, whereas the role of the legs was to support the body weight. Similar conclusions as to the role of the limbs were reached by McIntyre & Bates (1982) in a study of the mechanics of ladder ascents and Quaine et al. (1997b) in their study into the effect of leg movement on the forces at the holds. Dewar (1977) suggests that as the area of support on a ladder for the feet is small, the role of the hands is to contribute to the stability of the body and that this role becomes more important as the ladder gets steeper. When climbers were subjected to voluntary and imposed foot movements it was found that there was a 'reinforcement of the upper supports' (Rougier, 1993), which opposed the backward disequilibrium. It was also found that expert climbers would accept more pronounced backward unbalance more easily than novice climbers (Rougier, 1993).

In the horizontal plane, Gray (1944) gave a theoretical argument for the adoption of diagonal posture accompanying loss of support on one limb, which has also been supported experimentally (Dufosse et al., 1982). Quaine et al. (1997a) investigated loss of support in the vertical plane by studying the force changes accompanying the transition from a quadrupedal to tripedal posture on a climbing frame. The climbers' initial position was characterised by an even distribution of body weight with loss of support produced by a voluntary removal of the right hand, which was maintained 2 cm from the hold. The authors claimed that as the amplitude of the movement was small, the centre of mass remained 'essentially unmoved' (Quaine et al, 1997a, p.17) and showed results of a less than 5mm lateral shift in trunk position. Quaine et al. (1997a) demonstrated that in the vertical environment there is a unique solution to maintaining balance when a loss of support from one limb occurs, which is different from Gray's (1944) theoretical pattern in the horizontal plane. In the initial quadrupedal position, the vertical forces on the four limbs were equalised, the lateral forces on the left foot and right hand opposed the lateral forces on the right foot and left hand and the A/P forces on the hands opposed the A/P forces on the feet. When the right hand was removed, a reorganisation of the forces occurred on the remaining supports. More precisely, the vertical forces of the left foot increased, as opposed to decreased, as did the vertical forces of the left hand, whereas the right foot maintained a fairly consistent vertical force. The lateral forces of the left hand and left foot increased and remained opposed to each other, but the lateral force at the right foot decreased and increased in the same direction as the left foot. The A/P forces of the right foot decreased, leaving the left foot and left hand to increase the A/P forces and remain opposed to each other. So the vertical and horizontal forces increased on the contralateral holds, whereas the vertical force remained constant on the ipsilateral hold and the horizontal force decreased to zero.

The maintenance of equilibrium, with quasi-static centre of mass, through a contralateral transfer of forces has been supported by further, more complete, work by the Quaine group (e.g. Quaine & Martin, 1999, Noé et al., 2001). Quaine & Martin (1999) suggest that the dynamics of the supporting reaction forces imply that the climber cannot be thought of as a rigid object, as in the theoretical work of Gray (1944). Noé et al. (2001) interpret the results of Quaine et al.'s (1997a) studies as representing a continuum of force change from diagonal to contralateral, as the angle of support surface increases from 0° to 90°. As Quaine et al. (1997a) had already indicated that climbers preferred to move the centre of mass closer to the wall, to reduce the body weight moment in a four-point support, one would therefore assume that the climbers would also try to reduce the body weight moment for a three-point support posture (Quaine & Martin, 1999). It may be that the kinematic techniques used by the Quaine group were not sensitive enough to detect centre of mass movement, but there is still not the clear uncoupling in the responses of the limb pairs. The response of the skilled climbers may in fact be the most efficient response where there is no base of support upon which to vertically project the centre of mass and the response of the skilled climbers has been modified by the highly constraining environment, as suggested by Quaine et al. (1996). In fact, the methodology used by Quaine, by imposing an initial posture of upper arms and thighs horizontal, is also highly constraining and it may be because of this that the climbers did not move their centre of mass.

The study by Quaine et al. (1997a) presents an insufficient mechanical analysis of the climber in a vertical environment, as the authors did not analyse the moment reactions. A later study by Quaine & Martin (1999) rectified this situation. A similar methodology to that of Quaine et al. (1997a) was used, but in the Quaine & Martin (1999) study the loss of support was through the right foot. It was shown that in order to restore equilibrium about the vertical axis, a decrease in the anterior-posterior force at the right hand hold was required. The centre of mass is quasi-unmoved, so that the body weight moment about the lateral and anterior-posterior axes remains unchanged. Therefore, the anterior-posterior force on the left hand hold must increase, which in turn means that the anterior-posterior force to the left foothold must also increase, if translation equilibrium about anterior-posterior axis is to be maintained. The lateral force on the right hand goes to zero and is transferred to the left hand, which decreases the clockwise moment due to the right hand and increases the counter clockwise moment due to the left hand, which maintains equilibrium about the anterior-posterior axis.

If the contralateral transfer of forces is a unique solution to equilibrium maintenance in a vertical environment, then context and expertise should not have an effect upon the pattern of force distribution. Rougier (1993) looked at force patterns occurring with movement of the right foot in experts and beginners in two situations. In the first situation the climber voluntarily displaced the foot, whilst in the second situation the climber had an unexpected perturbation of the right foot. Rougier (1993) showed that the novices tended to demonstrate more diagonal posture than a contralateral transfer of forces, evidenced by the expert climbers.

When beginner climbers have to counteract the perturbation caused by the loss of support of the right foot, they increase the vertical force on the left foot and show a larger increase in force on the right hand than on the left hand, which only increases slightly. Thus the beginner climbers are showing diagonal support behaviour, although not as clearly as in the Dufosse et al. (1982) study. The expert climbers however show a different behaviour. Following the loss of support on the right foot there is a definite delay in response. When the response occurs, the left foot, right hand and left hand all increase in force by similar amounts. The left and right hand virtually mirror each other in force increase. This in itself could be a learned behaviour; as Rougier (1993) points out, expert climbers are more likely to accept more pronounced backward disequilibrium. Expert climbers will have had more experience of a foot unexpectedly slipping and losing support from that foot, so they have learned how to react to that situation, which is the behaviour observed by Rougier (1993). However, the vertical forces applied by the climber oppose vertical collapse due to gravitational forces (Quaine et al. 1997a). Therefore a delayed response in the vertical forces of the three remaining supports, accompanying loss of support of the right foot, is simply not possible. The results of Rougier (1993) are therefore highly questionable.

The work of Quaine's group has identified the existence of anticipatory postural adjustments in balance maintenance in rock climbing environments. When a limb is to be displaced voluntarily, the changes in force applied by the limbs precede the onset of movement (Rougier, 1993; Quaine et al., 1997a; Quaine et al., 1997b; Metzger & Rougier, 1993; Dufosse et al., 1982). These force changes have been coined Anticipatory Postural Adjustments (APA) (Bouisset & Zattara, 1987). APAs are dynamic movements created in the body to balance the forces of inertia due to the displacement of a limb, which disturb postural equilibrium (Bouisset & Zattara, 1987). The duration of APAs increases with the dynamic asymmetry of the impending voluntary movement (Bouisset & Zattara, 1987). The existence of APAs suggests that the postural response is coordinated among the limbs (Dufosse et al., 1982). APAs have been shown in both the hands and feet (Quaine et al., 1997a; Quaine et al., 1997b). Given the more thorough three-dimensional mechanical analysis of the later studies, it is likely that APAs are evident in force changes by the hands and feet. Rougier (1993) infers specific roles for the contralateral hand and the ipsilateral hand, for foot displacements. The contralateral hand is used to displace laterally and accelerate the centre of mass, while the ipsilateral hand acts to counteract the 'flag effect' (a rotation about the vertical axis passing through the contralateral support). Gelat (1993) supports the importance of the contralateral hand with findings that the contralateral hand is loaded first and that the latency of the anticipatory force on the contralateral hand increases with movement difficulty, supporting Bouisset & Zattara's (1987) findings. Quaine et al. (1997b) looked at the lateral and anterior-posterior forces, as well as the vertical forces at each hold. These results showed an increase in force in lateral and anterior-posterior directions upon the contralateral hand, whereas the forces in the same directions on the ipsilateral hand went close to zero. Thus the results of Quaine et al. (1997b) support the inferences of Rougier (1993). When the limb to be displaced is a hand, a similar strategy is seen; the contralateral holds increase in force in the lateral and anterior-posterior directions, particularly the contralateral hand support. Thus it would appear that the contralateral supporting limb is of great importance to maintaining balance during limb movement.

In the climbing-specific literature, the majority of the posturo-kinetic studies have focussed on foot movements (Quaine et al., 1997b; Rougier, 1993; Metzger & Rougier, 1993, Noé et al., 2001); only Quaine et al. (1997a) report force patterns when a hand movement is made. The paucity of kinetic studies into hand movements means that the results from Quaine et al. (1997a) study cannot be corroborated, but there is also a question of whether the same strategy is utilised by the climber for hand movements as for foot movements.

There is a suggestion that different patterns of force change occur when the support holds are placed at greater lateral lengths (Metzger & Rougier, 1993). However, this study had only three participants and recorded three strategies. So there are no clear patterns reported.

2.4.1.3. Overhanging Environment

In the previous sections, the pattern of force change associated with loss of support of one limb has been discussed in reference to the horizontal and vertical environment. The main difference in these environments is the vertical projection of the centre of mass onto a base of support. Noé et al. (2001) argue that the results of Quaine et al. (1996) suggest that as the angle of support surface increases, from 0° to 90°, a continuum of force re-organisation, from diagonal to contralateral, is used by the climber to maintain balance. So when there is a base of support, which the centre of mass can be projected onto, a diagonal transfer of forces is demonstrated, whereas contralateral transfer is associated with positions with no base of support. Noé argues that the diagonal posture characterises a stable centre of mass. However, it has already been demonstrated that the postural support is dependent upon context and level of expertise, and that diagonal posture is not the sole response to loss of support from a limb.

In an overhanging environment, a significant sustentation base also exists onto which the centre of mass can be projected (Noé et al., 2001). Therefore the suggestion by Noé et al. (2001) is that the pattern of force change in the overhanging situation will lie on the continuum from contralateral transfer to diagonal. The results show that, although a contralateral transfer exists in the overhanging situation, this transfer is less extensive than in the vertical environment.

Research into balance control with respect to base of support has modelled the body as an inverted pendulum with the whole-body centre of mass as a point mass (e.g. Pai & Patton, 1997; Babic et al., 2001; Pai & Iqbal, 1999). A study by Noé et al. (2003) demonstrated that APAs disappeared in the lower limbs when the hands were used for balance, but did not transfer to the arms. The implication of this result is that the body cannot be modelled as an inverted pendulum when the arms make a contribution to balance maintenance (Noé et al., 2003).

Noé et al.'s (2001) study suggests that in the overhanging situation equilibrium, preservation is easier to manage from a mechanical point of view. The existence of a base of support means that the external constraints are weaker, that is the horizontal forces are now less important and there is a change in the role of the vertical forces applied to the holds. In vertical quadrupedia, the role of the vertical forces is to prevent vertical collapse and the horizontal forces counterbalance the body weight moment. In the overhanging situation, the vertical forces balance body weight and the body weight moment (Noé et al., 2001).

The mechanically easier body posture in the overhanging environment seems incongruous with the physiological experiments of Watts & Drobish (1998), who demonstrated greater energy cost per metre with overhanging surfaces. This can be explained by the fact that in the overhanging situation the arms have to accommodate vertical forces. The musculature of the arms is much smaller than that of the legs, so it follows that the physiological requirements are greater in the overhanging situation, than in the vertical environment.

2.4.1.4. General Criticisms of Posturo-kinetic Studies

A methodological constraint often applied with the posturo-kinetic studies (e.g. Quaine et al., 1997a) is that of an imposed frog type posture. This is to ensure no torque is applied to the holds by the hands and feet, as this would impact on the kinetic measurements. However this solution does not allow the climber to adopt the most mechanically efficient posture from which to perform an actual limb movement. Metzger & Rougier (1993) and Rougier (1993) did not impose an equalised initial body position, but these authors only studied vertical force patterns. This is a major limitation because, when studying quadrupedal activity, a three- dimensional analysis of the forces is required (Gray, 1944). The studies of Quaine et al. (1997a,b), Quaine & Martin (1999) and Noé et al. (2001) demonstrate empirically that for rock climbing, three-dimensional analysis is required.

A problem that all the studies, except Rougier (1993), suffer from is the very small sample of participants used. Metzger & Rougier (1993) only used three climbers, Gelat (1993) used five, Quaine et al. (1997a,b) used six and Noé et al.(2001) used seven. It could be argued that the sample numbers were too small to be generally applicable. However the applicability of these results is to a small, specific population, especially if one considers that the participants were pooled from populations of specific expertise levels in rock climbing. A further criticism of the work is the lack of quantification of level of expertise of the subjects, Quaine et al. (1997a) and Noé et al. (2001) state that the climbers were international standard, but do not report what level of expertise classifies a climber as being of international standard. This is in contrast to the physiological research, where level of expertise is generally taken to be of a performance level of F6c and above.

All the studies use male climbers, except Quaine et al. (1997a,b) who do not state whether the subjects were male or female. As males have different body anthropometry from women, it may not be reasonable to expect females to produce the same results as the males.
There is distinct lack of reporting of errors in data collection and analysis. This has consequences concerning accuracy and reliability of the results reported by the studies.

2.4.2. Kinematic Studies

Cordier et al. (1993) were using the climber-environment system as a way to study the optimisation of complex motor behaviour from a global perspective. Werner et al. (2000), however, were interested in the different techniques of climbers to solve a problem, in this case surmounting a roof. Climbers were filmed while competing in the 1993 World Championships in Innsbruck, using two synchronised cameras. Werner et al. (2000) looked at the centre of mass trajectories in the frontal and sagittal planes and also the distance of the centre of mass from the climbing wall. The roof task was split into three phases. Phase 1 ended when the centre of mass passed the constructed perpendicular plane containing the edge line of the roof (Werner et al., 2000). Phase 2 finished when the centre of mass passed the horizontal plane containing the edge of the line of the roof and Phase 3 was from the height of the edge to the finishing position. Despite the route being difficult, differences in centre of mass path were observable. At the edge of the roof, there was a low difference in horizontal coordinates in the frontal plane, seemingly implying that there was one optimal way of passing the edge, though one climber used a different foot step (Werner et al., 2000). Unfortunately, it is not reported which climber used the different foot step, so it is not known how much difference in centre of mass path existed, compared with the other climbers. Phase 2 also showed the smallest differences in coordinates in the sagittal plane. In phases 1 and 3, the coordinates in the frontal and sagittal plane were highly variable. The best climber needed the shortest time in phase 1 but similar time in the other two phases, kept the Centre of Mass the closest to the climbing wall in all three phases and showed the most consistent vertical velocity of his centre of mass (Werner et al., 2000).

Werner et al. (2000) conclude that distance from the climbing wall and the vertical velocity of the centre of mass were important factors. The study is limited in that only four of the competitors were selected for analysis, with no apparent justification. No statistical analysis was therefore reported. The authors acknowledge that there were instances of anatomical points being obscured by the climber, creating errors in the digitising process. The analyses of the climbers' strategies is limited by only studying the centre of mass trajectories and the authors even note, as discussed above, that one climber used a different foot step. The Werner et al. (2000) study should be viewed as a preliminary study that identified that different solutions for passing a roof exist and that factors of centre of mass vertical velocity and distance from the climbing wall may be influential.

2.4.3. Electromyography Studies

A number of studies have used electromyography (EMG) to study the activity of muscles involved in rock climbing. EMG measures the change in electrical potential in a muscle that occurs during contraction (Burden & Bartlett, 1997). Muscle contractions are created by the innervation of muscle fibres. Muscle fibres that are innervated by the same single motor neuron are collectively known, along with the motor neuron, as the motor unit (Hamill & Knutsen, 1995). Action potentials generated by the motor neuron propagate along the branches of the axon to, and subsequently along, each single muscle fibre as a depolarisation wave (Winter, 2005). The accumulated action potentials along all the muscle fibres in a motor unit are termed the 'motor unit action potential' (MUAP) (Burden & Bartlett, 1997). It is MUAP's that are recorded in EMG through electrodes attached to the surface of the skin or inside the muscle.

Electrodes placed inside the muscle (indwelling or fine wire electrodes) are used when muscles deep in the body or analysis of very fine movements are of interest (Winter, 2005; Burden & Bartlett, 1997). The process is highly invasive, with hyperdermic needles used to place the electrodes into the muscle (Winter, 2005). A drawback of this technique is that the placement of the electrodes, and the associated cabling, can provide a limitation to free movement by the participant. Indwelling electrodes are less susceptible to cross-talk however (see below) (De Luca, 1997), but not as reliable as surface electrodes (Komi & Buskirk, 1970). In sport and exercise biomechanics the non-invasive nature of passive surface electrodes means that these types of electrode are generally preferred to indwelling ones (Burden & Bartlett, 1997). Surface electrodes record the MUAP's from the superficial muscles in a particular measurement volume determined by the placement of the electrodes (Winter, 2005; Hamill & Knutsen, 1997). As such, surface electrode EMG (SEMG) is concerned with the analysis of the composite activity of the muscle (Winter, 2005). The electrodes generally consist of silver-silver chloride disks, varying in size upto about 1cm in diameter, used in combination with a conducting gel (Burden & Bartlett, 1997).

The detected EMG signal has a large number of inter-relating factors which influence the signal fidelity (Hamill & Knutsen, 1997; De Luca, 1997). The raw EMG signal has a low amplitude and must be detected with a differential set-up (Winter, 2005). The shape and area of the detection surfaces of the electrode, as well as the distance between the detection surfaces, are important in determining the amplitude and frequency of the measured signal (De Luca, 1997).

The placement of the electrodes sets the size of the detection volume and thus the number of muscle fibres 'seen' by the EMG equipment. The spacing of the electrodes also determines the frequency spectrum of the signal. If the distances between the detection surfaces are too small the surfaces can be electrically shunted if the skin becomes moist with sweat (De Luca, 1997). The orientation of the electrodes in relation to the muscle fibres affects the amplitude and frequency of the EMG (Winter, 2005). Different orientations of the electrode will influence the value of the conduction velocity of the action potential detected by the electrodes, which in turn influences the signal fidelity (De Luca, 1997). The measurement of the conduction velocity and the spatial filtering of the signal, determined by the relative spacing of the electrode to the active muscle units, are two of the most important factors to affect the EMG signal (De Luca, 1997). If the position of the muscle fibres changes in relation to the electrode then the spatial filtering characteristics will be altered and it is possible that new active muscle units will move into the detection volume while other motor units move out. Therefore when a muscle makes an anisometric contraction the electrode position should also change, which is difficult to do when the electrode is attached to the surface of the skin. Stable EMG signals can only be achieved when an isometric contraction of the muscle is performed (De Luca, 1997).

There are other extrinsic factors which affect the EMG signal. Any electromagnetic radiation in the vicinity of the participant will be conducted through the participant and detected on the EMG equipment. The most common sources of electromagnetic radiation are power cords, electric machines and lighting (Winter, 2005). Power hum can be removed through common mode rejection process (Burden & Bartlett, 1997; Winter, 1997). Providing that a differential set-up is used, the signal from one electrode is subtracted from the signal from the second electrode, thus removing the common mode signal, which is mostly power hum (Burden & Bartlett, 1997). In reality the elimination of the common mode signal is not complete. For instance if imbalances exist between the two signals in the impedances of the cabling or the electrode skin interface then a common mode signal will be present (Burden & Bartlett, 1997). Cable movement also affects the EMG signal. Movement artefacts, such as cable movement or the touching of electrodes, are characterised by low frequency jumps in the baseline of the signal (Burden & Bartlett, 1997; Winter, 2005). Filtering can remove the movement artefact noise from the signal but taping of the cables to the skin and using high quality cables can reduce this noise initially (Burden & Bartlett, 1997). Alternatively cables can be eliminated entirely by using a telemetric battery operated system, removing the problems of movement artefacts and power hum from cabling.

There are intrinisic physiological, anatomical and biochemical factors that influence the EMG signal fidelity. These factors include: the fibre type of the muscle, number of active motor units at any particular time, firing rate of the motor units, recruitment stability of the motor units, depth and location of the active fibre with regard to the electrode, blood flow through the muscle removing metabolites, the amount of tissue between the electrode and the surface of the muscle and the characteristics of the conduction volume (De Luca, 1997; Burden & Bartlett, 1997).

A particularly important issue in EMG analysis, whatever the type of electrode used, is that of cross-talk. Cross-talk occurs when the electrode detects MUAP's from muscles other than the actual muscle of interest (Winter, 2005). In the leg it has been demonstrated that a surface electrode can detect 17% of electrical activity in adjacent muscles (De Luca & Merletti, 1988), a situation which could lead to misinterpretation of the EMG signal. Cross-talk signals can be reduced by placement of the electrode on the belly of the muscle (De Luca, 1997) and by reducing the size of the electrode, and therefore the detection volume (Winter, 2005). If the muscles of interest are in close proximity, cross-talk may still present a problem. A number of processes have been suggested to eliminate the cross-talk component of the EMG signal. Manual resistance tests attempt to isolate the contractions of particular muscles and characterise the electrical activity for each individual muscle (Winter, 2005). This information can then be used when analysing subsequent signals to identify the existence of cross-talk. However, it is still possible that adjacent muscles are being activated by the participant during the manual resistance tests (De Luca, 1997). An alternate method is to cross-correlate the signal taken from one muscle with the signal taken from the adjacent muscle (Winter, 2005). If a cross-correlation value of less than 0.3 is found between the signals then there is no cross-talk present (De Luca, 1997). However the fact that muscle tissue is not homogenous and isotropic means that differing impedances will exist between the source of the electrical activity and the detecting electrode, thus altering the frequency spectrum of the EMG signal (De Luca, 1997). As the frequency spectrums of the two signals are uncorrelated, then the cross-correlation method is not a valid means of identifying cross-talk. The third method for reducing cross-talk is to use the double differentiation method. Double differentiation requires three detection surfaces equally spaced on a single surface electrode. Differential signals are obtained from surfaces 1 and 2 and also from surfaces 2 and 3. The resulting differential signal is then subsequently found (De Luca, 1997). The method works by essentially reducing the detection volume of the electrode and thus removing electrical activity originating at distances further from the electrode, originating from adjacent muscles (De Luca, 1997).

There have been three main applications of EMG analyses: 1) initiation of muscle activity, 2) relating the electrical activity of the muscle to the amount of force produced and 3) as an index of fatigue. In rock climbing orientated research, work has focussed on muscle activity and fatigue. Koukoubis et al. (1995) performed an EMG analysis on the dominant arm musculature during a pull up. The authors found that the flexor digitorum was the most active muscle during hanging and that this activity was continued during the pull-up task with the brachioradialis showing peak activation at the beginning of the pull-up. However, there is a question of applicability to rock climbing as there is no involvement of the legs. Watts et al. (2003) did use a realistic climbing movement to study the forearm activity involved in six different types of grip. The researchers found that muscle activity was greatest when the hand was either in the crimp position or in a two finger pocket using a combination of the V and IV digits. The authors also related the EMG analysis to maximum voluntary contractions using a hand dynamometer, concluding that the hand dynamometry lacks specificity to rock climbing tasks.

Analysis of different types of hand grip was also the focus of the research by Quaine & Vigouroux (2004) but in this study EMG was used as an index of fatigue. Quaine & Vigouroux (2004) found that the rate of fatigue in the forearms was not dependant on the type of grip utilised by the climber. It would seem that failure in rock climbing is not related to the ability of the forearm muscles to produce concentric force (Watts et al., 2003) but the ability to recover between contractions. Quaine et al. (2003) found that expert climbers were able to perform more repetitions of force application using the finger tips than novices. Both groups demonstrated decreases in the mean frequency of extensor and flexor EMG power spectra but at different rates. Thus it would appear that the ability to recover between contractions is an indicator of success in climbing.

EMG analyses of in rock climbing appear to be an attractive type of analysis. Currently the research has been limited to studying the amount of activity and the rate of fatigue in arm musculature. EMG analyses have been used to study the coordination patterns of muscle activity in other tasks, for example in vertical jumping (Bobbert & van Ingen Schenau, 1988) and cycling (Neptune et al. (1997). This type of analysis could also be utilised for rock climbing. However, EMG equipment is currently very expensive and limited in the number of muscles which can be measured. The Noraxon telemetric system, for instance, costs in the region of £18,000 for a 12 channel unit (Bodycare, 2005). Therefore currently EMG analyses are limited to studying specific muscles during movements, not whole-body movement analyses.

2.5. Reaching and Grasping

The work of Cordier and Werner focussed on the displacement of climbers' centre of mass over a route. In order to displace the centre of mass along a route, the climber must perform a sequence of grasping movements (Bourdin et al., 1998). Bourdin et al. (1998, 1999) investigated grasping movements in rock climbing situations using the theoretical backdrop of prehension task research in the field of motor control.

Prehension tasks can be thought to consist of two main components. The first component involves the arm moving the hand in to the vicinity of the target object (known as the 'transport phase' or 'free motion phase'), the second parallel component of the task is then to orientate the hand and shape the fingers of the hand in preparation of grasping the target object and then successfully closing the fingers to grip the target object (the 'grasping phase') (Jeannerod, 1981, 1984; Jeannerod et al., 1998; Rand et al., 2000; Michaelson et al., 2004). The two components have been shown to have a precise temporal relationship (Jeannerod, 1981, 1984; Jeannerod et al., 1998; Marteniuk et al., 1990; Wallace & Weeks, 1988; Wallace et al., 1990; Zaal & Bootsma, 2000; Rand et al., 2000).

Extensive research into prehensile movements has been undertaken for over twenty years, but there is still debate into reaching and grasping movement control. The initial view was based on a visuomotor channel hypothesis, in which the two components of prehension were planned and controlled independently, but were temporally linked (Jeannerod, 1981, 1984). In this theory, each component behaved as an identifiable system (Jeannerod et al., 1998). The transport component was affected by the spatial aspects of action and controlled by the proximal musculature, whereas the distal musculature controlled the grasping phase, based on visual analysis of the extrinsic and intrinsic properties of the target object (Jeannerod, 1981,1984). For example, when the target object size increased, the size of maximal grip aperture would also increase (Marteniuk et al., 1987; Marteniuk et al., 1990; Jeannerod, 1981, 1984), but the transportation phase remained invariant (Jeannerod, 1981,1984). Jeannerod (1984) also demonstrated that the peak hand amplitude and peak hand deceleration coincided. Support for the visuo-motor theory came primarily from physiological and anatomical studies in monkeys (Jeannerod et al., 1998), which found different neural pathways for the components of prehension. Although the components of prehension may vary in the neural organisation, the two components can never be strictly independent, as they must converge to the same final goal (Marteniuk et al., 1990; Paulignan et al., 1997; Jeannerod et al., 1998).

Researchers in the early 1990s, proposed that if the components of prehension were not independent in terms of planning and control, then the temporal and spatial aspects of the components should covary. Studies have shown that changes in distance of the object (Paulignan et al., 1997; Jakobson & Goodale, 1991), or object location (Paulignan et al., 1991), affect grip size as well as transport duration; changes in object size have been shown to alter the kinematics of the transport phase (Mateniuk et al., 1990; Zaal & Bootsma, 1993; Jakobson & Goodale, 1991). Movement speed affects the amount of covariance between the components (Wallace et al., 1990); at higher velocities the components tend to covary. Movement outcome, intent and object properties have all been shown to affect movement organisation (Marteniuk et al., 1987; Marteniuk et al., 1990; Zaal & Bootsma, 1993). Increase in grasp precision requirements, such as whether to grasp a light bulb or tennis ball, increase total movement duration (Marteniuk et al., 1987). Specifically, the total movement duration is increased through a disproportionate increase in the deceleration phase, termed a 'precision effect', which has been reported in both aiming (Mackenzie et al., 1987) and prehension movements (Marteniuk et al., 1987). The covariance changes in these studies were of relatively small amplitudes, but taken to represent the underlying coordination mechanism (Paulignan et al., 1997; Jeannerod et al., 1998). Jeannerod et al. (1998) suggest that an alternative interpretation of these studies is that they show evidence of cross-talk between the components within a coordination mechanism.

Contemporary views on coordination have to incorporate the redundancy in degrees of freedom problem. Degrees of freedom can be thought of as the number of independent coordinates that specify the organisation of the system (Newell & McDonald, 1994). At the behavioural level, degrees of freedom are the peripheral mechanical and physiological component degrees of freedom defining the joint configuration of the system (Newell & Vaillancourt, 2001). A large number of potential configurations for the system exist, due to the number of joint configurations. Thus for any movement, the system is over-determined; there are more biomechanical degrees of freedom present than required for the movement. The redundancy problem is how to coordinate all these degrees of freedom to produce smooth, efficient, variable movement (Bernstein, 1967; Thelen, 1995; Newell & Vaillencourt, 2001), yet at the same time it is the redundancy in biomechanical degrees of freedom that affords flexibility in the resolution of task solutions (Newell & McDonald, 1994). The computational load on the central nervous system (CNS) is reduced through controlling a few critical variables (Jeannerod et al., 1998) and formation of self-organising ensembles of degrees of freedom defined as coordinative structures (Turvey, 1990). Coordinative structures form through a confluence of constraints within the performer, the task and the environment (Newell, 1986). For example, patients with hemiparesis demonstrate integration of trunk movements into a coordinative structure for prehension when distal deficiencies exist (Michaelson et al., 2004). The implication is that the CNS accounts for the biomechanical deficiencies in the distal joints when planning the movement by forming a new coordinative structure, through recruiting the degrees of freedom associated with the trunk, to produce a successful reach and grasp.

Interestingly, despite the large number of degrees of freedom in the arm, the final hand and arm posture tends to remain invariant (Jeannerod et al., 1998). Stable final arm postures have been demonstrated for particular object orientations (Desmurget et al., 1997) and position (Gréa et al., 2000), while changes in object orientation have been shown to produce changes in the final arm posture (Desmurget et al., 1997; Stelmach et al., 1994). The variability in the trajectories of the fingers has been shown to decrease dramatically over the final part of the prehension trajectory as the fingers tend to converge on the same points of contact over repeated reaching and grasping movements at the same object (Paulignan et al., 1997). In the study by Paulignan et al. (1997), prehensile movements for cylindrical objects in a variety of locations in the workspace were studied. The cylindrical shapes meant that the objects had a number of opposition axes, that is there were a number of ways in which the fingers could be positioned upon the object to pick it up. The study found that the orientation of the opposition axis (the position of the fingers on the object) was invariant with respect to the body-centred reference frame and that the forearm and hand were displaced as a whole unit, regardless of object position in the workspace. Thus the orientation of the opposition axis is a controlled variable in prehensile movements (Paulignan et al., 1997). The trajectory of the limb endpoint has been shown to be a controlled variable (Jeannerod et al., 1998) with movement planning occurring in joint space when the prehension movement is unconstrained (Desmurget et al., 1997). Thus the finding by Paulignan et al. (1997) that final finger position occurs through choosing an invariant final arm posture, not an invariant visual landmark on the object, supports the notion of a global planning strategy for prehension (Jeannerod et al., 1998). The idea of planning the prehension movement in terms of final arm posture fits with the notions of Rosenbaum (e.g. Rosenbaum et al., 1992, 1996) concerning grasping in terms of end-state comfort.

The global planning strategy for prehension also sits within a coordinative structure idea of control. The work of Paulignan et al. (1997) showed that distal joints remained invariant, so to keep the orientation of the opposition axis constant, changes occurred in the proximal linkages. Thus there is a coordinative structure of maintaining the distal joint relationships and adapting the proximal degrees of freedom to adapt the coordinative structure to the exact performer, task, environment relationship. The fact that the opposition axis is orientated in a body-centred reference frame means that an economical solution, in terms of degrees of freedom, to producing an optimal arm posture for a prehensile movement to a constraining object shape, would be to rotate the body around the arm (Paulignan et al., 1997; Jeannerod et al., 1998). Thus the CNS integrates more proximal degrees of freedom to solve the movement problem at hand, thus reducing the computational load on the CNS.

The work of Bourdin et al. (1998, 1999) and Nougier et al. (1993) differed from previous work on prehensile movements, in that the organisation of reaching was studied in terms of the influence of postural constraint. In contrast to the standard protocols for analysing prehension, which involve grasping an object and manipulating the object, the grasping movement in rock climbing requires climbers to grasp a hold and manipulate their bodies around that hold. Postural stability before, during and after the grasping movement determines the success of the task rather than the grasping movement alone (Bourdin et al., 1998). The existence of a postural constraint in the prehensile movement served to remove the effect of precision requirements on the transport phase. That is the duration of the transport phase remains constant regardless of the size of target hold. Bourdin et al. (1998) suggest that the climbers used a strategy of optimising the duration of the tripedal position during the reach. The tripedal position is more difficult posturally than a quadrupedal position, so minimising the duration of this phase would be beneficial, but if the movement of the hand is too fast the posture may be impaired (Bourdin et al., 1998). When postural constraints increased, through the contralateral hand grasping a smaller hold, the duration of the transport phase decreased (Bourdin et al., 1998; Bourdin et al., 1999), irrespective of the precision requirements (Bourdin et al., 1999). More precisely, the duration of the acceleration phase increased and that of the deceleration phase decreased. The results of Bourdin et al. (1998, 1999) contrast starkly with 'traditional' prehension results, which demonstrate target object size effects on the transport phase (Marteniuk et al.,1990; Zaal & Bootsma, 1993; Jakobson & Goodale, 1991). Increased precision requirements have resulted in longer transport durations, through a relative increase in the deceleration phase, the so-called 'precision effect' (Marteniuk et al., 1987). The acceleration/deceleration pattern of the hand movement in Bourdin et al. (1999) work is more reminiscent of aiming movements, where the target is allowed to decelerate the hand (Marteniuk et al., 1987). In fact, Bourdin et al. (1999) suggest that the climbers used the target hold as a mechanical stop, and that the impact velocity was an important contributor to the movement organisation.

The 'traditional' work on prehension extended the work on Fitt's Law. A generalisation was made that the precision requirements of the task could be described through the effect the index of object difficulty had on the movement duration (Marteniuk et al., 1987). Bourdin et al. (1998, 1999) demonstrated that in posturally demanding situations the movement does not obey Fitt's Law. Instead, Bourdin et al. (1999) propose that climbers do not use supplementary feedback adjustments during the reach but delay adjustments until the target hold has been contacted. At contact, there is a more prominent utilisation of tactile and kinaesthetic feedback when postural constraints and the index of difficulty of the target hold increase. The results of Bourdin et al.'s (1998, 1999) work imply that the postural requirements are hierarchially more important than the precision constraints in the organisation of the successful prehensile movements. In posturally constraining environments, such as in rock climbing, where the target object is fixed in the environment, there is no requirement to reduce the hand velocity, so tripedal support duration can be reduced, even in grasping movements to more difficult holds, through a mechanism of delaying the adjustments until contact with the target hold and subsequent utilisation of kinaesthetic feedback.

The work of Bourdin et al. (1998, 1999) is limited both in terms of the kinetic and kinematic analyses. In the first study, Bourdin et al. (1998), only vertical forces at the handholds are reported. The authors cite the work of Quaine et al. (1995) as justification for only using the vertical forces, as these forces are attributed to stability maintenance in rock climbing. Unfortunately, the work of Quaine et al. (1995) was only published in France and therefore the validity of Bourdin et al. (1998) justification cannot be commented on from the original source. However, as previously discussed, kinetic analyses require appreciation of the horizontal as well as the vertical forces, and should include analysis of the body weight moments as well (Quaine & Martin, 1999).

In the second study, Bourdin et al. (1999), the kinetic data was only used to derive free motion phase duration, peak grasping force, time to peak grasping force. A full analysis, in the vein of Noé et al. (2001) for example, would have provided greater insight into balance maintenance in an actual grasping movement. Currently the only complete analyses are Quaine & Martin (1999) and Noé et al. (2001), which looked at changes from four- to three-point supports.

In terms of kinematics, the studies are extremely limited. The first study, Bourdin et al. (1998), did not use any kinematically derived measures. The second study, Bourdin et al. (1999), only studied the movement of the reaching hand via a single LED placed on the metacarpophalangeal joint of the middle finger. Thus there is no analysis of the initial and final arm postures, or of how the movements of the joints were organised during the prehension task.

To our knowledge the only study to look at the kinematics of a reaching movement is that of Bursnall & Messenger (2000). Bursnall & Messenger (2000) compared strategies in two conditions, high and low reach, on an 8.5° overhanging wall. The results showed that the pelvic tilt data suggested that the role of the legs was to push the body towards the target. There was also an indication that in the high-reach trials the body was positioned closer to the wall. However, the authors made only qualitative inferences on strategy, due to the preliminary nature of the study, although they were able to establish that the Qualysis ProReflex Motion Capture System was a valid tool with which to measure three-dimensional kinematics of climbing movement.

In this body of research, limited attention has been paid to the technique or strategy employed by climbers when solving climbing movement problems, particularly on overhanging walls. This is probably due to the complexity of the movements involved and the technical challenges required of three-dimensional (3D) kinematic analysis.

2.6. Three-dimensional Kinematic Theory

2.6.1. Position and Orientation of Rigid Bodies

In order to model the human body during motion, data is needed which represents the motions of the various parts of the body. The human body is frequently divided into segments, which are modelled as rigid bodies rotating about the joint axes (Zatsiorsky, 2002).

To define a rigid object in three-dimensional Cartesian space, an orthogonal right hand Cartesian coordinate system must be attached to the rigid object. The three dimensional Cartesian space has a right-handed coordinate system attached, known as the global coordinate system (GCS). The right-handed Cartesian coordinate system attached to the rigid object is often called the local coordinate system (LCS) (Berme et al., 1990; Zatsiorsky, 1998). To define an LCS, a minimum of three non-collinear markers are required to define a plane (Winter, 2005). One vector in the plane is taken as a LCS axis. A third vector, orthogonal to the plane, is defined as the second axis of the LCS. The third axis of the LCS is calculated as the cross-product of the first two LCS axes. A mutually orthogonal right hand coordinate system is thus defined, once each axis has been divided by its own length to create unit vectors.

Once the LCS has been defined, the position and attitude (rotation) of the coordinate system needs determining with reference to the GCS. The LCS is initially thought to be positioned and aligned as for the GCS. The position and attitude of the LCS with respect to the GCS can then be described as a sequence of translation by a 3x1 column position vector **p** followed by rotation by a 3x3 attitude matrix R (Equation 2-1).

The attitude matrix is constructed using the notion of direction cosines (Fioretti et al., 1997, Zatsiorsky, 1998). The LCS attached to a segment is composed of three orthogonal unit vectors. Each unit vector can be depicted by its components in the GCS. The cosine of the angle the unit vector makes with each co-ordinate axis of the global system can be calculated by dividing each component of the unit vector by the length of the unit vector (which is equal to 1 by definition) (Zatsiorsky, 1998). The angles made by the unit vector and the GCS axes are known as the direction angles, the cosines of those angles are called the direction cosines (Zatsiorsky, 1998). The direction cosines of the unit vector are simply the components of the unit vector (Berme et al., 1990). There are nine direction cosines, which can be written in matrix form as a 3x3 matrix.

$$[R] = \begin{bmatrix} \cos_{11} & \cos_{12} & \cos_{13} \\ \cos_{21} & \cos_{22} & \cos_{23} \\ \cos_{31} & \cos_{32} & \cos_{33} \end{bmatrix} \qquad \textbf{Equation 2-1}$$

where $\cos_{32}$ represents the cosine of the angle between the third axis of the global system and the second axis of the local system.

The attitude matrix has the properties of being a proper orthogonal matrix because $[R]^T = [R]^{-1}$ and the determinant of the matrix must equal +1 (Zatsiorsky, 1998).

However, the position and orientation of the LCS with respect to the GCS can be defined by a single 4x4 *transformation* matrix (Equation 2-2).

$$[T] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \mathbf{p}_x & \cos_{11} & \cos_{12} & \cos_{13} \\ \mathbf{p}_y & \cos_{21} & \cos_{22} & \cos_{23} \\ \mathbf{p}_z & \cos_{31} & \cos_{32} & \cos_{33} \end{bmatrix}$$ **Equation 2-2**

If the position and orientation of the GCS with respect to the LCS is required then the inverse of the transformation matrix must be used. However the transformation matrix is not orthogonal so the inverse is not simply the transpose of $[T]$.

$$[T]^{-1} = \left[\begin{array}{c|ccc} 1 & 0 & 0 & 0 \\ \hline -[R]^T[\mathbf{p}] & & [R]^T & \end{array}\right]$$ **Equation 2-3**

The relationship of two coordinate systems can be applied to absolute movement of a body segment within an external global space and also to the relative motion of two body segments. The usual way of analysing relative motion is for the distal segment position and orientation to be defined with respect to the proximal segment. The proximal segment is thought of as a stationary, 'global' coordinate system and the motion of the distal segment 'local' coordinate system is measured with respect to the proximal 'global' coordinate system. If the relative orientation of the two segments is of interest, i.e. just the joint rotations, then only the attitude matrix is required. So at each frame the distal segment orientation relative to the proximal can be defined by a 3x3 attitude matrix. While this gives a complete description of relative orientation, the attitude matrix is not easily interpretable and, with nine direction cosines, is redundant (Zatsiorsky, 1998). The attitude matrix can be parameterised into less redundant and more immediately interpretable conventions. The most popular conventions in biomechanics are Euler/Cardan angles and Helical axes.

2.6.2. Cardan/Euler Angles

Cardanic/Eulerian rotation sequences allow a segment or joint attitude to be defined with respect to a reference attitude, through an ordered sequence of rotations around the axes of one of the Cartesian co-ordinate systems, either the global, external coordinate system or the local segment embedded coordinate system (Woltring, 1994).

$$R_{ijk} = R_i(\phi_i)R_j(\phi_j)R_k(\phi_k)$$ **Equation 2-4**

where i, j and k indicate planar rotations about the co-ordinate axes (1:x, 2:y, 3:z) of either co-ordinate system (Woltring, 1994; Woltring, 1991). Eulerian angles are an ordered sequence of three rotations about two different axes (Fioretti et al., 1997) whereas Cardan angles are an ordered sequence of three rotations about three axes (Zatsiorsky, 1998).

The 'basic rotation matrices' (Fioretti et al., 1997) are defined as:

$$R_1(\phi_1)=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\phi_1 & -\sin\phi_1\\ 0 & \sin\phi_1 & \cos\phi_1\end{bmatrix}$$ **Equation 2-5**

$$R_2(\phi_2)=\begin{bmatrix}\cos\phi_2 & 0 & \sin\phi_2\\ 0 & 1 & 0\\ -\sin\phi_2 & 0 & \cos\phi_2\end{bmatrix}$$ **Equation 2-6**

$$R_3(\phi_3)=\begin{bmatrix}\cos\phi_3 & -\sin\phi_3 & 0\\ \sin\phi_3 & \cos\phi_3 & 0\\ 0 & 0 & 1\end{bmatrix}$$ **Equation 2-7**

where ϕ_i represents a rotation about the ith co-ordinate axis in a right hand screw sense.

Cardanic/Eulerian angles suffer from a problem known as 'gimbal lock' (Zatsiorsky, 1998, 1997; Woltring, 1994; Fioretti et al., 1997). Gimbal lock occurs when the two axis systems achieve a singular position; where the first and third axes are parallel and thus cannot be determined, only the sum or difference is defined (Zatsiorsky, 1998, Woltring, 1994). This situation occurs when the rotation about the second floating axis is of the order of $k\pi/2$ ($k=1,2,\ldots n$) (Fioretti et al., 1997). As a singular position is approached, the effect of noise in the measurements will have an increasing effect on the angles calculated (Woltring, 1994).

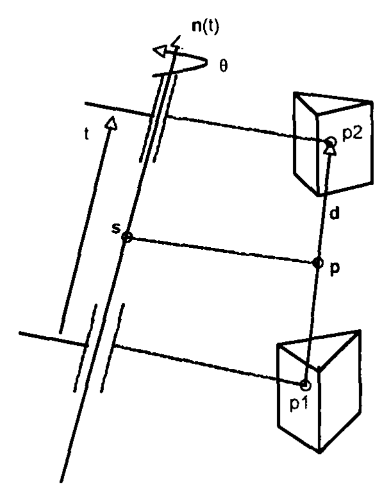
Gimbal lock can often be avoided by judicious selection of reference frame or angular convention. For example, using Grood & Suntay's (1983) convention in the knee, the floating axis corresponds to the adduction/abduction motion, which does not obtain values near $\pi/2$, and thus the problem of gimbal lock does not occur.

A further problem with defining attitude by a sequence of three rotations about the coordinate axes is that, although geometrically the three rotations will produce the end position of the segment, anatomically those rotations may be impossible. This is known as 'Codman's paradox' (Woltring, 1994). For example, the arm can be flexed 180° from a neutral position. It would also be possible, geometrically, to abduct the arm 180° and internally rotate it by 180° to achieve the same orientation. Clearly, the second sequence of rotations is anatomically impossible.

Helical axes are an alternative way of representing three-dimensional movement. There are essentially two types: finite and instantaneous helical axes. Finite helical axes are a discrete representation of the movement of a segment about and along a single axis. Instantaneous helical axes describe an axis that a rigid body can be thought of as moving around and along at any instant in time.

2.6.3. Finite Helical Axes (FHA)

According to Chasles Theorem, any movement can be described by a rotation, θ, about an axis and a translation, t, along the axis (Zatsiorsky, 1998; Woltring et al., 1994). This axis is defined in direction by a unit vector, **n**, and in space by a position, **s**, of some point on the axis (Figure 2-1) (Spoor & Veldpaus, 1980; Woltring et al., 1985).



(Woltring et al., 1985)

Figure 2-1 Helical axis for a finite displacement of a rigid object

n is the unit direction vector of helical axis, **s** is the projection onto the helical axis of the midpoint **p** on the finite translation vector **d** from $\mathbf{p}_1$ to $\mathbf{p}_2$, θ is the finite rotation angle about the axis, t is the shift along the axis.

Let segment A have a right handed Cartesian coordinate system attached (x_{local}) and be a rigid body. Segment A can therefore be defined by a position vector ($\mathbf{p}_i$) and an orthonormal attitude matrix (R_i) with determinant +1, with respect to an external global right handed Cartesian coordinate system (y_{global}). Segment A moves from an initial position (i=1) to a second position (i=2). Assuming that the landmarks (k) on the segment are error free, $\mathbf{p}_i$ and R_i can be determined from the rigid-body equation,

$$y_{ik} = \mathbf{p}_i + R_i x_k$$ **Equation 2-8**

where $R_i'R_i = I$; $i = 1,2$; $k = 1,\ldots,m$ (Woltring et al. 1985).

θ and **n** can be derived using the methods of Spoor & Veldpaus (1980),

$$\sin\theta = \sqrt{(R_{32} - R_{23})^2 + (R_{13} - R_{31})^2 + (R_{21} - R_{12})^2}$$ **Equation 2-9**

$$\sin\theta\mathbf{n} = \frac{1}{2}\begin{bmatrix} R_{32} - R_{23} \\ R_{13} - R_{31} \\ R_{21} - R_{12} \end{bmatrix}$$ **Equation 2-10**

Spoor & Veldpaus (1980) originally used the projection from the origin of the global coordinate system onto the helical axis, but Woltring et al. (1985) recommend using the mean value of the origin of the local coordinate system instead. In this way, **s** has been shown to be the most precise of all the points on the helical axis (Woltring et al., 1985). So **s** is the projection of **p** onto the helical axis along the finite translation vector **d** (Figure 2-1). The line **s-p** is the shortest line between the helical axis and the landmarks (on the segment) mean position.

$$\mathbf{p} \triangleq \frac{1}{2}(\mathbf{p}_1 + \mathbf{p}_2)$$ **Equation 2-11**

$$\mathbf{d} \triangleq \mathbf{p}_2 - \mathbf{p}_1$$ **Equation 2-12**

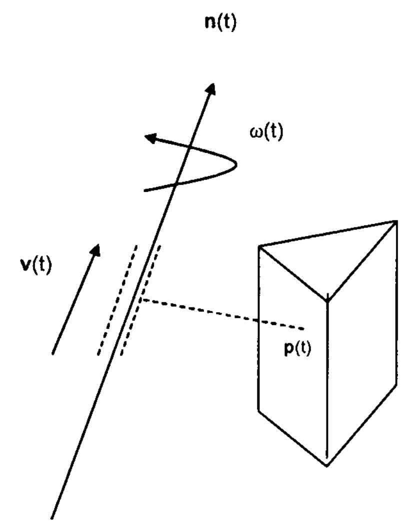
$$\mathbf{s} = \mathbf{p} + \left\{2\tan\left(\frac{1}{2}\theta\right)\right\}^{-1} \mathbf{n} * \mathbf{d}$$ **Equation 2-13**

(Woltring et al., 1985)

The FHA relates two discrete poses (Figure 2-1). Decomposition of the FHA into orthogonal components in either coordinate system, which are identical but opposite in sign, allows attitude to be represented by a compact 3x1 vector, the attitude vector (Woltring, 1994; Woltring et al., 1994).

2.6.4. Instantaneous Helical Axes (IHA)

Unlike the FHA, the IHA is an axis that an individual segment is moving about with respect to another segment at any instant, (Figure 2-2) (Woltring et al., 1994). This axis will vary in position and direction during a rotational movement. If the rotational movement is about a hinge joint, such as the elbow, the IHA will have a constant direction, whereas in a perfect ball and socket joint the IHAs will pass through a fixed centre of rotation. This idea is expanded on in Chapter 3 when rotational centre of the shoulder joint is discussed.



(Woltring et al., 1985)

Figure 2-2 Helical axis representation of a moving rigid object at an instant in time

n is the unit direction of the vector, ω is the angular rotation vector, v is the translation velocity, **p** is the position vector of the rigid object.

IHAs can be expressed directly as an axis with unit direction vector **n** and position **s**, defined as the projection of **p** (origin of the local coordinate system) onto the helical axis.

$$\mathbf{n} = \frac{\mathbf{w}}{\omega} \qquad \textbf{Equation 2-14}$$

$$\omega = \sqrt{\mathbf{w}'.\mathbf{w}} \qquad \textbf{Equation 2-15}$$

$$v = \dot{\mathbf{p}}'.\mathbf{n} \qquad \textbf{Equation 2-16}$$

$$\mathbf{s} = \mathbf{p} + \left(\mathbf{w} * \frac{\dot{\mathbf{p}}}{\omega^2} \right) \qquad \textbf{Equation 2-17}$$

(Stokdijk et al., 1999)

where **w** is the angular velocity vector of the local coordinate system with respect to the global coordinate system, v is the translation speed along the axis, **p** is the position vector of the local coordinate system in the global coordinate system and $\dot{\mathbf{p}}$ is the derivative of **p**. Angular velocity cannot be calculated as a time derivative of an orientation angle, thus **w** cannot be found by differentiation of a set of attitude angles (Zatsiorsky, 1998; Woltring et al., 1994). Instead, the Poisson equation (c.f. Woltring et al., 1994) must be used.

$$A\{\omega\} = \dot{R}R' \qquad \textbf{Equation 2-18}$$

where

$$A\{\boldsymbol{\omega}\} = \begin{pmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega 1 & 0 \end{pmatrix} \qquad \boldsymbol{\omega} = \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix}$$

If the raw data is appropriately smoothed (Woltring et al., 1994), the finite difference approximation of Poisson's equation is given by

$$A\{\omega\} \approx \frac{1}{4\tau}(R_+R'_- - R_-R'_+) \qquad \textbf{Equation 2-19}$$

where R_+ and R_- are the attitude matrices at sampling times +1 and -1 respectively and τ is the time interval.

The translation velocity vector can be found by direct differentiation of the position vector of the segment,

$$\dot{\mathbf{p}} = \frac{1}{2\tau}\mathbf{p}_+ - \mathbf{p}_- \qquad \textbf{Equation 2-20}$$

where $\mathbf{p}_+$ and $\mathbf{p}_-$ are the position vectors at sampling times +1 and -1 respectively and τ is the time interval.

IHAs can also be estimated by FHAs (Woltring et al., 1985; Woltring, 1991; Woltring et al., 1994). However, the FHAs are very sensitive to noise (Cheze, 2000; Spoor, 1984; Woltring & Huiskes, 1985). The error in the position and direction of the helical axis has been shown to be inversely proportional to the magnitude of the rotation about the axis (Woltring et al., 1985; Spoor, 1984). This is primarily due to the fact that the helical axis is undefined when there is no rotation (Woltring et al. 1985; Woltring, 1990). So when θ is small, the noise level will be high, but if the FHA is to approximate the IHA, θ cannot be too large or the movement will be undersampled (Woltring et al., 1994). To overcome this small angle noise effect, the raw data should be sufficiently oversampled and optimally low-pass filtered (Woltring, 1990; Woltring et al., 1994). Natural splines with a Generalised Cross Validated (GCV) criterion have been shown to suppress the small angle noise effect.

2.6.5. Smoothing Techniques

The previous section has already alluded to the fact that there will be errors in the position data of the markers. In fact, all raw kinematic data will contain errors arising from sources in the data collection process (Winter, 2005). These errors are known as instrumental or photogrammatical errors (Cappozzo et al., 1996; Cappello et al. 1997; Lucchetti et al., 1998). There are two types of error: systematic and random (Lucchetti et al., 1998). The systematic error is due to nonlinearities in the instrumentation (Hatze,1990), which can not be corrected by the calibration process (Cappozzo & Gazzani, 1990). These errors introduce a constant bias into the data and are usually of low frequency, less than 10 Hz (Wood, 1982; Medved, 2001). As such, systematic errors are difficult to resolve, as they lie in the same range as the signal to be measured (Hatze, 1990).

The random error is an inherent repercussion of representing a continuous signal as a set of discrete data (D'Amico & Ferrigno, 1990). One of the impacts in processing time-varying data is the non-violation of the sampling theorem (Winter, 2005). The sampling theorem essentially states that the sampling frequency must be twice as large as the greatest frequency present in the actual signal. If the sampling theorem is violated, then aliasing errors occur, resulting in false frequencies occurring in the data.

The random error, or noise, is the components of the signal which are not due to the motion measured (Winter, 2005). The noise is assumed to be random, additive, of high frequency and to have a normally-distributed zero mean (Woltring, 1995; Hatze, 1990; Wood, 1982). The noise amplification effect of the differentiation process has been well documented (e.g. Winter, 2005; Woltring, 1995; Bartlett, 1997; Wood, 1982). The high frequency components (errors) of a position signal will dominate more in velocity and acceleration data (Woltring, 1995). It is therefore desirable to remove the high frequency component of the signal, or smooth the signal (Winter, 2005; Wood, 1982; Woltring, 1985).

The removal of high frequency components from the signal can be achieved using a smoothing process (Wood, 1982; Bartlett, 1997; Winter, 2005). At this point there should be a clarification of terminology. Smoothing and low pass filtering are generally used interchangeably. The difference stems from viewing noise reduction from a signal engineering approach (low pass filtering) or a statistical approach (smoothing). Interestingly the two approaches have actually been shown to be equivalent with the GCV quintic splines smoothing procedure being equivalent to a double Butterworth filtering without phase distortion (Woltring et al. 1994; Woltring, 1990; Woltring, 1995, Bartlett, 1997). Both these techniques are discussed later in the text.

There are a number of considerations for smoothing data. Firstly the high frequency components, although reduced, are not completely removed. There is an overlap of signal and noise which means that the low pass filter will distort some of the signal while allowing some of the noise through (Winter, 2005). Secondly the low pass filter has to be applied to raw data prior to any nonlinear transformations (Bartlett, 1997; Woltring, 1995). Non-linear transformations will map high frequency, white noise into the low frequency domain and low frequency signal components in to the high frequency domain (Woltring, 1995). Thus the assumptions of the noise frequency would be violated. The mapping of 3D landmark data to rigid body models is highly non-linear so the filter or smoothing procedure should be applied prior to the construction of local coordinate systems (Woltring, 1995). The 3D reconstruction of markers is only mildly non-linear whereas the mapping of 3D landmark data to rigid body models is highly non-linear so the filter or smoothing procedure should be applied prior to the construction of local coordinate systems (Woltring, 1995).

The most common smoothing operations in biomechanics are: digital low pass filters (e.g. 4th order Butterworth Filter), Fourier series truncation and Quintic spline curve fitting (Bartlett, 1997). Digital filters stem from an electrical engineering discipline (Woltring, 1985) and therefore, were designed to work on a cyclical signal (Bartlett, 1997). They essentially work by taking a series of numbers, applying a number of mathematical operators, which have a weighting coefficient and a time delay, to produce a set of numbers of reduced frequency (Wood, 1982). The weighting coefficients depend upon the desired cut-off frequency (Wood, 1982). Butterworth filters are the most common digital filter to be used (Winter, 2005; Bartlett, 1997). However Butterworth filters have a number of problems. As there is a time delay in the way the filter works, a second reverse filtering operation is required to remove the time lag. The filter is recursive, which although speeding up the filter, requires the use of padding at the ends of the sequence (Bartlett, 1997). The main problem with the Butterworth filter is that the cut-off frequency has to be decided by the researcher. A residual analysis, as advocated by Winter (2005) can guide the researcher as to which cut-off frequency, this process is still inherently subjective and time consuming.

Fourier series truncation involves transforming the data from the time domain into the frequency domain. The data is reconstructed up to the cut-off frequency and the number of terms in the signal are truncated (Bartlett, 1997). The Fourier analysis is ideal for analysing periodic signals, the cut-off frequencies can be infinitely steep and can be differentiated analytically (Wood, 1982; Bartlett, 1997). However they still suffer from the need for an arbitrarily decided cut-off frequency.

Spline techniques are a series of polynomial curves through one or more points, which a re-joined together at 'knots' in a way which produces an overall smooth continuous function (Wood, 1982; Woltring, 1985). The process is analogous to taking a set of data in the time domain and drawing a smooth curve through all the data points. The user is required to define the degree of the spline, the required accuracy of the fit and the number and position of the knots. The degree of the spline function determines to which derivative level the data will be smoothed to. Quintic splines smooth to the fourth derivative level. These splines force the third derivative values to go to zero at the endpoints of the data series (Woltring, 1985). If cubic splines were used then the second derivative level data (acceleration data) would vanish at the data boundaries. Thus by using quintic splines boundary effects at the acceleration data can be avoided. The use of a Generalised Cross Validated (GCV) criterion to natural quintic splines has a number of benefits. Firstly the process is based on the work of Reinsch (1967, 1971), which treats every data point in the same way by placing a knot at each point (Wood, 1982; Bartlett, 1997). The GCV criterion automates the choice of the best smoothing spline based on the statistical properties of the actual data (Woltring, 1995; D'Amico & Ferrigno, 1992). Thus the user does not apply an arbitrary smoothing parameter. However GCV Quintic splines have been shown to undersmooth at the derivative levels (Woltring, 1995). This is because there is a compromise between smoothing at the proper data level and biasing in the derivative levels, so the splines try to smooth as little as possible (Woltring, 1995).

There is clearly a need to use a smoothing process on kinematic data prior to any non-linear processing. Essentially the choice is between a filtering technique or spline fitting procedure. The filtering techniques require an arbitrary cut-off frequency, whereas the GCV quintic splines provide a smoothing parameter based on the statistical properties of the data itself. This property alone makes the GCV quintic splines technique more appealing. The filtering techniques would require an initial residual analysis to be performed for each set of data, whereas the spline procedure is automated. To measure movement of the whole body, a minimum of three markers per body segment is required. This means that there will be a large set of data to be smoothed for each data collection, which would require separate levels of smoothing. The automated process of the splines would therefore involve less processing time. Splines and quintic splines have been shown to be well suited to the smoothing of biomechanical data (Wood, 1982; Bartlett, 1997). In the case of helical axes, the use of GCV natural quintic splines smoothing procedures has been shown to substantially suppress the small angle noise effect (de Lange et al., 1990; Woltring, 1990). It is proposed therefore to use the GCV natural quintic spline package (GCVSPL) of Woltring (1986) to smooth the raw kinematic data.

2.6.6. Skin Movement Artefacts

The effect of instrumental errors can be minimised through the use of a smoothing procedure, as has been shown. However there is another potential source of error, which has been shown to be even more critical and overwhelming in terms of magnitude (Cappozzo et al. 1996). These are the errors due to markers on the skin moving relative to the underlying bone (Tranberg & Karlsson, 1998; Reinschmidt et al., 1997). The aim of a three-dimensional kinematic study of human movement is to describe the motion of the underlying skeletal structure accurately. Coordinate systems are attached to the underlying bone structure; these are known as 'anatomical coordinate systems'. In order to define the anatomical coordinate systems in a consistent manner, identifiable bony landmarks are needed. In general the bony landmarks, from which the anatomical coordinate system is created, should be part of the body segment that the coordinate system is to be attached to (Cappozzo et al., 1997).

One method is to place markers on these palpable bony landmarks, allow the body segments to move and construct the coordinate systems directly from the three-dimensional positional data of the markers (Lu & O'Connor, 1999). The assumption is that during movement, the marker accurately defines the motion of the bony landmark; that is to say, the marker does not move relative to the landmark. Unfortunately, this assumption has been shown to be erroneous (Cappozzo et al., 1996, Fuller et al., 1997). Skin markers can move in a range of a few millimetres to 40mm with respect to the underlying bone during voluntary motion (Cappozzo et al., 1996; Tranberg & Karlsson, 1998). The largest artefacts are demonstrated by markers positioned above bony landmarks, are greater in the proximal segments and are linked to the angular motion of the nearest joint (Cappozzo et al. 1996; Tranberg & Karlsson, 1998). In knee joint kinematics during walking, skin movement errors have resulted in inaccuracies of 10%, 50% and 100% in flexion-extension, adduction-abduction and internal-external rotation movement range angles respectively (Cappello et al., 1997). The problem of skin movement artefacts is further complicated by the frequency content of these errors being the same as the underlying bone movement (Cappozzo et al., 1996, Fuller et al., 1997).

Markers are often placed on the skin, but sometimes stalks are used to increase the offset of the marker cluster and improve the three-dimensional measurements (Cappozzo, 1984; Cappello et al., 1997; Karlsson & Tranberg, 1999). However, stalk markers have been shown to have resonant frequencies in the range of 23-51Hz which can increase the errors (Karlsson & Tranberg, 1999).

Skin movement artefacts can be minimised through considerate placement of the markers and through optimisation routines (Cappozzo et al., 1997). Markers should not be placed near bony landmarks or the joint areas, as skin movement relative to the underlying bone is greatest in these areas (Cappozzo et al., 1997). The marker cluster, $n \geq 3$, should not be thought of as rigid, but deformable with respect to each individual marker and to the bone (Cappozzo et al. 1997). The distances between the markers should be as large as possible, in order to minimise error propagation, and the markers must be identifiable by the motion capture system during the whole movement (Cappozzo et al., 1997; Cappozzo et al., 1996). The technical marker cluster may therefore have an arbitrary and non-repeatable geometric relationship to the underlying bone (Cappozzo, 1991), as priority is given to the experimental requirements when placing these technical markers. A bone-embedded technical coordinate system is constructed from the deformable marker cluster using an optimisation routine.

Optimisation routines, such as that of Söderkvist & Wedin (1993), exploit the redundancy in the marker cluster data to create a coordinate system. Each marker has three translational degrees of freedom (dof), so the minimum marker cluster of three markers will have at least 9 dof. A coordinate system only has 6 dof (3 translational dof and 3 rotational dof). Therefore there is a redundancy in the number of dof needed to create the coordinate system. A least squares-based procedure can find an optimal bone-embedded coordinate system at each instant of time (Cappozzo et al., 1997). The bone-embedded frame does not necessarily align with the anatomy of the body segment.

The anatomical bone-embedded frame is calculated through measurement of the local vectors of the bony landmarks in the technical coordinate system in a post hoc data collection. Additional anatomical markers are placed on the anatomical landmarks. The participant assumes a pose which allows the motion capture system to measure positions of both the technical and anatomical markers (Cappozzo et al., 1995). Anatomical bony landmarks are identified relative to the technical coordinate system as time invariant local vectors (Cappozzo, 1991; Cappozzo et al., 1996). These local vectors are then used to recreate the anatomical landmarks during the movement trial. Anatomical coordinate systems are then created from these reconstructed anatomical landmarks with rigid body assumptions.

2.6.7. Body Segment Inertia Parameters

The body segment inertia parameters (BSIP) consist of the mass, inertia tensor and location of the centre of mass for each body segment (Reid & Jensen, 1990). Ideally, to determine the BSIP for an individual, these properties would be measured directly. This is not, however, an easy operation (Zatsiorsky, 2002). A way of determining BSIP for an individual is to use published data and adjust this average data to the specifics of that individual. A number of studies have been performed which allow BSIP data to be calculated (e.g. Dempster, 1955; Yeadon, 1990; Zatsiorsky & Seluyanov, 1983). The decision of which study to base the BSIP data upon depends on participants for which the BSIPs are to be found, the methodology of the original study and the required accuracy versus the complexity of scaling the data to the individual (Zatsiorsky, 2002).

The human body is heterogeneous, in the sense that the density is not constant through the whole body. As the body ages, the density of the body segments decrease as bone and muscle mass is lost and fat is gained (Reid & Jensen, 1990; Zatsiorsky, 2002). Any BSIP data must therefore come from studies which used a sample population similar to the population in the present study. Cadaver studies, (e.g. Clauser et al., 1969; Dempster, 1955; Chandler et al., 1975), are particularly problematic as they suffer from a small population pool, which is of elderly Caucasian males (Reid & Jensen, 1990). The applicability of these studies is also questionable, as the density of tissue in dead cadavers may be different from that of living tissue. If the cadaver is not frozen, there are problems with body fluid loss when segmenting the body (Reid & Jensen, 1990). If the cadaver is frozen, the density of body fluid is reduced, thus affecting the BSIP (Reid & Jensen, 1990). The trunks of the cadavers also differ dramatically. The lungs shrink and increase in density upon death and there is organ collapse within the trunk, creating space to be filled by air, thus altering the density properties of the trunk substantially (Zatsiorsky, 2002).

The Zatsiorsky group (Zatsiorsky & Seluyanov, 1983, 1985; Zatsiorsky et al., 1990) performed one of the most comprehensive studies into BSIPs of living subjects. This work has been collated by Zatsiorsky (2002). The sample population consisted of young physically fit Caucasian males and females (100 males, 14 females; mean ages of 24 and 19 respectively). Mean errors in estimates of the longitudinal position of the centre of mass were found to be -4 ± 13mm in male college athletes using the data of Zatsiorsky et al. (1990), compared with true centre of mass positions determined by a precision reaction board (de Leva, 1993 cited in de Leva, 1996). de Leva (1996) has made adjustments to the mean relative centre of mass positions and radii of gyration data of the Zatsiorsky group so as to be referenced to joint centres as opposed to bony landmarks.

The BSIP in this research will be based upon the adjusted values of de Leva (1996). This data provides a compromise between the accuracy of BSIP estimation and the complexity of their calculation.

2.7. Technique Research in Biomechanics

Despite the little research into technique in rock climbing, attention has been paid to the topic in other sports, especially with regard to closed skills in qualitative movement-based sports such as gymnastics (Takei et al., 1995), diving (Sanders & Burnett, 2004) and ice skating (King et al.,1994, 2004). The majority of biomechanical research into sports technique in the last ten years has been purely descriptive in terms of the kinematic or kinetic characteristics of a movement (Lees, 2002). The study by King et al. (1994) is one of a minority which has attempted to identify key characteristic variables by quantifying the effect of different ways of performing a technique using kinematic measures. Takei et al. (1995) studied the effect of one variable, grip technique, on performance of the Felge to handstand mount on the parallel bars in men's artistic gymnastics. Performance was determined by height of the centre of mass and body angle achieved at bar regrasp. These authors hypothesised what effect different grips (inner or outer) would have on the performance variables, and suggested further hypotheses on the causes of the effect in the main hypothesis. The mount was broken down into five phases and comparisons of kinematic variables made in all phases, as it was felt that differences in performance in later stages would be caused by differences in technique in early stages.

Lees (2002) argued that technique analysis has several goals. The first goal involves describing the sequence of movements (i.e. how the movement task was achieved), through variables such as relative position and orientation of body segments over time. The analytical goals are to investigate the most effective way movements are made and the effect of technique has on performance; these are difficult to achieve without using performance or outcome measures. Lees (2002) suggested that technique needs to be characterised in a way that refers only to the sequence of movements, without reference to how successfully the task was performed. Thus, a task may be performed badly using a correct sequence of movements, while conversely, a poor technique may result in a successful performance.

2.7.1. Quantification of Coordination

Technique analysis in biomechanics lacks a coherent conceptual base. Frameworks have been suggested, such as the biomechanically-based model of Norman (1975) or the Hay & Reid (1982) deterministic model, but these are ill-defined and fail to distinguish technique from performance variables (Lees, 2002). A recent approach to quantifying a sequence of movements is using Dynamical Systems Theory (DST) as a conceptual framework. The advantage of DST is that the variables represent the organisation of body segment movements by the neuro-muscular system without reference to the performance outcome.

Within the DST conceptual framework, movement is viewed as a confluence of constraints between the organism, the task and the environment (Newell, 1986); efficient, fluent movement is characterised by a release of constraints and utilisation of the passive forces within the system (Vereijken et al., 1992; Bernstein, 1967; Newell, 1986). In a more constraining system, the redundant degrees of freedom (Chapter 2.5) will be controlled; this control is manifested in the inter- and intra-segmental coupling of body segments. For example, in the context of the movement patterns associated with learning a ski slalom-like movement, Vereijken et al (1992) have defined the constraint of degrees of freedom as the minimisation of the standard deviations of joint angle. Temprado et al. (1997) were able to characterise the different techniques used by novices and by experts in a volleyball serve in terms of the coupling phase relationships between the different arm segments. These authors measured the phase relationship using inter-segment cross correlations of the horizontal displacement of the arm segments.

The DST approach thus provides a useful conceptual framework for characterising technique without the need for reference to the performance outcome. The use of DST to represent coordination in three-dimensional movements has had limited application (e.g. Lees & Nolan, 2000). Quantitative coordination measures, such as relative phase, are primarily two-dimensional methods and would be difficult to apply to three-dimensional joint rotation sequences in the whole body.

2.7.2. Technique Effectiveness

A common reason for performing an analysis of technique is as a prerequisite for improving performance (Lees, 2002). However, Lees has argued that further research is required: firstly, to diagnose errors in performance and secondly, to establish a process of intervention to produce the required outcome. Essentially, the issue is how technique analysis can be shown to improve performance.

In sports such as track and field, performance can be measured through the global outcome: for example, the length of a long jump (Seyfarth et al., 1999). In artistic sports such as gymnastics, performance can be determined through subjective judging of the aesthetics and specific criteria of the sport (Bradshaw, 2004). Ostensibly, the performance of a reaching task in rock climbing can be measured as success or failure in reaching and maintaining a new hold. This level of analysis gives limited insight, however. The task goals need to be defined in a more quantitative manner, as has been done in the studies of Takei et al. (1995) and King et al. (2004). The raising of the body's centre of mass would seem an intuitive task goal in rock climbing and, as has been previously discussed, this measure has received some attention (Werner et al., 2000; Cordier et al., 1993; Testa et al., 1999). For example, Cordier et al. (1993) measured the fluency of the centre of mass trajectory, which Kösstermeyer (2002) has defined as a component of good climbing technique, using the notion of geometric entropy. From a dynamical systems point of view, geometric entropy can be regarded as a reduction of constraint. In the DST approach, release of constraints and utilisation of passive forces characterise fluent, efficient movement (Vereijken et al., 1992; Bernstein, 1967; Newell, 1986). Efficiency of movement technique can be thought of as a task goal. It has been shown that, in overhanging situations, there is an increased energy cost of climbing (Watts, 2004); this leaves the climber with less energy to tackle the subsequent climbing problems and therefore less chance of success on the route. While efficiency can be difficult to define and measure, estimates of the mechanical work and energetics associated with each technique allow the influence of technique on task performance to be assessed (Dainty & Norman, 1987).

Two main work/power models have been applied to solely kinematic data, the Centre of Mass model (Willems et al., 1995; Thys et al., 1996) and the Fraction model (Pierrynowski et al., 1980) (term coined by Aleshinsky, 1986a). However, there are a number of issues that precluded their use in this work. The Centre of Mass model will be taken first. Theoretically, the validity of summing external work (mechanical energy changes associated with the whole-body centre of mass) and internal work (mechanical energy changes of the body segments relative to the whole-body centre of mass) to give the total energy of the body representing mechanical energy expenditure (MEE) has been shown to be unjustified (Aleshinsky, 1986b). Internal and external work cannot be assumed to be independent, and therefore cannot be summed, because external forces exist in the equations for both quantities (Aleshinsky, 1986b). The model also assumes complete intercompensation of energy sources (Aleshinsky, 1986a, b). Thus x amount of negative work in one joint, such as the ankle, and x amount of positive work in another joint, the elbow for example, would result in no total work performed, clearly unrealistic.

The Fraction model calculates the change in mechanical energy of the total body through the mechanical changes in the rigid body segments (Zatsiorsky & Gregor, 2000). The model replaces the joint torques with a resultant force and couple acting at the segment centre of mass. Thus, if one joint torque performs positive work on the segment and another performs negative work on the segment, then the resultant force and couple do not represent the actual amounts of work being performed. The total work done on the body is estimated using different equations, assuming different levels of energy transfer within and between segments (Pierrynowski et al., 1980). If external forces are absent, then the total work done on the body equals MEE if all the sources of energy (joint torques) are intercompensated and recuperated (already discussed as unrealistic), or all the joints either perform positive work or negative work (Zatsiorsky, 2002). Using the second assumption, MEE has been estimated in the analysis of lifting loads (de Looze et al., 1992) and in sporting movements such as speed skating (van Ingen Schenau & Cavanagh, 1990), where the small amount of negative work is ignored. At first, the Fraction model appears attractive to apply to climbing, as it is a predominantly lifting activity. However, the model could only be applied if no synchronised anti-symmetric joint movements were demonstrated to exist in the whole-body movement.

The only non-controversial model for work is that of Aleshinsky (1986a,b), as it is based on the classical definition of work. The model requires the use of kinetic data and is still limited by the assumptions of the model, such as using only single-joint muscles. A problem that all contemporary work/power models have is that they cannot account for isometric muscle contraction; if there is no movement, then there is no mechanical work done, but there is still metabolic work done by the muscles around the joint. Isometric contractions, particularly in the upper arms, have already been suggested to be an integral part of rock climbing activity (Billat et al., 1995; Booth et al., 1999).

2.8. Conclusion

The review of the scientific literature demonstrated that there is a limited research base into reaching movements in rock climbing environments. To date, only four studies have been performed, three posturo-kinetic based and one kinematic based. The postural requirement of rock climbing has been demonstrated to alter the organisation of the reaching strategy (Bourdin et al., 1998, 1999; Nougier et al., 1993) compared with 'traditional' prehension tasks in non-posturally constraining environments (e.g. Marteniuk et al., 1987; Jeannerod, 1984). However, unlike the 'traditional' prehension studies, the climbing-specific studies do not report any detailed kinematics. Thus there is no information about the way the climbers orientated their bodies or the specific coordination within the reaching arm in the completion of the task. The posturo-kinetic study of Bourdin et al. (1999) did use kinematic analyses, but was limited to a single marker on the reaching hand. Indeed, only one study (Bursnall & Messenger, 2000) attempts to compare the strategies of climbers in successful arm-reaching tasks, but this again is limited in nature. There is, therefore, a need for a detailed three-dimensional kinematic study of the strategies used in reaching movement tasks in rock climbing environments.

In a reaching movement in rock climbing, the primary goal is not the actual movement of the hand to the new support, but postural stability (Bourdin et al., 1999). The relative merits of a strategy employed by a climber to make a reaching move could therefore be judged not only on the actual movement of the hand but on the stability afforded by the strategy of the rest of the body. Overhanging climbing has been shown to be energetically more demanding than vertical climbing (Watts & Drobish, 1998) yet mechanically more stable (Noé et al., 2001). The greater physiological cost is attributed to the functional anatomy of the arms, which now have to apply vertical forces to counteract the body weight, and the body weight moment, being less adapted to support body weight compared to the legs. Strategies for reducing the energetic cost of single reaching movements would be beneficial to climbers, as they would allow more reaching movements to be achieved for the same total energetic cost. Geometric entropy, a measure of smoothness of the centre of mass trajectory, has been demonstrated to be an index of performance (Cordier et al., 1994). In three-dimensional movements, geometric entropy cannot be calculated, but the deviation of the centre of mass path from the most direct route would give a cost index of movement trajectory of the strategy. So the effectiveness of the strategy adopted by the climber in a reaching task can be evaluated on performance measures of: energetics, stability and whole-body centre of mass trajectory efficiency as well as the characteristics of the actual arm movement.

The literature review demonstrates that the specific research question of this work has received no attention by other researchers. In order to answer the research question, a three-dimensional kinematic methodology must be developed (Objective 2), which, as the review highlights, has not been produced before. The methodology will be based, where possible on International Society of Biomechanics (ISB) published recommendations (Wu & Cavannagh, 1995; Wu et al., 2002; Wu et al., 2005), and be developed through increasingly sophisticated validation experiments. As there is a limited research base, a qualitative study is needed, to establish if climbers make reach movements with markedly different ipsilateral foot orientations. Establishment of the environmental conditions of the studies will be derived from the qualitative study.

Chapter 3. Pilot Study 1:BICC Climbing Competition

3.1. Introduction

The purpose of Pilot Study 1 was three fold. The first aim was to investigate the techniques used by a population of climbers to make hand reaches, the second to attempt to explain the performances of that climbing population and the third to provide a quantitative, logical basis for further, more detailed analyses of rock climbing technique.

3.2. 2001 British Indoor Climbing Championship

The British Indoor Climbing Championship (BICC) consists of five or six competitions held at different climbing walls around the country. The 5th round of the BICC took place at the Leeds Wall on the 31st March 2001.

3.3. Participants

The population to be studied consisted of all the competitors (n=17) in the 5th round of the BICC. Consent for filming was given by the British Mountaineering Council. No statistics of the competitors ages, weight or standard were supplied. One competitor was disqualified, so the number of analysed performances was sixteen. A population of climbers competing in a competition provided a good arena in which to perform the investigation. Assumptions could be made that the climbers are of a high level of expertise to be competing in this event and that the competitors would be trying to produce maximal performances.

3.4. Equipment and Set-up

The semi-final round was filmed using a Panasonic NV-DS11 camera. The camera was set up on a second floor balcony, approximately 10m away from the wall and 4m above floor level. The camera followed the climber up the route, rather than having the whole route in the field of view. In this way a clearer image of the climber could be viewed upon playback, making the movements more easily recognisable.

The layout of the competition route is shown in Figure 3-1, kindly provided by The Leeds Wall. The wall is initially overhung by 8.5° then, at a height of 6m, the wall barrels outwards. The placement of the bolts defines the general route the climbers must take up the wall. Distances between the bolts on the wall are given in Figure 3-1.

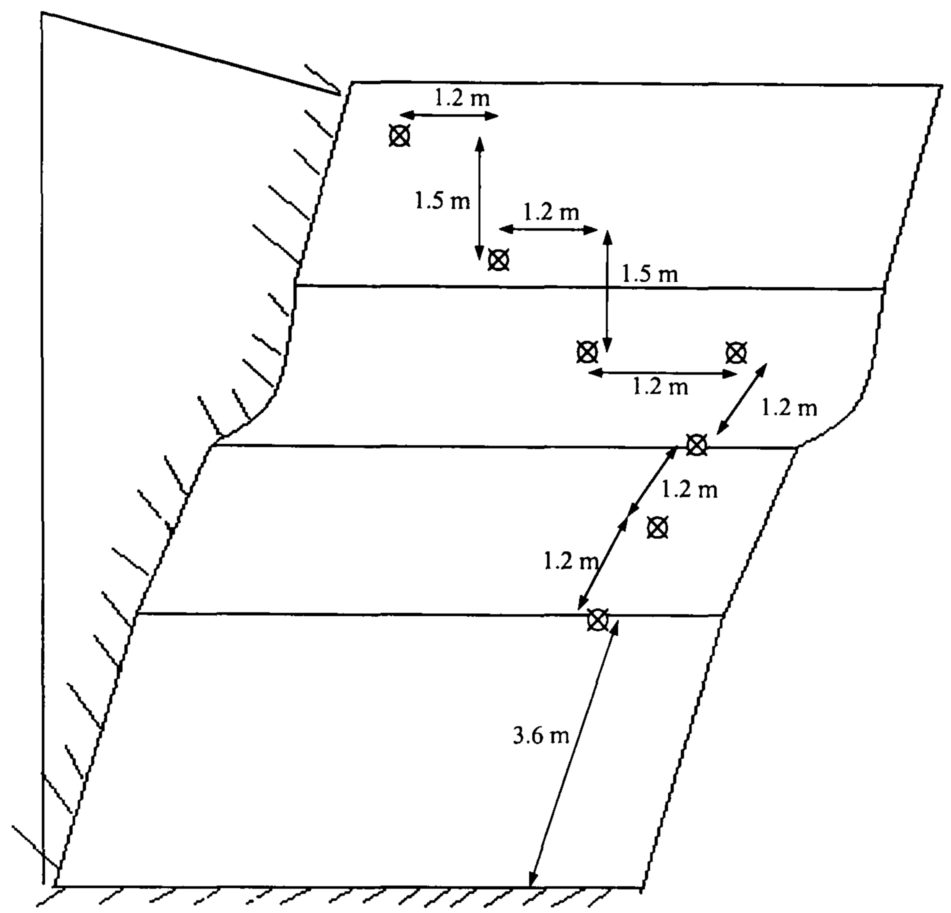


Figure 3-1 Competition route.
The circles with crosses represent the location of the bolts, which the climbers clip the rope to.

3.5. Methods

The competitors were kept in the isolation area until called to climb. This ensured that the climbers could not observe other performances, prior to their own. Once climbers started they had 10 minutes in which to complete the route. If climbers fell they were not allowed back on the climbing wall.

3.5.1. Notational Analysis

In summary, the movement was defined using the following framework:

1. Whether the limb moved
2. Which side of the body the limb was on
3. The direction in which the limb moved, recorded as a number on a clock face, with the hold the limb moved from being the centre of the clock

Action performed by the limb

4. Hand
    i. Whether one arm crossed over the other
    ii. Generic type of grasp
    iii. Type of handhold
    iv. Whether the hold was diagonal

5. Foot
    i. Whether one foot crossed over the other
    ii. Type of foot hold involved
    iii. Part of the foot involved
    iv. Whether the foot flagged

6. Whether the movement appeared to be performed in control or not
7. Whether a simultaneous movement of two limbs occurred
8. Comments

Table 3-1, below, explains the notation used on the record sheet. The data were transferred to an Excel spreadsheet and analysed using logical text function.

3.5.2. Data Analysis

3.5.2.1. Performance Analysis

The distances between the bolts were taken from the diagram of the wall (Figure 3-1). The distance the climbers achieved from the last bolt they clipped was estimated from the video footage, so the total distance the climbers moved could then be calculated. The distance from the last clipped bolt was taken as the distance of the waist from the last clipped bolt. In the competition, the distance was taken as the highest hold the hand touched, thus climbers sometimes just thrust their hand as high as possible to touch a hold in order to get a higher placing. However, in practical terms the climbers had not gained more height, so it was decided to use the waist as a reference marker, rather than the hand. Using the total number of moves from the notation data, the climbers' movement time from the video footage as well the distance the climber travelled were used to define performance characteristics over the whole route.

Table 3-1 Table of variables studied, the notation symbols and description

Variable	Notation	Description
Hand	H	Hand
Foot	F	Foot
Limb crossover	Xo	One limb (arm or leg) is placed behind the contralateral limb
Limb crossunder	Xu	One limb (arm or leg) is placed between the contralateral limb and wall
Limb moved into space	A	Limb moves into position away from wall
Overgrasp	O	Hand orientation on the hold
Undergrasp	U	Hand orientation on the hold
Side grasp	S	Hand orientation on the hold
Crimp	^	Finger grasp of hold
Open hand	\	Finger grasp of hold
Cup	)	Finger grasp of hold
Grab rope	Rp	Hand grasp of the rope
Clip rope	C	Hand places the rope into a karabiner to safeguard a fall
Chalk hand	D	Hand dips into a bag of magnesium carbonate, which is attached to the rear of the harness
Diagonal hold	/ or \	Orientation of hold if not utilized in a vertical or lateral manner
Inside edge	Ie	Orientation of the foot on the hold
Outside edge	Oe	Orientation of the foot on the hold
Smear	Sm	Orientation of the foot on the hold
Toe	T	Part of the foot placed on the hold
Heel	H	Part of the foot placed on the hold
Flag	Fl	The foot is not placed on a hold but is against the wall providing a balance role
Control	1	The movement of the limb appears qualitatively to be smooth and fluent
Simultaneous	+	Two limbs move at the same time

3.5.2.2. Notation Data Analysis

The notation data allowed the incidences of the way in which each hold was utilised and the direction of limb movement to be calculated.

3.5.2.3. Technique Incidence

The notation data enabled the type of technique used by each climber when performing a hand reaching movement to be established. The notation scheme had three ways in which the foot could be used on the hold: Inside Edge, Outside Edge and the Toe Edge; a fourth option was for the foot to be away from the wall. Thus four separate techniques were possible. The Inside Edge (IE) technique is characterised by the use of the inside edge of the ipsilateral foot (to the reaching hand). When the outside edge of the foot is utilised, the knee must be turned under the body in the Outside Edge (OE) technique. When the Toe Edge (TE) technique is used, the foot is positioned perpendicular to the wall with the front of the toe in contact with the hold, while an ipsilateral reach is made. Similarly if the foot is not in contact with the wall, the technique is called Air technique.

The total incidence of each technique for the whole population of competitors was summed and compared as percentages of total hand reaches. For each climber the number of incidences of each technique was converted into a percentage. Percentage of use of each technique was compared to climbers rank.

3.5.2.4. Qualifiers vs Non-qualifiers

The climbers in the top six positions qualified for the final. In order to investigate why this group of climbers qualified and the rest failed to, the climbers' data was split into two groups: qualifiers for the final and non-qualifiers. The incidences of each measure were identified in each section of the route. A section of route was defined by the space between two bolts; the clipping of the bolt with the rope indicated the end of section. The group data were averaged and comparisons made between groups and section of route.

3.5.2.5. Statistical Analysis

The population under investigation was small (n=16) and the frequencies of the measures were also relatively low. Data were tested for normality using a Shapiro-Wilk test, which demonstrated non-normally distributed data. Non-parametric tests were therefore applied. One-tailed Spearman's Rho tests were used to correlate measures against position. Statistical analyses were performed using SPSS.

3.6. Results

3.6.1. Global Variables

Table 3-2 The height, total time and total no. of moves by each climber

Position	Climber	Height (m) waist	Height (m) hand	Total Time (s)	Total Moves
1	7	12.3	13.5	141	119
2=	4	12.3	13.2	124	101
2=	1	12.3	13.2	127	89
4=	17	12.6	13.2	117	95
4=	13	12	13.2	165	113
6	2	11.7	12.6	113	92
7	8	11.1	12	124	87
8	6	10.2	11.4	101	93
9	14	9	10.2	97	72
10=	12	8.7	10.2	87	65
10=	16	8.4	8.4	75	59
10=	11	8.4	8.4	86	68
10=	3	8.4	8.4	90	77
14	5	8.1	8.4	71	58
15	15	8.1	8.4	105	70
16	9	7.8	8.4	82	76
disq*	10	0	0	0	0

*disq - disqualified

The last six placed climbers all reached with their hands to the same height. However, one of the joint tenth climbers, climber12, hand reached the same height as climber 14, who came one place higher (Table 3-2). The top five climbers all reached the same height with their hands, although climber 17, who came joint 4th, achieved the highest height with their waists.

The top five ranked climbers used in the region of one hundred limb movements to cover approximately 12m of climbing distance. These climbers also had total climbing times around 2 minutes. The longest time was taken by climber 13, who came joint 4th, with 165 seconds.

3.6.2. Incidence of Hold Types

Figure 3-2 shows that four grasps were most commonly utilised. The most common type of grasp was the overgrasp grip, with the least common type being an open grip. The single most common handhold was the open overgrasp grip, with the overgrasp crimp hold the second most used grasp. There were no incidences of undergrasp crimps, undergrasp diagonal crimps, diagonal undergrasp open grasps or side open grasps.

In contrast, there were incidences of all the foothold types (Figure 3-3). Climbers used the inside of the foot for the majority of foot placements and preferred to use the toe rather than the heel. The technique of flagging was used with both the outside and inside of the foot being employed; inside edge flags were the second most commonly used. Moves where the foot was moved into a position with no contact with the wall had the third highest average incidence.

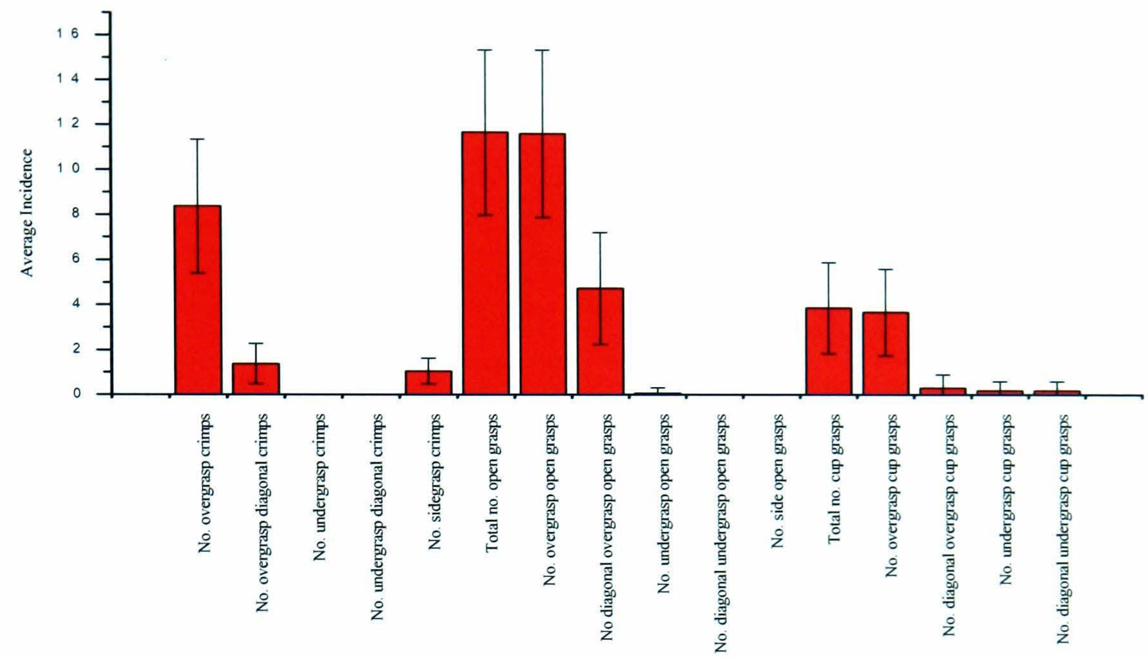


Figure 3-2 Incidence of each type of hand grasp

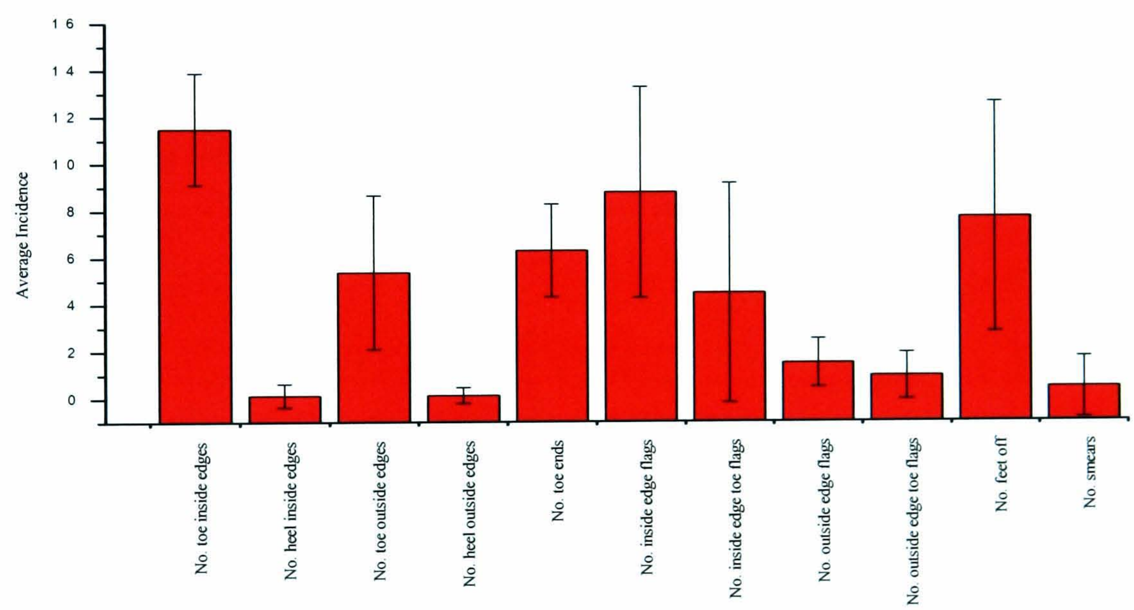


Figure 3-3 Incidence of each type of foot support

3.6.3. Direction of Hand Movements

The plot of the direction of hand movements shows that the majority were in the direction above the previous hold (Figure 3-4). The results show a bias to left hand directed movements, which is unsurprising as the route involved a left hand traverse after the 4th section. A spike occurs at six o'clock on the clock face. This can be explained by the climbers either reaching for the rope to clip into the bolts or chalking their hands in little pouches attached to the climbers waist.

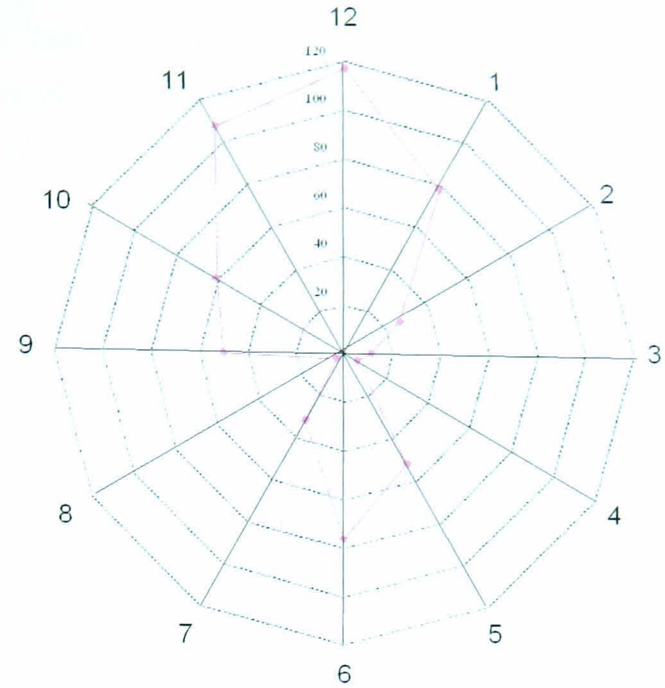


Figure 3-4 Direction of hand reaches

3.6.4. Technique Incidence

The most popular technique for making an arm reach was to stay front-on (44%), (Figure 3-5). The second most frequent technique was the OE technique (28%), though the TE technique was used almost as much (25%). Only a small percentage (3%) of arm reaches were performed with the ipsilateral leg away from the wall.

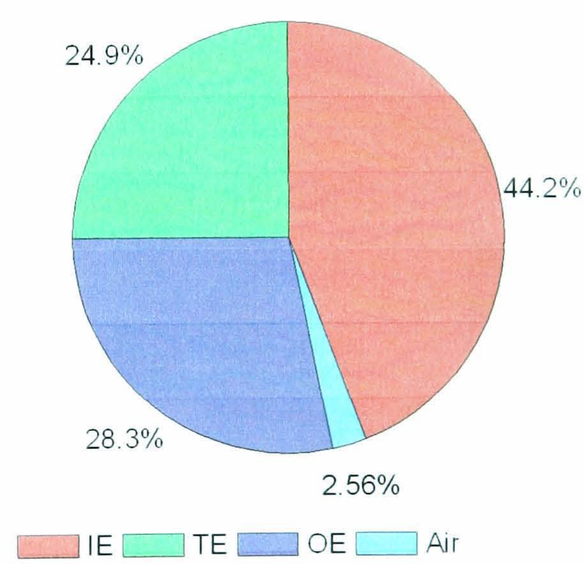


Figure 3-5 Incidence of technique for all the climbers

Figure 3-6 demonstrates a significant negative correlation (rho = -0.592; $p<0.01$) between the use of OE technique and ranking, and a significant positive correlation (rho = +0.368; $p<0.05$) between IE technique and ranking. Thus higher ranking climbers showed more OE and less IE technique. However, the use of IE techniques was not a pre-requisite for achieving a higher position, as shown by the second placed climber who performed 50% of reaches with IE technique. The air technique was found to have a significant negative relationship with rank (rho = -0.508; p<0.01). The use of the air technique was low compared to the other techniques and was only used by climbers placed in the top ten. No significant correlation was found between incidence of TE technique and ranking.

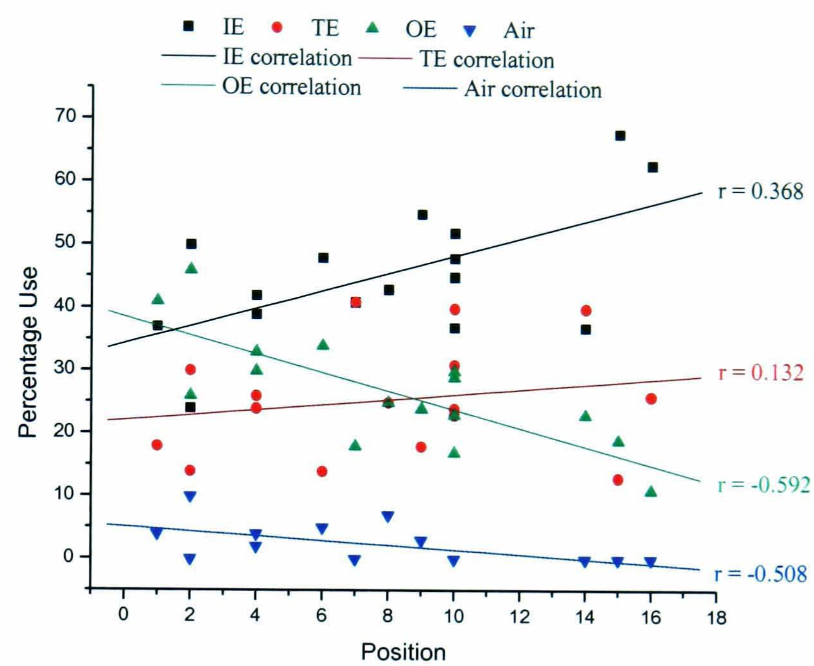


Figure 3-6 Percentage use of each technique related to final position

Note that percentage use is positively correlated with increased position number (i.e. reverse rank)

3.6.5. <u>Technique</u>

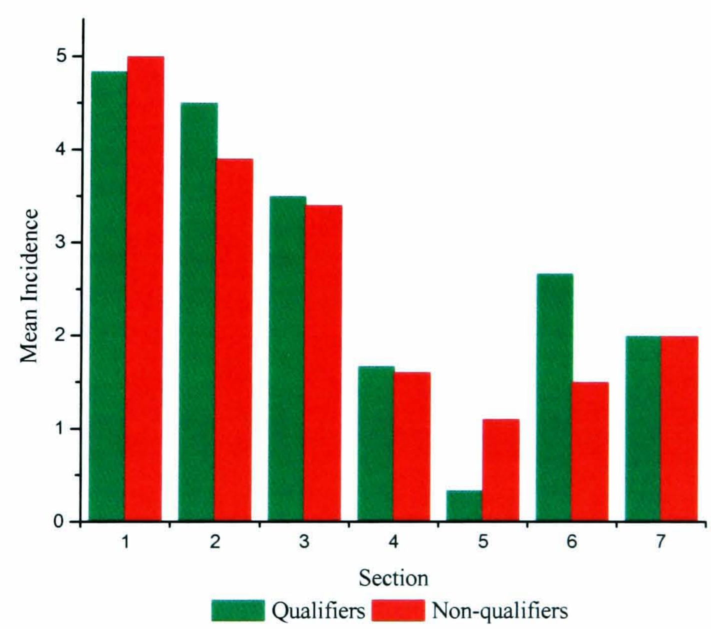


Figure 3-7 Mean incidence of inside edge technique in each section of climb for qualifiers and non-qualifiers

The general trend for the use of the IE technique by both groups was for there to be a decrease in use through the sections, with a minimum usage in section 5. In section 6, the qualifying group showed a higher incidence of IE technique than the non-qualifiers, but in section 7, both groups had similar incidences.

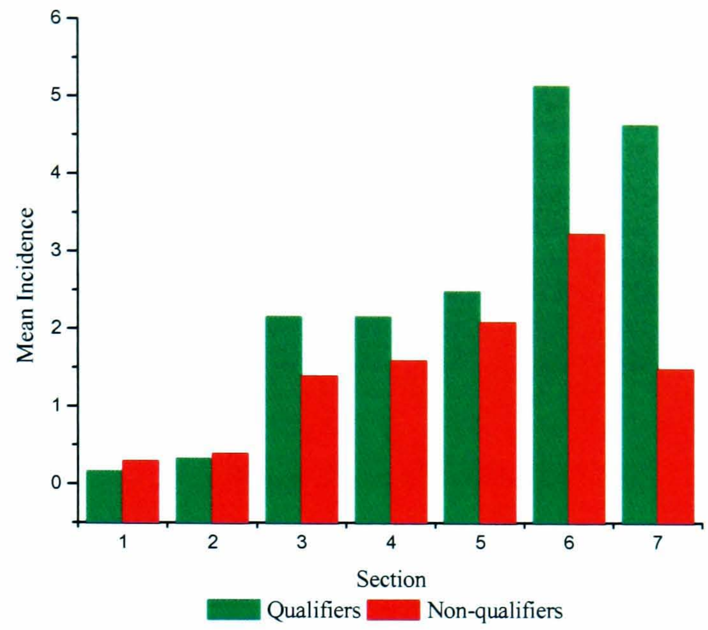


Figure 3-8 Mean Incidence of outside edge technique in each section of climb for qualifiers and non-qualifiers

Similar amounts of OE technique were used by both groups in sections 1 and 2 but from section 3 onwards, the qualifiers, on average, demonstrated a greater incidence. Specifically, in sections 3, 4 and 5 the qualifiers show a slightly higher incidence of OE technique, but in section 6 the gap increased markedly and did again in section 7.

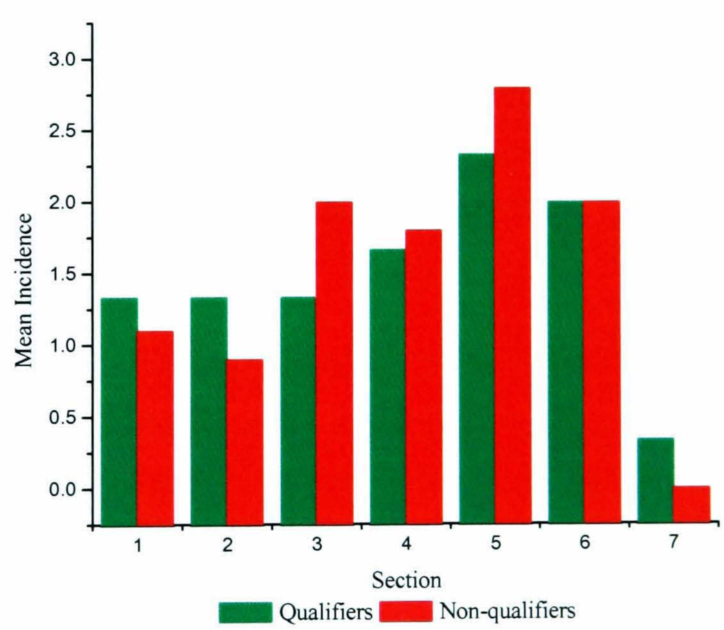


Figure 3-9 Mean incidence of toe edge technique in each section of climb for qualifiers and non-qualifiers

The non-qualifier group showed less use of the TE technique in sections 1 and 2, but for sections 3, 4 and 5 the non-qualifiers demonstrated greater use of TE technique. In sections 6 and 7, both groups employed similar amounts of TE technique.

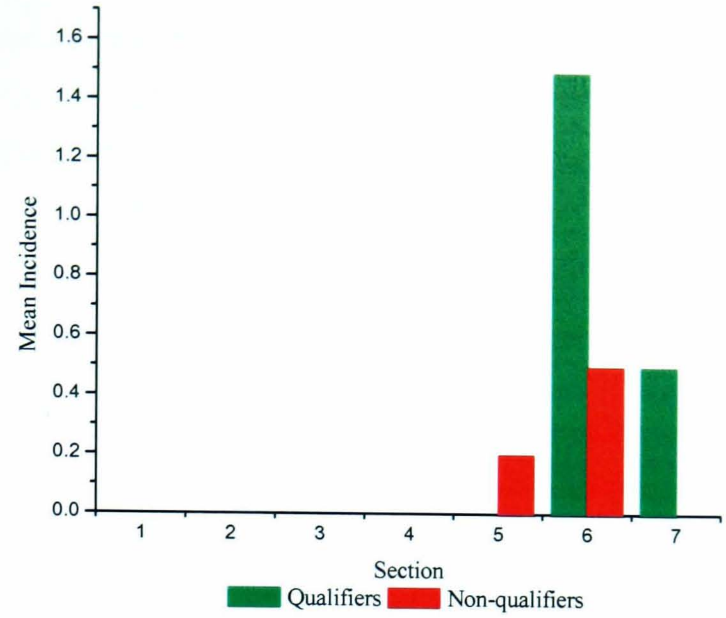


Figure 3-10 Mean incidence of air technique in each section of climb for qualifiers and non-qualifiers

The qualifier group showed a greater mean incidence of air technique in section 6 and in fact section 6 was the first section in which this group demonstrated any use of the technique at all. The non-qualifiers on the other hand started to use the air technique in section 5 but also had a peak in section 6.

3.7. Discussion

3.7.1. Global Variables

The global performance measures demonstrated that large a number of limb movements, in the region of one hundred, are required, even for rock climbs of relatively short length. The top ranked climbers climbed for approximately two minutes to cover distances of around 12m. These measures illustrate that rock climbing is a slow activity.

3.7.2. Technique Incidence

The most common technique was the IE technique, involving 44% of all hand reaches. The data also demonstrated that the TE technique was almost as common as the OE technique (25% and 28% respectively). It is interesting to speculate whether the TE technique may be an indication of climbers trying to use the OE technique, but failing to rotate the foot sufficiently. If this were the case, and TE and OE usage are conflated, the OE technique would have been more frequent than the IE technique, suggesting that the OE technique was the preferred technique for this population of climbers. When the percentage usage of each technique is compared to performance (taken as ranking in the competition), then the increased use of the OE technique shows significant correlations with increased ranking at the 1% level; and increased use of the IE technique is significantly correlated to lower rankings at the 5% level. Alternatively the TE technique may offer performance benefits in its own right, however this technique did not show significant correlation with ranking and in fact the correlation was very low (rho = -0.132). The use of the air technique was found to be significantly correlated with increased rank (rho = -0.508); with the climbers ranked in the bottom 6 making no use of it at all. In fact the air technique is only demonstrated from section 5 onwards by any climber (figure 3-10). The bottom six climbers fell in section 5, whereas the other climbers managed to get to sections 6 and 7, so the bottom 6 ranked climbers may not have progressed far enough to have to use the air technique, or maybe they fell because they failed to use the air technique.

3.7.3. Logical Basis for Further Studies

The second aim of this study was to look at the way holds were utilised and direction of arm movements of climbers in a 'natural' setting, so as to provide a logical rationale for further detailed laboratory based studies. The direction of the arm movements was mostly upward and diagonally leftwards, which is to be expected as the route had a left traverse for section 5 and then rose diagonally leftwards in sections 6 and 7.

The foothold analysis showed a large variability in the way the feet can be used by the climbers. There was at least one incidence of each type of foot placement. The most commonly used part of the foot was the inside toe section. When the climbers used their feet on the holds, the edging parts of the shoes were used in preference to the smearing technique.

In contrast to the feet, the handholds were utilised in a far more standardised way. The most common way of orientating the hand was in an overgrasp, with open grips being the most frequent followed by the crimp grip. It is interesting that the crimp grip was not the most commonly used by these climbers in this competition, something which contrasts with previous studies (e.g. Schweizer, 2001) claiming that the crimp grip to be the most common type. It may be that the competition organisers were trying to reduce the risk of injury by using holds which forced the climber to utilise an open style of grip. Alternatively, forcing the climbers to use the open grip style may have been intended to ensure the difficulty of the route was sufficiently high, as the route was not particularly long.

3.8. Conclusion

The qualitative study has demonstrated that competition climbers in overhanging situations make hand reaches with the ipsilateral foot in different orientations. The data also suggests that there may be performance benefits in using the outside edge technique as opposed to the inside edge technique.

A more detailed comparison of hand reaches performed with the foot in different orientations is now required. The methodology for performing three-dimensional kinematic analyses on climbers in overhanging environments will be the focus of Chapter 4.

Chapter 4. Method Validation

4.1. Introduction

The survey of the literature in Chapter 2 demonstrated that three-dimensional kinematic whole-body analyses of climbing movements have not been previously undertaken. The purpose of this chapter is to establish a reliable, accurate and repeatable methodology that will permit three-dimensional kinematic measurements of a climber's motion. The methodology makes use of standard techniques and where possible, International Society of Biomechanics (ISB) recommendations, but applied to the specifics of a climbing environment.

The chapter begins with simple validation tests of key concepts using test data and rigid models. The aim of the validation exercise is not only to establish that the theory has been applied correctly but also that the implementation of the mathematics in the (mostly custom written) Matlab programs. The second section of the chapter develops a kinematic model of a climber, and deals with the application of local coordinate systems to the body segments. Particular problems with the shoulder joint centre and the hip joint centre are considered. The final part of the chapter consists of two pilot studies focusing on the measurement of climbers who are performing a hand reaching task. This section attempts to validate the climbing movement problem to be used, highlight the difficulties in measuring the kinematics of a human performing a climbing movement and resolve them.

4.2. Validation of Key Three Dimensional Kinematic concepts

4.2.1. Use of Generalised Cross Validated Natural Quintic Spline (GCVSPL) Package for Data Smoothing

Vaughan's (1982) set of vertical coordinates of a falling golf ball were used to test the GCVSPL (Woltring, 1986) program in Matlab. The acceleration of the ball was derived from the raw data using the double finite difference technique. The raw data was smoothed using the GCVSPL program at the GCV criterion and acceleration values calculated a second time. The results are shown in Figure 4-1.

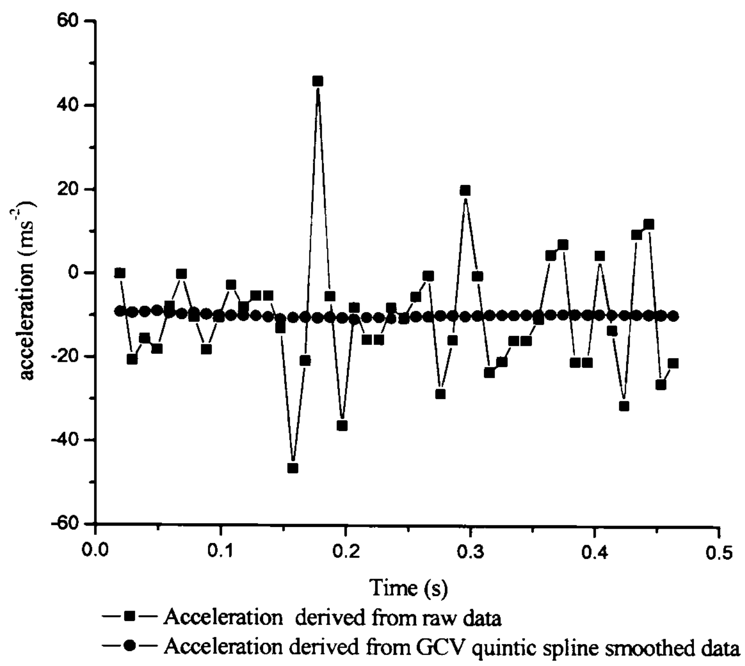


Figure 4-1 Acceleration due to gravity values derived from smoothed and unsmoothed Vaughan's (1982) falling golf ball data using the double finite difference technique

The mean acceleration for the raw data was -9.91±15.18ms^{-2} and for the smoothed data, -9.56±0.48ms^{-2}. As the motion was that of a projectile, the only force acting was that of gravity (air resistance is assumed to be negligible), so the vertical acceleration of the ball should be -9.81ms^{-2}. Although the GCVSPL operation has not improved the mean of the dataset, Figure 4-1 demonstrates that the smoothing procedure has substantially smoothed the data and improved the estimate of acceleration due to gravity of the data series. The smoothed data is also far less variable, as shown by the massive reduction in the standard deviation (Table 4-1). Table 4-1 demonstrates that the GCV criterion does not result in the optimal smoothing at the 2nd derivative level.

Table 4-1 Mean and standard deviation (SD) acceleration values of the falling golf ball data set with increasing levels of smoothing

	Smoothing Parameter				
	No Smoothing	5.98×10^{-7} (GCV)	5.98×10^{-6}	5.98×10^{-5}	5.98×10^{-4}
Mean	-9.91	-9.56	-9.66	-9.71	-9.72
SD	15.18	0.48	0.31	0.22	0.16

4.2.2. ProReflex System Validation

Seven ProReflex Motion Capture Units's (MCU) were set up in a semi-circular fashion from ceiling mountings. A measurement volume of 1.6x2.1x3.2m was defined. The ProReflex system was calibrated using the calibration frame and wand method, as per the manufacturers guidelines before each data collection.

Three data collections were performed to establish the accuracy, precision and reliability of the ProReflex Motion Capture System. The data for all three tests was collected at 150Hz.

4.2.2.1. Test 1

The first test involved a five second data collection of stationary markers on the climbing wall. The raw positional data of one marker (diameter Ø18mm) was smoothed using the GCVSPL program in Matlab. The standard deviation of the markers positional coordinate data was calculated for each trial. The mean error over the seven trials was found.

Table 4-2 Standard deviations of a stationary marker coordinates over a five second period over seven trials

	Standard Deviation of a single stationary marker co-ordinates (mm)		
Trial	x	y	z
1	0.02	0.03	0.03
2	0.02	0.03	0.03
3	0.01	0.00	0.01
4	0.01	0.01	0.02
5	0.02	0.02	0.02
6	0.01	0.02	0.02
7	0.06	0.05	0.13
Mean	0.02	0.02	0.04

The standard deviation in the position of a static marker gives a measure of the precision of the motion system. Table 4-2 demonstrates that the ProReflex system is extremely precise in locating a static marker, with a mean standard deviation of ≤0.04mm. The system is also reliably precise as shown by the standard deviation of ≤0.04mm over the seven trials.

4.2.2.2. Test 2

The second test involved manoeuvring a wooden model of the arm, with three markers (Ø18mm) in a fixed arrangement, around the measurement volume. The position data of the three markers were smoothed using GCVSPL program. One of the internal angles of the triangle was found by calculating the angle between two vectors (Equation 4-1).

$$\cos\theta = \frac{\mathbf{u}.\mathbf{v}}{|\mathbf{u}|\ |\mathbf{v}|}$$ **Equation 4-1**

Seven trials were performed. The mean angle and standard deviation were calculated for each trial. The mean and standard deviation of the seven trials were taken to represent the ability of the system to precisely and reliably measure a fixed angle between three markers on a moving rigid body.

Table 4-3 Mean and standard deviation (SD) of the internal angle of the three markers over seven trials

	Angle (°)	
Trial	Mean	SD
1	53.82	0.29
2	53.86	0.33
3	53.98	0.27
4	54.02	0.33
5	53.93	0.21
6	54.01	0.26
7	53.62	0.35
Mean	53.89	0.29
SD	0.13	0.05

Table 4-3 shows that the system can consistently measure the angle with a precision of 0.29±0.05°. The system was also highly reliable in that it measured a fixed angle to ±0.13° over the seven trials.

4.2.2.3. Test 3

The third test consisted of throwing a marker (Ø18mm) through the measurement volume, a total of seven times. Each trial was clipped to include only the time when the marker was airborne. The marker coordinates were smoothed using GCVSPL program. The smoothing was increased to a factor of 10^{-6}. The vertical and horizontal acceleration of the ball was calculated, using double finite difference technique. The mean and standard deviations were calculated within each trial. In the x and y directions, the acceleration should be $0ms^{-2}$, whereas in the z direction the acceleration is due to gravity and therefore should equal $-9.81ms^{-2}$. The error of the mean acceleration from these values was calculated to give an overall mean error for the seven trials. This test is the most stringent test of the system's accuracy due to the build up of measurement error in the derivation process to calculate acceleration.

Table 4-4 Mean and standard deviation (SD) values for the acceleration of a projectile in the x, y and z directions

		Acceleration ms^{-2}		
Trial		x	y	z
1	Mean	-0.13	-0.78	-9.87
	SD	0.06	0.09	0.54
2	Mean	0.08	-0.82	-9.97
	SD	0.06	0.27	0.43
3	Mean	0.29	-1.26	-9.93
	SD	0.54	0.26	0.50
4	Mean	-0.09	-0.64	-9.78
	SD	0.04	0.06	0.31
5	Mean	0.13	-0.63	-9.75
	SD	0.04	0.07	0.39
6	Mean	-0.05	-0.82	-9.75
	SD	0.05	0.05	0.27
7	Mean	0.19	-0.98	-9.83
	SD	0.38	0.04	0.52

Table 4-5 Mean and standard deviation (SD) of the mean acceleration errors over the seven trial in the x, y and z directions

	Mean Error ms^{-2}		
Trial	x	y	z
1	-0.13	-0.78	-0.06
2	0.08	-0.82	-0.16
3	0.29	-1.26	-0.12
4	-0.09	-0.64	0.03
5	0.13	-0.63	0.06
6	-0.05	-0.82	0.06
7	0.19	-0.98	-0.02
Mean	0.06	-0.85	-0.03
SD	0.16	0.22	0.09

Tables 4-4 and 4-5 show that the ProReflex system is capable of locating a moving marker with great accuracy. The largest mean error was $-1.26ms^{-2}$ in the y direction. The system reliably measured accelerations with a mean error of $\leq 0.85ms^{-2}$ in any direction over the seven trials with a mean precision $\leq 0.22ms^{-2}$. The effect of an acceleration error of the magnitude of $0.85ms^{-2}$ at a frame rate of 150Hz would be an error of $0.006ms^{-1}$ in the change in velocity and $4x10^{-5}m$ in the change in displacement between two time points.

4.2.3. Reconstruction of an Anatomical Marker in a Technical Coordinate System

Three technical markers (Ø18mm) were placed on the forearm segment of a rigid multi-segment model of the arm. A fourth 'anatomical' marker (Ø18mm) was placed on the pivot at the elbow joint. An initial data collection was performed of the rigid model in a fixed position, at a frame rate of 240Hz. The raw data was smoothed using the GCVSPL program. The technical marker coordinate system inverse transformation matrix (Chapter 2.6.1) was determined using a Matlab program based on the work Söederqvist & Wedin (1993), i.e. a singular value decomposition technique to provide a least squares estimate for the transformation parameters (Challis, 1995). The global coordinates of the pivot marker were converted to local coordinates in the technical markers coordinate system using Equation 4-2. A mean value of the local coordinates was taken to be the local time invariant vector of the 'anatomical' landmark in the technical coordinate system.

$$[P_L] = [T]^{-1}[P_G]$$ **Equation 4-2**

A second data collection was then performed with the rigid model of the arm undergoing flexion and extension. The raw data was smoothed using the GCVSPL program and a local coordinate system fixed to the technical markers as before, but this time the transformation matrix (Chapter 2.6.1) was calculated. The local vector of the anatomical marker was used to reconstruct the anatomical marker's global coordinates in each frame, using Equation 4-3. The reconstructed coordinates were then compared with the actual coordinates of the anatomical marker.

$$[P_G]=[T][P_L]$$ **Equation 4-3**

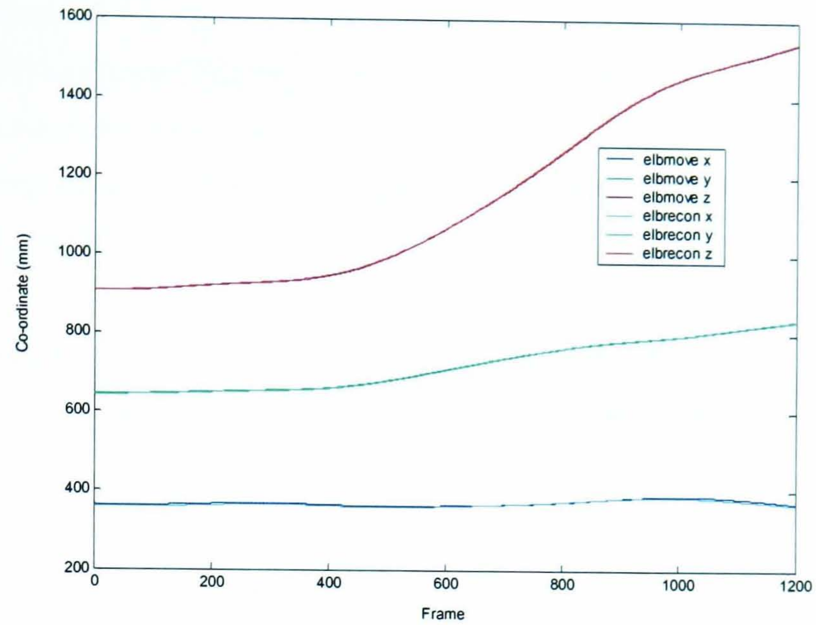


Figure 4-2 Comparison of the measured (elbmove) and estimated (elbrecon) co-ordinates of the elbow joint centre in the multi-segment rigid model

Table 4-6 Error in the estimated elbow joint centre of the multi-segment rigid model

	Error (mm)		
	x	y	z
Mean	2.7	1.5	-1.7
SD	1.9	0.6	0.8

Figure 4-2 and Table 4-6 demonstrate that the data conditioning process, conducted through custom programs in Matlab, is able to reconstruct anatomical landmarks correctly during a movement trial. The mean error in reconstruction is <3mm in one direction. The marker's diameter is 18mm, so the error constitutes less than a sixth of the marker diameter.

4.2.4. Use of Finite Helical Axes, Instantaneous Helical Axes and Sphere-Fitting Regression equation in determining the Pivot Point

The mean pivot point of the Instantaneous Helical Axes (IHA) (calculated directly and estimated from Finite Helical Axes [FHA]) and the sphere-fitting method were validated by using a rigid model of the arm with a hinge joint at the elbow. Three technical markers were placed on the upper arm, three technical markers on the forearm and a marker on the elbow joint. A data collection was performed at 250 Hz of the model moving through an angle of 70° at the elbow. The technical markers were smoothed using the GCVSPL program and local coordinate systems attached using the least squares algorithm of Söederqvist & Wedin (1993). The forearm coordinate system was defined in the upper arm coordinate system.

4.2.4.1. Helical Axes

Finite Helical Axes (FHA) and Instantaneous Helical Axes (IHA) were found using Equations 2-8 to 2-13 in Chapter 2.6.3 and Equations 2-14 to 2-20, in Chapter 2.6.4, respectively. In order to calculate IHAs the angular velocity must be of sufficient magnitude for reasonably small standard deviations on the coordinate data (Woltring et al., 1994). A low angular velocity can cause outliers, thus values of s and n that exceeded three standard deviations from the mean were discarded (Stokdijk et al., 1999).

Once the IHAs (either calculated directly or approximated from FHAs) had been calculated, the mean pivot point closest to all the IHAs in a least squared sense was computed as the optimal pivot point (S_{opt}).

$$\mathbf{S}_{opt} = Q^{-1}\frac{1}{N}\sum_{i=1}^{N} Q_i \mathbf{s}_i \qquad \textbf{Equation 4-4}$$

with

$$Q = \frac{1}{N}\sum_{i=1}^{N} Q_i \qquad Q_i = I - \mathbf{n}_i.\mathbf{n}_i'$$

(Woltring, 1990; Stokdijk et al. 1999)

where $\mathbf{s}_i$ is the position vector of the IHA at time i, $\mathbf{n}$ is the unit direction of the helical axis and N is the sample size.

The position vector $\mathbf{S}_{opt}$ is calculated in the upper arm coordinate system. The coordinates of the mean pivot point were then converted back into the global coordinate system. This value was then compared with the coordinates of the marker placed on the elbow joint.

4.2.4.2. Sphere Method

The location of the elbow joint was calculated as the centre of rotation between the upper arm and forearm by fitting a sphere to the path of the centroid of the forearm cluster. The centre of rotation was calculated by finding the elbow joint coordinates in the upper arm coordinate system (x_c, y_c and z_c) and a value for a sphere radius R that minimises the function

$$f(x_c, y_c, z_c, R) = \frac{1}{n}\sum_{i=1}^{n}\left|\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2 + (z_i - z_c)^2} - R\right| \qquad \textbf{Equation 4-5}$$

(Piazza et al., 2001)

where x_i, y_i and z_i are the coordinates of the centroid of the forearm marker cluster in the upper arm coordinate system at frame i and n is the number of frames of data.

The fminunc unconstrained minimisation function from the MATLAB Optimisation Toolbox, which employs a Broyden-Fletcher-Goldfarb-Shanno quasi-Newton method with a mixed quadratic and cubic line search procedure was used to minimise the above function as in the methodology of Piazza et al. (2001). Piazza et al. (2001) suggest using ten initial estimates for x_c, y_c and z_c to avoid finding non-global local minima for function f. Ten random estimates for the position of the elbow joint, within 100mm of the actual elbow joint, were generated. Ten minimisations were performed and the results averaged to give a single estimate for the position of the elbow joint. This local vector was transformed into global coordinates of the elbow joint over the duration of the arm movement. These values were then compared with the actual values of the elbow joint.

Table 4-7 Mean and standard deviations (SD) of the errors in estimating the elbow joint centre from the finite helical axes (FHA), instantaneous helical axes (IHA) and sphere methods

		Errors in elbow joint location (mm)		
		x	y	z
FHA	Mean	8.0	8.7	1.9
	SD	1.8	0.9	0.5
IHA	Mean	5.3	9.3	1.7
	SD	1.8	0.8	0.6
Sphere fitting	Mean	2.5	-5.8	-9.3
	SD	9.8	4.9	3.9

The mean errors in locating the elbow joint for all three methods are in the range of 1-10mm in any single direction (Table 4-7). The markers on the rigid model had diameters of 18mm, so the mean error represents approximately the radius of a marker. This equates to the standard error permitted by the ProReflex system in marker identification. The error in location of the joint centre is thus acceptable.

The FHA's were shown to give approximate values of the IHAs, and the results supported Woltring's (1991) assertion that the small angle noise effect can be suppressed by use of natural quintic splines with the GCV criterion in the raw data smoothing process.

The helical axes were much more consistent than the sphere-fitting method in locating the joint centre, as demonstrated by the lower standard deviations. This could have been due to the planar nature of the model movement, though Piazza et al. (2001) have demonstrated that the sphere-fitting method is still applicable when there is small joint motion and when motion is restricted to a single plane.

This experiment validated the custom Matlab programs for calculating helical axes (both finite and instantaneous) and using them to find a mean pivot closest to the mean of the helical axes in a least squares sense. The sphere fitting Matlab programs are also validated.

4.2.5. Cardanic Parameterisation of the Orientation Matrix

Six markers were placed on a right angle frame, as in Figure 4-3. Three markers were assigned as segment S (S1-S3) and three markers assigned as segment R (R1-R3). Coordinate systems were attached to the segments as in Figure 4-3. Segment S was defined as the proximal segment, with segment R as the distal. The orientation of the distal segment relative to the proximal was then calculated. As segment R is rotated 90° to segment S in the horizontal plane, the rotation of segment R relative to segment S should be -90°.

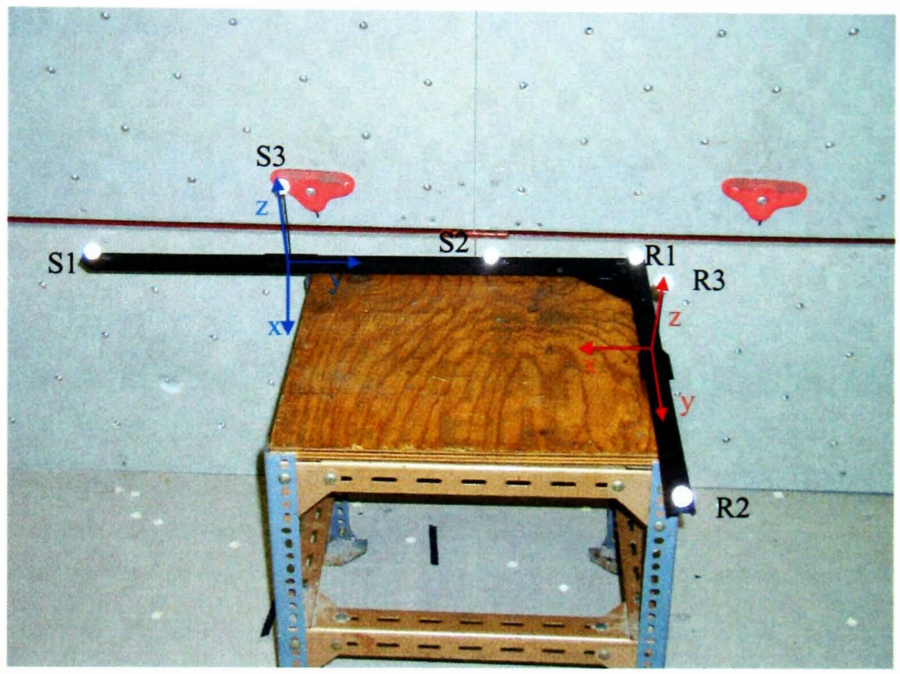


Figure 4-3 Segment S markers and coordinate system (blue) with segment R markers and coordinate system (red)

Table 4-8 Angular orientation of segment R relative to segment S using the Cardan sequence Zx'y"

	Rotation °	
Z	x	y
-89.8	4.2	-4.5

Table 4-8 demonstrates that the orientation of segment R relative to segment S was correctly determined.

4.2.6. External Energy/Work Calculation

Vaughan's falling golf ball data was used to validate the custom Matlab program for the calculation of potential energy, kinetic energy and external work. Potential energy was calculated by:

$$E_p = mgh \qquad \textbf{Equation 4-6}$$

where m is mass of the object, g is acceleration due to gravity, h is the vertical height of the object's centre of mass. Kinetic energy was calculated as in Equation 4-7:

$$E_k = \frac{1}{2} m v^2$$ **Equation 4-7**

where v is the linear velocity of the object's centre of mass. Total energy (E_T) was simply the summation of the kinetic and potential:

$$E_T = E_p + E_k$$ **Equation 4-8**

The amount of external work done on the ball between frames was calculated using:

$$W_{nc}\Big|_{t_1}^{t_2} = E_2 - E_1$$ **Equation 4-9**

where E_2 is the sum of the potential and kinetic energy at frame 2 (t_2) and E_1 is the sum of the potential and kinetic energy at frame 1 (t_1). If the whole-body centre of mass of the object is being analysed, then Equation 4-9 can be expanded and re-arranged as:

$$W_{nc}\Big|_{t_1}^{t_2} = mg(h_2 - h_1) + \left(\frac{mv_2^2}{2} - \frac{mv_1^2}{2} \right)$$ **Equation 4-10**

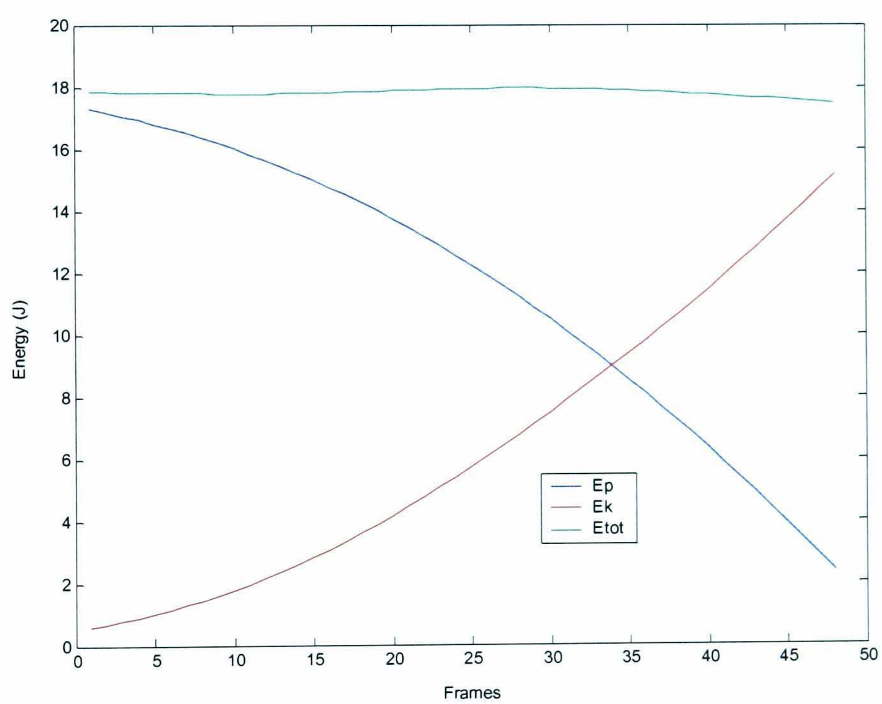


Figure 4-4 Changes in total (Etot), kinetic (Ek) and potential (Ep) energy levels of the falling golf ball

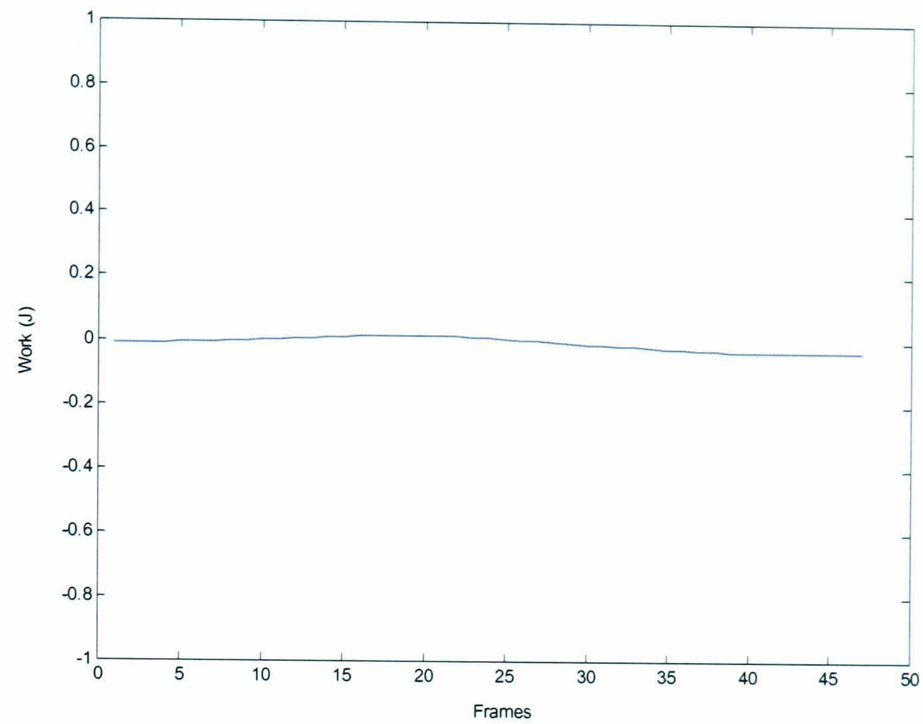


Figure 4-5 External Work done on the falling golf ball

A falling ball should gain kinetic energy, while losing potential energy so that the total energy on the ball remains constant, and therefore no work done. Figure 4-4 and Figure 4-5 demonstrate these trends, thus validating the calculation of energy and work of a point mass.

4.2.7. Conclusion

This section has shown the following to be acceptably valid for further research:

a) a smoothing protocol using natural quintic splines,

b) the accuracy, precision and reliability of the ProReflex Motion Capture System,

c) the construction of a technical coordinate system and the ability to reconstruct an 'anatomical' marker in a movement trial by the use of a static post-hoc trial,

d) the calculations of FHA and IHA and their use, plus the use of the sphere method, in locating a pivot point,

e) parameterisation of the orientation of a distal reference system with respect to a proximal reference system, and

f) the calculations of external work and energy of a point mass.

4.3. Kinematic Model of the Climber

The application of the key concepts to three dimensional motion has been validated in section 4.2, using rigid body models. These ideas will now be implemented in developing a kinematic model of a climber.

4.3.1. Segmented Model

A 14-segmental model of the human body was utilised. The assumption was made that the body segments behaved as rigid bodies connected by ideal joints, that is to say, the body segments were only permitted to rotate without translation at the joints.

4.3.2. Anatomical Coordinate Systems

The anatomical landmarks for each of the 14 body segments are listed in Appendix A and shown in Figure 4-6 to Figure 4-9. The majority of the anatomical landmarks are palpable and can therefore be identified in a static trial. However, the head of the femur and the head of the humerus are not palpable and therefore pose difficulties in identification. The Standardisation and Terminology Committee of the International Society of Biomechanics has developed a set of standards for identification of the hip joint centre (HJC) (head of the femur)(Wu et al., 2002) and Gleno-humeral rotation centre (GH) (head of the humerus) (Wu et al., 2005). The recommendation for the HJC is to use a 'functional' method, such as that of Cappozzo (1984), Shea et al. (1997), Leardini et al. (1999) and Piazza et al. (2001) (Wu et al., 2002). The 'functional' method involves determining the centre of rotation between the pelvis and the femur through an analysis of the spherical path formed by a femur fixed point, during motion about the hip (Piazza et al., 2001; Stagni et al., 2000; Leardini et al., 1999). The inherent assumption is that the joint can be modelled as a ball and socket joint, so the centre of the sphere is the HJC (Piazza et al., 2001). If the functional method cannot be applied, the recommendation is to use a 'prediction' method using regression equations, for example Bell et al. (1990). The recommendation for the GH is also to use a 'functional' approach but to use the mean pivot point of IHAs (Wu et al., 2005). Again, the joint is assumed to be a ball and socket joint. The functional methods for identification of the rotation centre of the hip and shoulder joint were validated in section 4.2.4.

The anatomical coordinate systems were based on the work of Cappozzo (Cappozzo, 1984; Cappozzo et al., 1995; Cappozzo et al., 1997) and ISB recommendations (Wu et al., 2005; Wu et al., 2002) for the upper limbs. The exceptions were the foot, head, hand and trunk segment. As the feet were not bare, markers were placed on the shoe approximating the second metatarsal head (SM), the dorsal aspect of the cuboidmetatarsal joint (CM) and the calcaneous posterior (CP) surface. The forearm was modelled as a single segment with a generic coordinate system (Wu et al., 2005). The hand was modelled as a single segment, using anatomical landmarks of the radial styloid (RS), ulnar styloid (US) and the third metatarsal head of the third finger (H1). The trunk was modelled as a single segment using the anatomical landmarks of the cervical vertebrae 7, thoracic vertebrae 8, and the hip joint centres. All the coordinate systems were placed at the segmental centre of mass (Wu & Cavannagh, 1995). The body segment anatomical coordinate systems are defined in Appendix A. Two additional coordinate systems are also defined: Pelvis and Thorax. These coordinate systems are defined to allow joint motions at the hip and shoulder joints to be determined.

4.3.3. Technical Coordinate Systems

The technical markers were placed uniquely for each participant. Figures 4-6 to 4-9 illustrate the approximate placement of the technical markers on each body segment. As the trunk was modelled as a single segment, the stiffest part of the spine was used for the technical markers. This is the section of the spine from C7 to T8 (White & Punjabi, 1990).

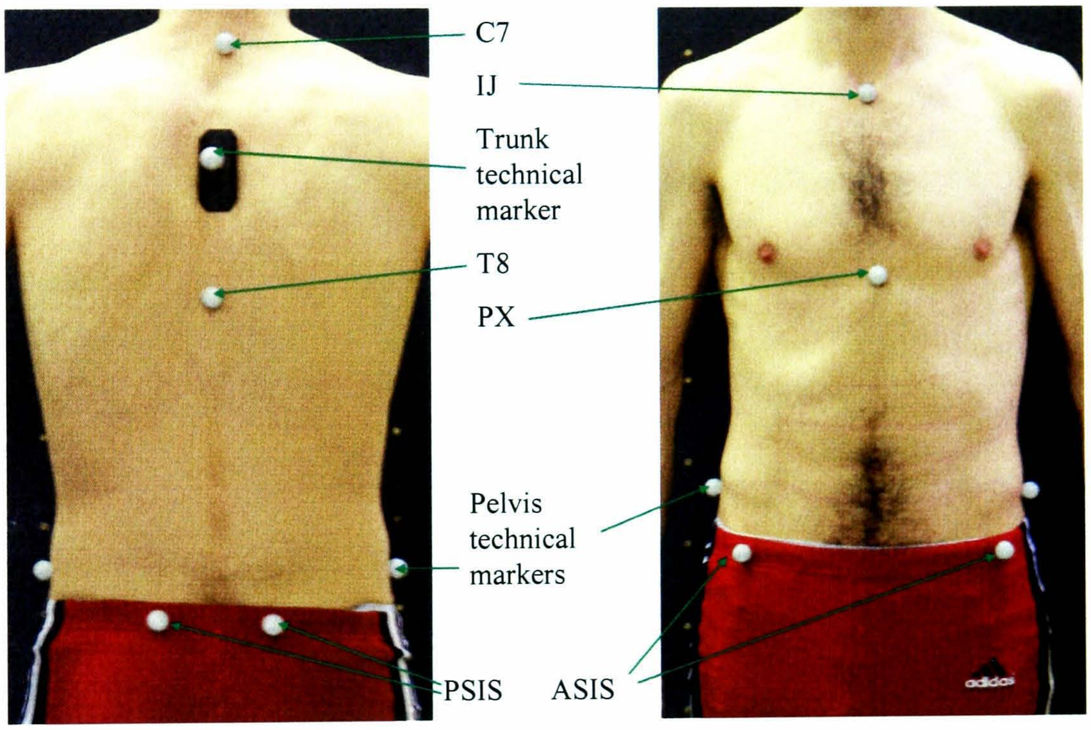


Figure 4-6 Anatomical and technical marker placement on the trunk and pelvis

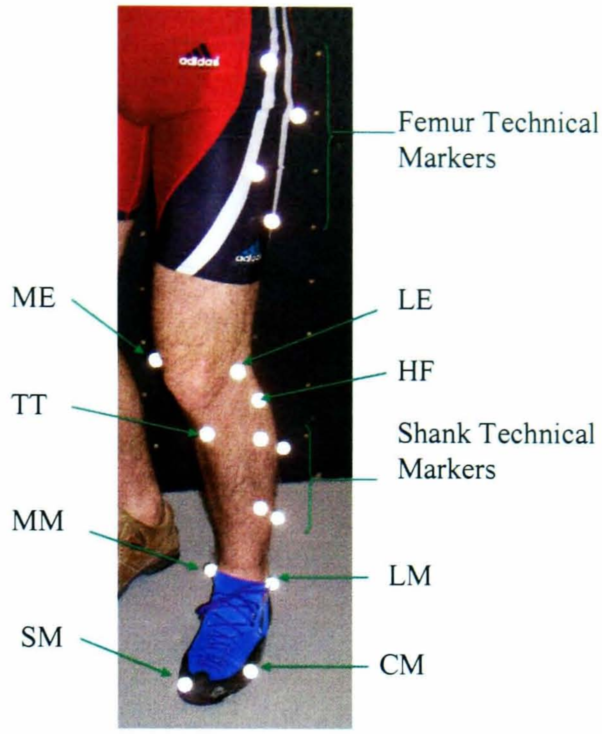


Figure 4-7 Anatomical and technical marker placement on the leg

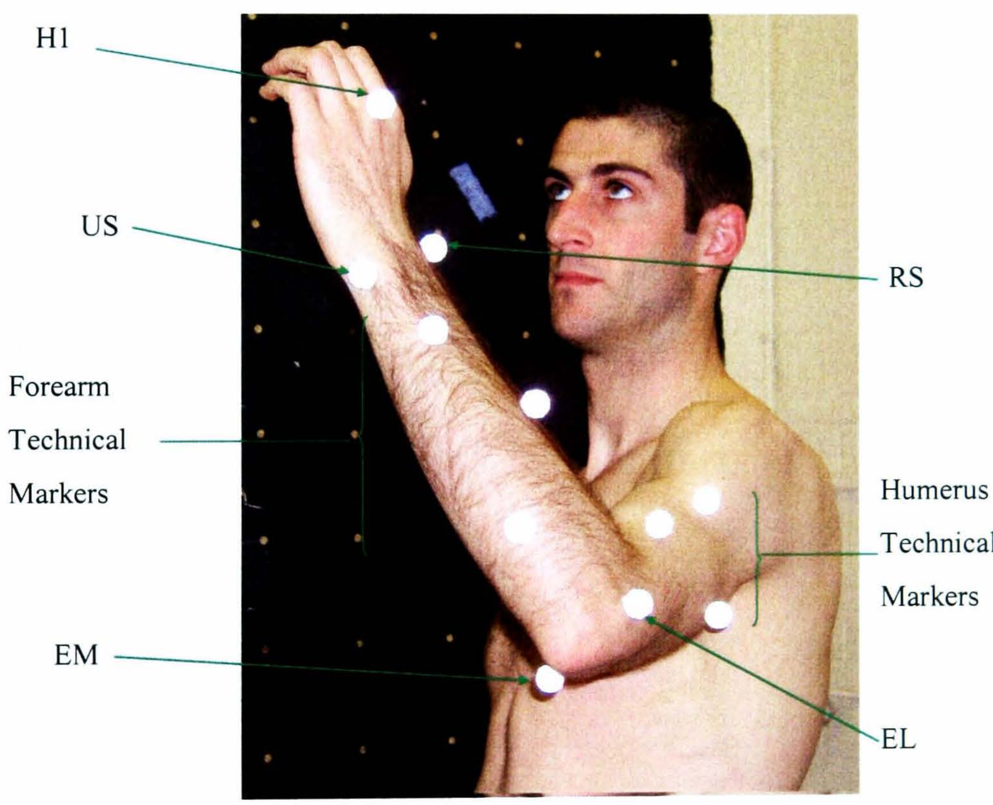


Figure 4-8 Anatomical and technical marker placement on the arm

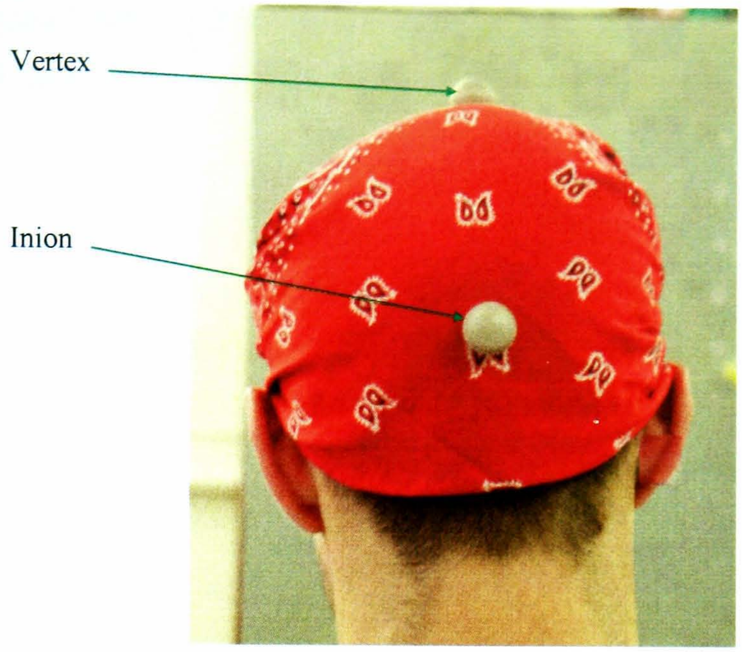


Figure 4-9 Anatomical marker placement on the head

4.3.4. Body Segment Inertia Parameters

Body Segment Inertia Parameters of de Leva (1996) were used, as discussed in Chapter 2.6.7. The centre of mass for each segment was located as a percentage of the segment length.

4.3.5. Whole Body Centre of Mass

The relative mass moments of each segment were calculated. The whole-body centre of mass position was calculated as the sum of the relative segmental mass moments divided by the total relative mass (Winter, 2005).

4.3.6. Joint Rotation Convention

Joint rotations were parameterised using the Cardan sequence Zx'y'' (Equation 4-11), except for the shoulder joint, which used the Euler sequence Yx'y''(Equation 4-12), as recommended by the ISB (Wu et al., 2005, 2002).

$$[R]=\begin{bmatrix} \cos\alpha\cos\gamma-\sin\alpha\sin\beta\sin\gamma & -\sin\alpha\cos\beta & \cos\alpha\sin\gamma-\sin\alpha\sin\beta\cos\gamma \\ \sin\alpha\cos\gamma+\cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta & \sin\alpha\sin\gamma-\cos\alpha\sin\beta\cos\gamma \\ -\sin\gamma\cos\beta & \sin\beta & \cos\beta\cos\gamma \end{bmatrix}$$

Equation 4-11

$$[R]=\begin{bmatrix} \cos\alpha\cos\gamma-\sin\alpha\cos\beta\sin\gamma & \sin\alpha\sin\beta & \cos\alpha\sin\gamma+\sin\alpha\cos\beta\cos\gamma \\ \sin\beta\sin\gamma & \cos\beta & -\sin\beta\cos\gamma \\ -\sin\alpha\cos\gamma-\cos\alpha\cos\beta\sin\gamma & \cos\alpha\sin\beta & -\sin\alpha\sin\gamma+\cos\alpha\cos\beta\cos\gamma \end{bmatrix}$$

Equation 4-12

In order to calculate joint rotations for left hand body segments, the raw data was mirrored with respect to the sagittal plane (Wu et al., 2005), then the definitions were applied as for right hand body segments.

4.3.7. Shoulder Centre

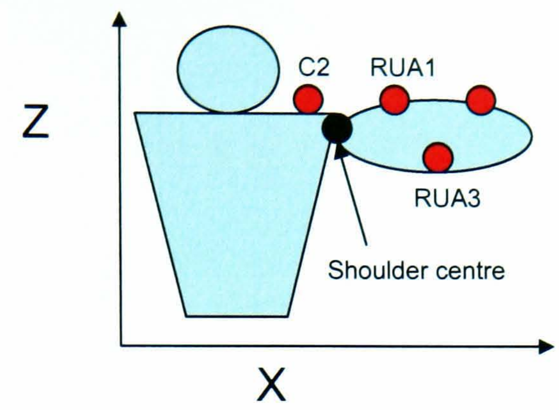
The purpose of this study was to produce a valid estimate for the Head of the Gleno-humeral (GH) to be used in a kinematic model of a rock climber. The first section describes the data conditioning performed to produce a local vector for the GH in the upper arm technical coördinate system. The estimates for the GH are shown to lie in the correct region of space. The effect of the level of smoothing on the reconstructed estimate of the GH was investigated.

The functional approach was taken to find the GH through the use of helical axes, as recommended by ISB (section 4.3.2). Five participants took part. Three technical markers (∅18mm) were placed on the upper arm. Anatomical markers were placed on C7, T8 and on the end of the clavicle. The C7 and T8 markers also acted as technical markers on the spine, with a third non-collinear technical marker placed on a stalk between C7 and T8.

Participants performed an abduction/adduction movement of the arm followed by a flexion/ extension movement. The abduction/adduction movements were in the XZ plane of the global coordinate system. The flexion/extension movements were in the YZ plane.

The raw data were smoothed using the GCVSPL program. Local coordinate systems were attached to the upper arm and the spine. The local coordinate system of the upper arm was then expressed in the spine technical coordinate system. The movement of the arm was split into four separate motions. For each motion of the arm, a set of IHAs were calculated (Equations 2-14 to 2-20, Chapter 2.6.4). The GH position vector was estimated as the mean pivot point closest to all the IHAs with respect to the spine coordinate system (Equation 4-4, section 4.2.4.1).

The position of the estimated GH was validated in a logical manner. For each movement, a snapshot of the arm in the horizontal position was taken (Figure 4-10 and 4-11). In the XZ plane, the GH should lie between the clavicle marker and the first technical marker on the arm in the global X direction, and between the clavicle marker and the third technical marker in the global Z direction (Figure 4-10). For the YZ plane, the GH should lie between the clavicle marker and the C7 marker in the global Y direction and between the clavicle marker and the third technical marker in the global Z direction (Figure 4-11).



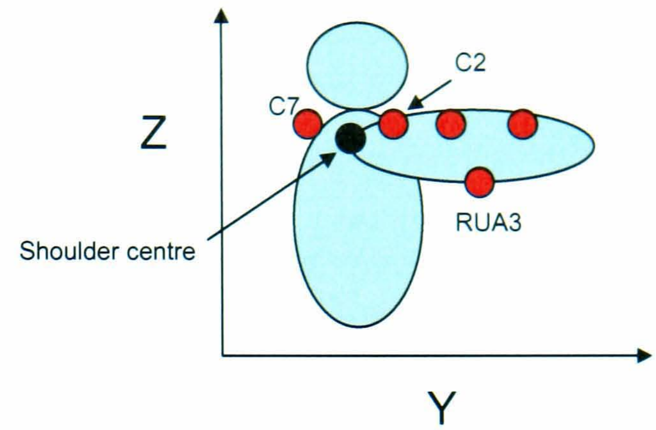


Figure 4-10 (Left) Diagrammatic representation of the relative position of the GH (shoulder centre) with the upper arm markers and clavicle marker in the global XZ plane

Figure 4-11 (Right) Diagrammatic representation of the relative position of the GH (shoulder centre) with the upper arm, clavicle and C7 marker in the global YZ plane

Table 4-9, below, presents the estimated positions of the GH in global space for adduction and extension movements. The estimates for the GH position all lie in the correct region of space. The flexion and abduction movements were not used to locate the GH position. Figure 4-12 illustrates why this was the case. In the flexion movement the trunk performs a substantial anti-clockwise rotation. This has the effect of moving the mean pivot point laterally and posteriorly. In the extension movement, however, the trunk remains relatively stationary and the mean pivot point provides a much better estimate of the GH.

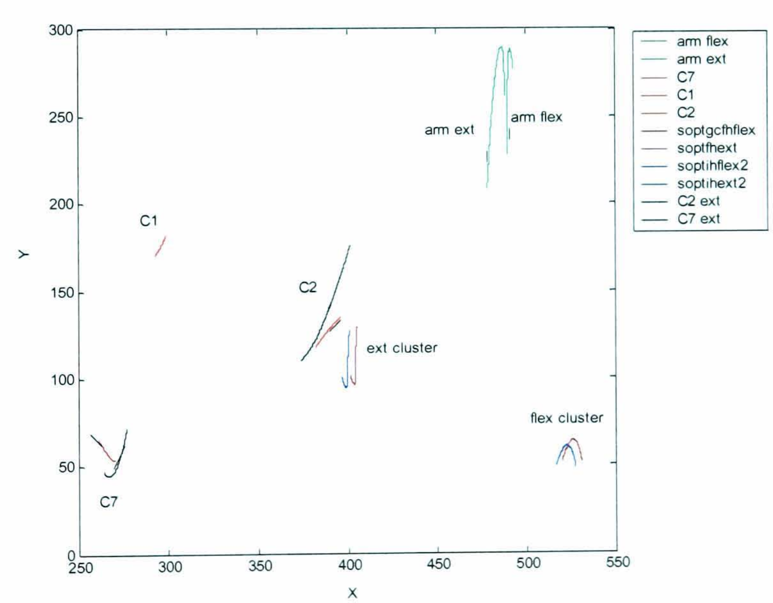


Figure 4-12 Displacements of the clavicle and C7 markers, the origin of the upper arm technical coordinate system and the locations of the mean pivot point (approximating the GH) for extension and flexion motions of the right arm, viewed in the global XY plane

Table 4-9 Marker coordinates and estimates for the GH coordinates in the left and right arm

Left Arm Coordinates (mm)

								Mean vector to calculate joint centre				
		C2	C7	LUA1	LUA3	Region	Sopt	e-7	e-8	e-9	e-10	e-11
Adduction	x	340	231	519	558	340 to 519	367	359	360	360	360	364
	y	263	315	321	338	263 to 315	343	283	284	285	292	299
	z	1441	1430	1426	1365	1364 to 1441	1395	1398	1399	1397	1398	1400

								Mean vector to calculate joint centre				
		C2	C7	RUA1	RUA3	Region	Sopt	e-7	e-8	e-9	e-10	e-11
Extension	x	372	265	500	525	372 to 500	396	423	424	425	431	439
	y	256	342	142	110	256 to 342	278	288	287	287	288	286
	z	1421	1427	1383	1326	1326 to 1421	1366	1359	1360	1358	1358	1360

Right Arm Coordinates (mm)

								Mean vector to calculate joint centre				
		C2	C7	RUA1	RUA3	Region	Sopt	e-7	e-8	e-9	e-10	e-11
Adduction	x	352	241	523	562	352 to 523	385	369	364	365	372	375
	y	118	79	70	61	79 to 118	53	106	107	106	97	91
	z	1425	1437	1418	1361	1361 to 1435	1362	1369	1370	1372	1371	1371

								Mean vector to calculate joint centre				
		C2	C7	RUA1	RUA3	Region	Sopt	e-7	e-8	e-9	e-10	e-11
Extension	x	383	269	483	495	383 to 483	414	430	427	428	438	445
	y	124	44	240	274	44 to 124	92	87	84	86	91	94
	z	1410	1434	1363	1310	1310 to 1410	1336	1328	1328	1330	1329	1327

The adduction and extension motions were felt to be more 'natural' motions of the arm. When the arm is raised, the musculature must lift the arm against gravity, but when the arm is lowered the work can be done by gravity, so the muscles are more relaxed, allowing a better movement as a ball and socket joint.

The mean pivot point was calculated as a local vector in the upper arm coordinate system. The local vector was constructed using the XZ data from the adduction movement and the YZ data from the extension movements.

The GCVSPL program is known to under-smooth at the derivative level (Woltring, 1991). We wished to see whether increased levels of smoothing would result in large variations in the GH position. The raw data was initially smoothed at the GCV criterion after which the smoothing parameter was increased by a factor of ten. Table 4-9 shows a representative set of reconstructed GH positions for each smoothing level. For each movement, the mean pivot point was calculated in the global coordinate system. The local vector for the GH position was created in the upper arm technical coordinate system. The position of the GH in global space was then recalculated from the local vector for the arm movement. A snap shot was again taken when the arm was horizontal.

The reconstructed GH positions for each smoothing level all lie in the correct region of space. There is no reason for increasing the smoothing above the GCV criterion, because there is no gold standard with which to compare the results. All the results are estimates of the true GH position; if all the estimates lie in the correct region of space, then there is no particular reason to accept or reject any of them. The use of the GCV criterion means that the choice of smoothing to use is not arbitrary. Table 4-9 shows that the GH position estimates do vary with levels of smoothing. The greatest range was 16mm - for the left arm in the both x direction for the extension trial and y direction for the adduction trial. The z direction values for both arms had the lowest range of values, all within 2mm or less.

4.3.8. Hip Joint

The location of the hip joint centre was initially calculated using the functional approach, as recommended by Wu et al. (2002). Five participants were analysed. Anatomical markers for the pelvis, were placed on both Anterior Superior Iliac Spines(ASIS) and on both Posterior Superior Iliac Spines (PSIS). Technical markers were placed on the thigh of the participant. The participants performed pure flexion, extension, abduction and adduction movements at the hip. The marker coordinates, anatomical and technical, were smoothed using the GCVSPL program at the GCV criterion. The anatomical markers were used to construct a pelvic coordinate system

(Appendix A). The centre of rotation was found using the methodology of Piazza et al. (2001) (see section 4.2.4.2) and Bell et al.'s (1990) regression equation (Equation 4-13).

$$x = -0.19\text{PW}, y = -0.30\text{PW}, z = 0.36\text{PW} \qquad \textbf{Equation 4-13}$$

where PW is Pelvis Width

The functional approach was unable to provide satisfactory estimates for the hip joint centre. Table 4-10 displays exemplar results of one subject. In the pelvis coordinate system, the z axis lies on the line of the ASIS's, pointing to the right. The hip joint centre should therefore have a z coordinate between that of the ASIS and PSIS.

Table 4-10 Coordinates (in the pelvis coordinate system) of the anatomical pelvis markers and the left and right hip joint centre estimates using the functional approach and Bell's regression equations.

		Hip Coordinates (mm)						
		RASIS	RPSIS	HJC Sphere	HJC Bell	LASIS	LPSIS	HJC Sphere
Adduction	x	-4.0	-190	-40	-44	6	-181	-25
	y	0.0	0	-78	-70	0	8	-116
	z	117	52	80	±84	-117	-36	-78
Abduction	x	-4	-192	-74		6	-180	-207
	y	0.	1	-81		0	7	-23
	z	117	52	89		-117	-35	-65
Flexion	x	-5	-192	-79		5	-184	-70
	y	0	-4	-105		0	7	-107
	z	117	55	-22		-117	-38	-50
Extension	x	-6	-190	-96		5	-184	-96
	y	0	-5	-85		0	8	-47
	z	117	55	90		-117	-38	71
All movements	x	-5	-191	-100		5	-182	-115
	y	0	-2	-34		0.0	8	21
	z	117	53	37		-117	-37	12

Estimates lying outside of the expected region of space underlined.

Table 4-10 shows that the functional method produced inaccurate z coordinates for both the left and right hip joint centre (defined in the pelvic coordinate system) in all types of movement except abduction. This result questions the general application of this technique. In the two comparative studies in Chapter 5 and 6, the regression equation of Bell et al. (1990) will be used following the suggestions of Stagni et al. (2000) and Wu et al. (2002), as this technique was shown to provide an estimate in the correct region of space (Table 4-10).

4.3.9. Sensitivity Analysis

The impact of a mislocation of the GH on the centre of mass location for the humerus and for the whole body, as well as the effect on the thoraco-humeral joint orientations was established using a sensitivity analysis. Stagni et al. (2000) performed a similar type of analysis on mislocations of the hip joint centre using a mislocation error of 30mm. This constitutes a larger error then the ranges of values seen in Table 4-9 and three times greater than the error identified in mislocation of the elbow joint centre in the rigid model validation study (section 4.2.4).

An error of 30mm was added and subtracted to the GH local vector in the upper arm technical system for *i,j* and *k* components. These estimates were then used in calculating the centres of mass for the humerus (section 4.3.4) and the whole body centre of mass (section 4.3.5) for a participant making a reaching movement on the climbing wall. The right arm performed the reaching movement while the left hand remained in contact with the wall. The effects of mislocations of the GH in both arms on segmental and whole body centre of mass were studied. Only data for the right arm, which actually performed the reach, is presented for the effect of mislocation on the thoraco-humeral joint orientations.

The largest mean errors in centre of mass location in the humerus were 12mm. This equates to just over the error in the ProReflex system for identification of a marker. The effect of a 30mm mislocation on the whole body centre of mass was less than 1mm. In the orientation angles the greatest mean error was 5°.

4.3.10. Limitations

To identify the shoulder joint centre, the movement of the upper arm was compared with the technical markers of the spine. A more accurate estimate might have resulted from comparison with the thorax. Ideally the clavicle or scapula should have been used. If the scapula had been used then the shoulder joint centre estimate from the functional method could have been compared with an estimate generated from the regression equations of Meskers et al. (1998), though there is a question about the accuracy of Meskers' equations.

The methodology utilised in this study has produced GH position estimates that have been shown to lie in the correct region of space. The sensitivity analysis shows that relatively large mislocations in GH position have relatively little impact on global whole body centre of mass and joint orientations.

Table 4-11 Impact of 30 millimetre mislocation in Gleno-humeral anatomical landmark on the orientation angles of the shoulder

		Mislocation in the Right SJC					
			+30mm in x			-30mm in x	
		Y	x'	y''	Y	x'	y''
Orientation angles (°)	Mean	-3.59	0.35	3.30	4.09	-0.33	-3.93
	SD	0.77	0.47	1.54	0.99	0.51	1.76
			+30mm in y			-30mm in y	
		Y	x'	y''	Y	x'	y''
Orientation angles (°)	Mean	-4.10	0.07	3.67	3.65	-0.01	-3.45
	SD	0.91	0.54	1.72	0.89	0.45	1.58
			+30mm in z			-30mm in z	
		Y	x'	y''	Y	x'	y''
Orientation angles (°)	Mean	0.34	4.90	0.98	-0.40	-4.86	-0.57
	SD	0.94	0.07	1.50	1.16	0.10	1.66

Table 4-12 Impact of 30 millimetre mislocation of Gleno-humeral anatomical landmark on the segmental centre of mass position and whole-body centre of mass location

		Mislocation in the Left SJC (mm)																	
		+30mm in x			-30mm in x			+30mm in y			-30mm in y			+30mm in z			-30mm in z		
		x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z
Humerus	Mean	0	-3	11	0	3	-11	1	-11	-2	-1	11	2	12	0	1	-12	0	-1
	SD	4	3	2	4	3	2	2	1	5	2	1	5	2	4	3	2	4	3
Whole Body CoM	Mean	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

		Mislocation in the Right SJC (mm)																	
		+30mm in x			-30mm in x			+30mm in y			-30mm in y			+30mm in z			-30mm in z		
		x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z
Humerus	Mean	-7	-9	0	7	9	0	-9	6	2	9	-6	-2	-1	1	-12	1	-1	12
	SD	4	1	3	4	1	3	1	4	3	1	4	3	2	4	1	2	4	1
Whole Body CoM	Mean	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.3.11. Conclusion

A kinematic model of a climber has been developed using the ideas from the first part of the chapter and ISB recommendations.

a) Anatomical and Technical marker placement and coordinate systems have been described.

b) Problems of GH and HJC identification have been identified and a methodology established and validated for the estimating their location.

c) A sensitivity analysis demonstrated that a severe mislocation of an anatomical landmark, in this case the GH, results in minimal errors in centre of mass location and orientation angle.

4.4. Measurement of a Climber on an Overhanging Wall

The next task was to apply the above ideas and concepts to a 'real' climbing situation, to establish a methodology for future studies.

4.4.1. Data Reduction Validation

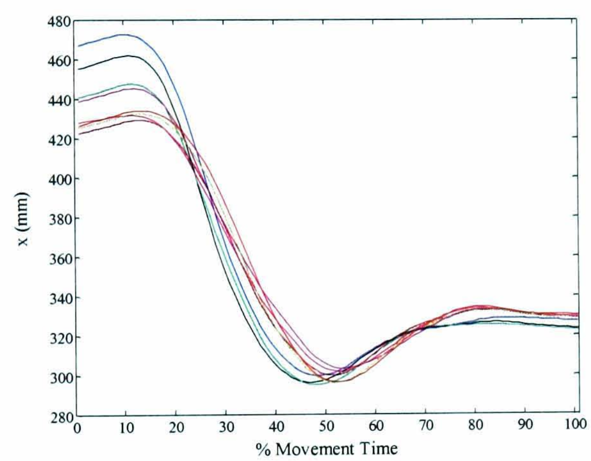
The purpose of this study was to determine the number of trials required to produce a representative set of data for a climber performing a reaching movement task on an overhanging climbing wall.

Technical and anatomical markers were placed on a single participant as described in sections 4.3.2 and 4.3.3. Static calibration trials were performed to calibrate the position of the anatomical landmarks relative to the technical coordinate systems. The shoulder and hip joint centres were identified using the methodology described in sections 4.3.7 and 4.3.8. The anatomical markers were removed for the climbing trials. The participant performed ten reaching trials on a climbing wall (see section 4.5.2 for details of the climbing problem set-up). The data was collected at 240Hz. The raw data was smoothed using the GCVSPL program. The whole body centre of mass displacement was calculated for each trial (section 4.3.5).

The centre of mass displacements were time normalised and averaged and the coefficient of variation calculated using the BIONICA program in Matlab. This procedure was performed for the first three trials, then the first four trials, then the first five trials and so on until all ten trials were included. The coefficients of variation for the different numbers of trials were tabulated (Table 4-13) and the mean displacements plotted in the x (Figure 4-13), y (Figure 4-14) and z (Figure 4-15) directions.

Table 4-13 Coefficient of variation in whole-body centre of mass coordinates for differing numbers of trials

No. Trials	Coefficient of Variation for whole-body centre of mass coordinates %		
	x	y	z
3	7	13	4
4	7	11	4
5	8	10	4
6	10	12	5
7	10	13	5
8	10	12	5
9	10	12	4
10	9	12	4



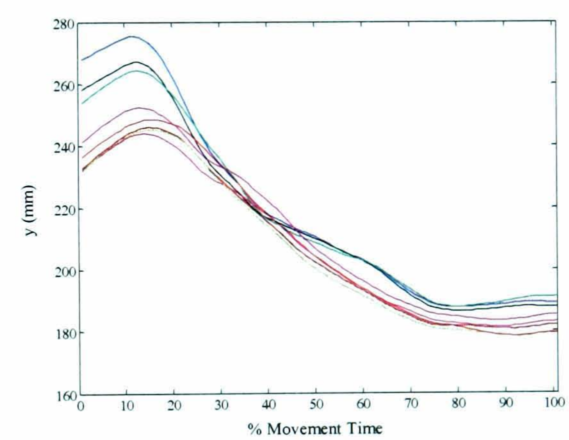


Figure 4-13 (Left) Mean centre of mass displacement in the x direction for differing numbers of trials

Figure 4-14 (Right) Mean centre of mass displacement in the y direction for differing numbers of trials

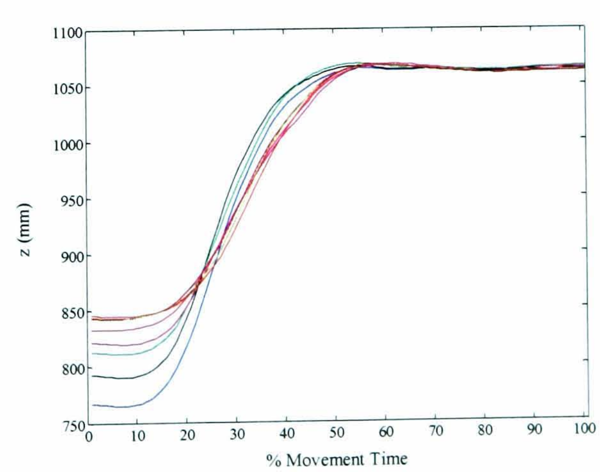


Figure 4-15 Mean centre of mass displacement in the z direction for differing numbers of trials

Table 4-13 shows little variation in the coefficient of variations of differing numbers of trials. Figures 4-13 to 4-15 demonstrate similar displacements patterns for the means of different numbers of trials. The greatest differences in the traces occur at the start of the movement, which is attributed to not having a set start position.

The conclusion from this study is that only three trials are required to give a representative set of results for a participant performing a reaching movement task on a climbing wall.

4.5. Pilot Study 2

A reaching movement problem was established based on the work of Pilot Study 1 (Chapter 2) and the experimental set-ups of previous research (e.g. Noé et al., 2001). The movement problem was based on an overhanging wall, using crimp grip style supports and required an arm reach diagonally upwards. In order to validate the movement problem, a group of five elite climbers attempted to solve the task using, in their view, the best technique.

4.5.1. Participants

A convenience sample of five local male, high standard climbers (onsight level above F7a) provided the population to be studied. The average age of the participants was 38.2±14.4 years, average mass was 66±8.3kg, average height was 1.77±0.070m, with average arm span 1.83±0.08m.

4.5.2. Equipment and Set-up

The climbing wall was set at an angle approximately 10° past the vertical. Six identical holds, 12cm wide and 2.5cm deep, were positioned on the climbing surface as indicated in Figure 4-16. Seven Qualisys Motion Capture Units (MCU) were placed in an approximate semi-circle about the climbing wall (Figure 4-17). Three-dimensional position data from retroreflective markers on the climbers' bodies were recorded during the reaching task using the ProReflex Motion Capture System.

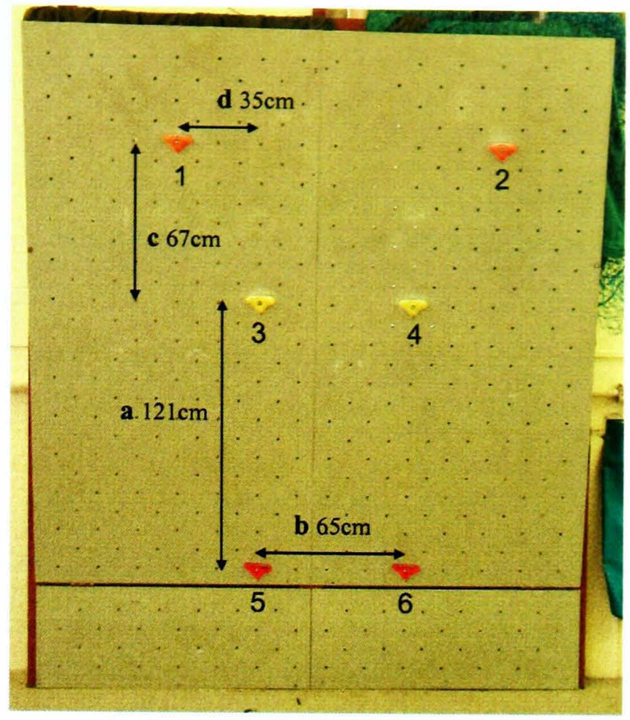


Figure 4-16 Configuration of the climbing holds on the overhanging climbing wall

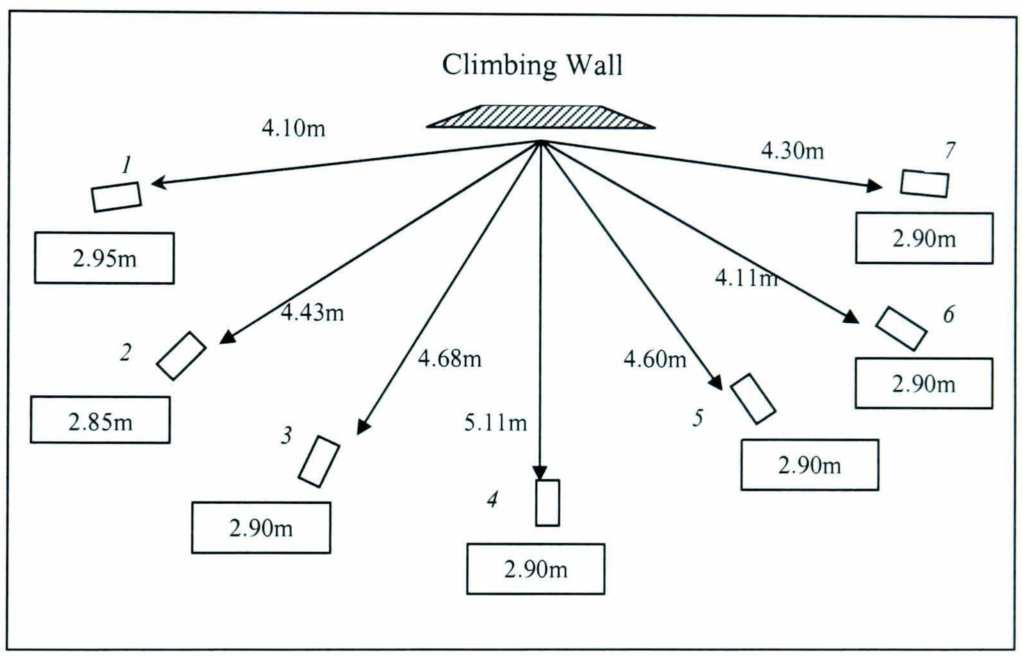


Figure 4-17 Configuration of the MCU's around the climbing wall.

The MCU's are numbered in italics, the distance of the camera to the climbing wall and height of camera from the ground (in box) are indicated

4.5.3. Methods

4.5.3.1. Static trials

Anatomical and technical markers were placed on the participants as described in sections 4.3.2 and 4.3.3. Seven calibration trials were performed prior to the climbing movements to determine the positions of the anatomical markers relative to the technical co-ordinate systems attached to the body segments. The anatomical markers were removed prior to the climbing trials. Three calibration trials were static, the remaining four involved movement of the arms and legs to determine the shoulder and hip joint centres respectively, as discussed previously (sections 4.3.7 and 4.3.8).

4.5.3.2. Climbing Trials

The climbers were allowed to choose the starting position, with their hands on holds three and four and their feet on holds five and six (Figure 4-16). The climber was then required to make a left hand reach for hold one, or alternatively perform a right hand reach for hold two (Figure 4-16). Ten left hand and right hand trials were performed in a random sequence. Participants were allowed as much rest between attempts as required.

4.5.4. Data Analysis

The three-dimensional position data in all seven calibration trials and twenty climbing trials were initially processed in Qualisys Tracking Manager (QTM).

4.5.4.1. Static Calibration Trials

The calibration trial data were smoothed using GCVSPL program. The local vectors of the anatomical markers were calculated with reference to the respective body segment technical marker set (section 4.2.3).

4.5.4.2. Shoulder and Hip Joint Centres

The position data were smoothed using GCVSPL program. The shoulder joint centre was calculated using functional method (section 4.3.7). The hip joint centre was calculated using the regression equations of Bell et al. (1990) (Equation 4-13) in the pelvis reference system (section 4.3.8). The shoulder joint centre and the hip joint centre were then both defined as local vectors in the humerus technical marker set and the femur technical marker set respectively.

4.5.4.3. Climbing Trials

Each climber performed ten left hand trials and ten right hand trials. Only right hand trials are presented. Three trials were selected and the mean taken as representative of that climber's movements in performing the reaching task.

Each climbing trial was smoothed initially using GCV quintic splines. The anatomical markers were reconstructed using the local vectors derived from the static trials (section 4.2.3). The segmental and whole-body centre of mass position were calculated using de Leva's (1996) adjustments of the Zatsiorsky & Seluyanov data (sections 4.3.4 and 4.3.5). The velocity of the centre of mass was calculated using the double finite difference technique. The trial was re-smoothed by visual inspection of the centre of mass velocity curve.

Anatomical local coordinate systems (Appendix A) were attached to each body segment with the origins at the segmental centre of mass. Orientation angles were calculated using ISB recommended conventions (section 4.3.6).

The external work performed by the whole-body centre of mass was calculated (Equation 4-10). Trajectory efficiency were calculated using Equation 4-14:

$$e = \frac{\text{distance}}{\text{displacement}}$$

Equation 4-14

4.5.5. Results

4.5.5.1. Scaling of the Climbing Problem

The vertical and horizontal distances between the holds (Figure 4-16) were calculated as a percentage of the participants' height and arm span respectively (Table 4-14). The mean percentages for the group were subsequently used to recalculate the distances a, b, c and d for each participant, to provide a climbing set-up scaled to the individual (Table 4-15). The climbing hold positions on the wall can be adjusted by ±17cm in the vertical and horizontal directions. This presents the limit to the 'fine-tuning' of the climbing problem to the individual participant. Table 4-15 demonstrates that the climbing holds did not need to be moved.

Table 4-14 Distances between climbing holds as percentages of the invidual participants height and arm span

			Length as a % of Participant Anthropometry			
Participant	Height (cm)	Arm Span (cm)	a	b	c	d
1	184	189	66	34	36	19
2	170	172	71	38	39	20
3	187	192	65	34	36	18
4	174	181	70	36	39	19
5	175	184	69	35	38	19
Mean	177	183	68	35	38	19

Table 4-15 Vertical and horizontal distances between climbing holds scaled to each individual climber

	Distance between climbing holds (cm)			
Participant	a	b	c	d
1	125	66	70	36
2	116	60	65	33
3	127	67	71	36
4	118	63	66	34
5	119	64	67	35
Range	116-125	60-67	65-71	33-36
Original length	121	65	67	35

4.5.5.2. Choice of Technique

Table 4-16 Technique (IE-Inside Edge, OE-Outside Edge, TE-Toe Edge) used by each participant for the reaching movement task

Participant	Technique for Arm Reach
1	IE
2	IE
3	OE
4	TE
5	OE

The use of three different techniques by the expert group of climbers was identified in the study (Table 4-16). Two climbers used the IE technique and two climbers used the OE technique; only one climber chose to use the TE technique.

There were a number of problems with the quality of the data collected during the climbing trials. Firstly the technical marker data had gaps. Small gaps could be filled using a spline program within QTM, but some markers showed gaps of the order of three hundred frames (just over a second of data). Clearly gaps of this magnitude were unacceptable and these trials were discarded. The problem of gaps in the data was particularly evident in the leg markers, which were obscured from the MCU's at certain times during the reaching task, especially in the Outside Edge (OE) technique. Gaps in the data also occurred because the markers were obscured in the starting position. A large number of ghost markers were identified and there were instances of QTM identifying two markers simultaneously for a single real marker.

The repercussions of the problems in the quality of the data were that only participants 1(P1), 4(P4) and 5(P5) had three trials which could be used.

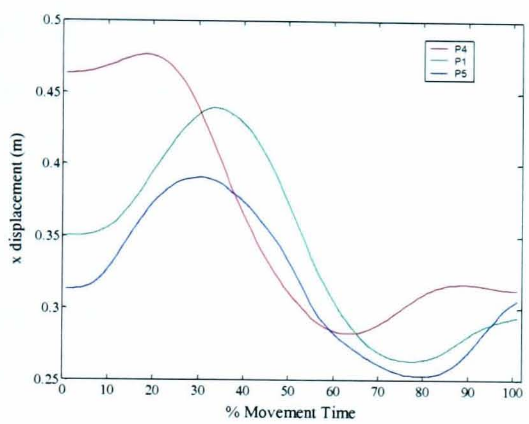
4.5.5.3. Movement Time

Table 4-17 Duration of the representative movement of participants 1, 4 and 5

Participant	Duration of movement (s)
1	1.8
4	2.0
5	2.7

Participant 5 (OE technique) had the longest duration for the reaching movement. The quickest movement was made by Participant 1, using the IE technique.

4.5.5.4. Centre of Mass Displacement



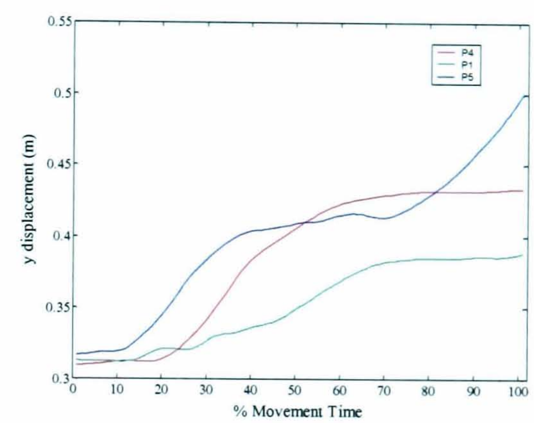


Figure 4-18 (Left) Centre of mass displacement for the representative trials of participants 1, 4 and 5 in the x direction

Figure 4-19 (Right) Centre of mass displacement for the representative trials of participants 1, 4 and 5 in the y direction

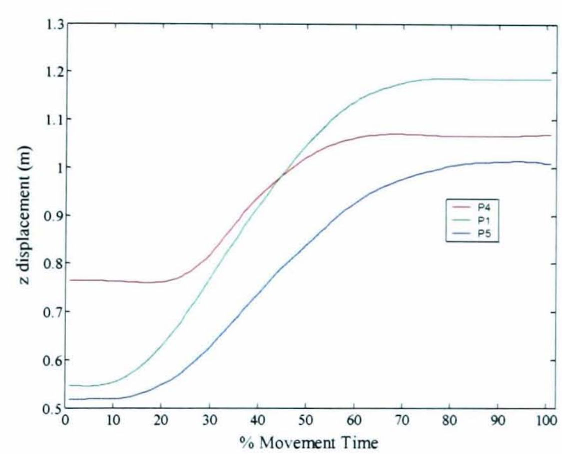


Figure 4-20 Centre of mass displacement for the representative trials of participants 1, 4 and 5 in the z direction

Similar patterns of centre of mass displacement are evident in the x and z direction, although there are differences in magnitude (Figure 4-18 and Figure 4-20), In the x direction, all three techniques show the centre of mass moving away from the wall initially, Although P4 has the greatest value, this actually only corresponds to a small change from the start value. P1 demonstrated the greatest movement away from the starting position. The movement away from the wall is followed by negative x displacement, until the 80% of movement time mark for P1 and P5. P4 shows an earlier trough at just over 60% movement time. All three participants then show a movement away from the wall again. The three participants finished the movement in far more similar position in the x axis than they started.

In the z direction, all three participants showed an initial plateau followed by an increase in displacement, ending in a second, final plateau. Again there is a difference in the starting values between the three participants, with P4 starting from the higher position. P1 showed the greatest increase in z displacement. P4 had the least increase in z direction but from an elevated start point. P1 and P5 had similar start points but by the end of the movement P1 had the lowest centre of mass position of all three participants.

All three participants had similar centre of mass values in the y direction at the start of movement. P4 and P1 showed similar trends. Both showed increases in y coordinate followed by a plateau, but P1 demonstrated the greater displacement. P5 also showed a positive displacement in the y direction and a plateau, but the plateau occurred earlier in the movement time compared with the other two participants and was followed by a second positive displacement. Thus P5 showed the greatest total displacement in the y direction. P1 demonstrated the least displacement.

4.5.5.5. Joint Orientations in the Starting Posture

The starting positions of P1 and P5 were in a squat position with flexion at the hips and the knees and the hips abducted. The elbows were much more extended in P1 and P5, with the angle of elevation in the shoulder much greater, than P4. P4 had more extended knee angles and less abduction in the hips. P1 has much greater plane of elevation in the left shoulder than the right whereas P4 was more evenly placed between the hand holds, as shown by the similar plane of elevation angles in the shoulders.

Table 4-18 Joint rotations at the start of centre of mass movement for participants 1, 4 and 5

		P5	P4	P1
Left ankle	Z	26.2	23.5	48.4
	x	38.1	48.3	11.2
	y	14.7	30.5	-12.5
Left knee	Z	-143.0	-74.6	-145.1
	x	-24.4	-36.0	-7.4
	y	-20.5	-0.7	-12.1
Left hip	Z	100.0	43.7	90.2
	x	-43.8	-11.0	-42.2
	y	7.9	-13.0	-1.0
Left shoulder	Y	43.8	53.7	98.1
	x	-142.1	-64.7	-114.8
	y	-82.1	-89.1	-106.8
Left elbow	Z	30.4	91.4	23.4
	y	100.5	122.3	137.5
Left wrist	Z	2.0	-9.2	11.6
	x	-7.8	-10.7	-7.8
Right ankle	Z	19.4	35.0	34.0
	x	39.4	30.3	4.2
	y	13.0	7.2	-28.8
Right knee	Z	-130.9	-62.5	-135.1
	x	-5.3	-10.1	8.9
	y	-43.5	-15.2	-6.6
Right hip	Z	84.4	46.0	83.5
	x	-17.3	-25.8	-38.0
	y	-12.4	-26.3	9.2
Right shoulder	Y	18.0	48.5	39.3
	x	-134.9	-94.1	-117.2
	y	-81.8	-71.0	-95.8
Right elbow	Z	26.8	85.0	25.8
	y	83.9	123.5	126.5
Right wrist	Z	-4.1	-3.4	15.3
	x	-5.0	1.7	-1.2

4.5.5.6. Efficiency

Table 4-19 Trajectory efficiency associated with whole-body centre of mass movement for participants 1, 4 and 5

Participant	Efficiency
1	1.16
4	1.22
5	1.29

Table 4-19 shows that Participant 1 had the most efficient trajectory. The results suggest that the IE technique was the most efficient technique and that the OE was the least.

4.5.5.7. Work

Table 4-20 External work values associated with whole-body centre of mass movement for participants 1, 4 and 5

Participant	Work (J)
1	395
4	191
5	323

The least value of work was associated with Participant 4, who used the TE technique. The greatest amount of external work was performed by Participant 1 using the IE technique.

4.5.6. Discussion

The elite group of climbers demonstrated all three foot orientations previously identified in performing the reaching task. This result not only validated the movement problem for use in a more controlled study but demonstrates a lack of consistency in technique within an elite group even for a simple reaching movement problem. This provides further evidence for the need to investigate the impact of ipsilateral foot orientation on reaching movement tasks.

The limited analysis in this study of the way in which climbers solved the reaching task suggests that different foot orientations may induce different whole-body movement characteristics and impact on the performance of the reaching task, as measured by the external work done by the centre of mass and the trajectory efficiency. However these differences could be due to the different starting positions. Participant 4 had a higher starting position than the other two climbers. This may explain the lower work value associated with participant 4's performance. The comparative studies (Chapter 5 and 6) need to use a consistent start position. Differences in the time taken to perform the task were identified, with participant 5 having the greatest time using the OE technique. However, the duration of the movement was measured from the start of the centre of mass motion to the end of the centre of mass movement. The greater time may be due to the climber re-orientating the ipsilateral foot rather than reaching for the new hold. Therefore in future studies the reaching task must be broken into discrete phases. This could be based on the temporal events in the reaching task, for instance when the hand leaves the initial support and when the hand makes contact with the target hold.

Although efforts were made to place the GCS of the ProReflex Motion Capture System in the same location for each participant, errors in the placement of the frame may have occurred. An inconsistent GCS will obviously impact upon the measures of the climber. Thus in the comparative studies (Chapters 5 and 6) a GCS will be attached to the wall. The collected raw data will need to be converted from the ProReflex GCS to the wall GCS prior to any data conditioning.

The results of this study highlighted several methodological problems. There were a number of issues with markers merging and being obscured. This was particularly a problem with the thigh and shank markers and especially with the climbers who employed the OE strategy. The problems with the quality of data must be addressed prior to more detailed studies.
A final limitation identified in this study is that the climbing problem can only be scaled to a limited extent to the individual participant's anthropometry.

4.5.7. Conclusion

The conclusions from Pilot Study 2 are:

a) The reaching movement problem was validated as suitable for comparison of different ipsilateral foot orientations, as within an elite group of climbers the three previously identified techniques (IE, OE and TE) were all freely chosen to be the best by at least one participant.

b) The fact that IE, OE and TE were all chosen within the elite group as the best technique for performing a hand reaching movement provides further evidence for a need to investigate the impact of different ipsilateral foot orientations on the reaching task performance.

c) There is an indication that the different ipsilateral foot orientations impact on the way the movement task is made, through differences in the time taken, the centre of mass displacement, the efficiency of the trajectory and the external work performed.

d) Different start positions were adopted by the climbers. In order to allow comparison of the different foot orientations on performance of the reaching task, a set start position is required.

e) The reaching movement needs to be spilt into phases.

f) Loss of technical marker data needs to be addressed before future studies can be conducted.

4.6. Pilot Study 3

4.6.1. Leg Marker Set-up Modification

Pilot Study 2 demonstrated that the ipsilateral leg technical marker data was lost during the reaching movement, particularly when the foot was orientated so that the outside edge of the foot was used on the foothold. The problem was resolved through two adaptations to the methodology. Firstly camera's 3, 4 and 5 (Figure 4-17) were lowered so that markers on the back of the leg could be identified in the field of view. Secondly the technical marker arrangement on the ipsilateral thigh and shank were modified. A number of arrangements were tested but the set up in Figure 4-21 was found to be the superior for tracking the markers over the whole reaching movement.

Figure 4-21 Modified technical marker arrangement for the leg

4.6.2. Modification to the Frame Rate.

A participant was marked up with 39 markers for a climbing trial. The participant performed the OE technique with the cameras set at different frame rates. The thigh markers were analysed because of the high level of data loss in these markers in Pilot Study 2.

Table 4-21 Effect of frame rate on the number of markers identified by QTM and the size of data gaps in the thigh technical markers

Frame Rate	Total No. Markers	No. Markers during Movement	Frame Gaps in Thigh markers		
			M1	M2	M3
240	69	44	12	34	0
200	70	51	105	51	0
150	61	41	0	0	0
100	49	40	0	0	0
50	45	40	0	0	0

Table 4-21 shows that decreasing the frame rate substantially improved the quality of the data. Future studies should be performed with a frame rate of 150Hz.

4.7. Conclusion

The purpose of this chapter was to establish a reliable, repeatable and accurate methodology for three-dimensional kinematic measurements of a climber performing a hand reaching task on an overhanging climbing wall. Key concepts of measuring motion in three dimensions, such as coordinate system construction, reconstruction of anatomical landmarks and relative orientation of two coordinate systems, were validated through a series of simple tests using rigid body models.

The second section of the chapter involved establishing a kinematic model of a climber. The placement of anatomical and technical markers was described, based on ISB recommendations.

The specific difficulties of identification of the GH and HJC were discussed. The methodology of the GH and HJC identification were established through two validation exercises. The identification of the GH will be conducted by finding the mean pivot point of a set of IHAs. The HJC will be estimated through Bell et al.'s (1990) regression equation, as the functional method was shown to produce unacceptable results. A sensitivity analysis demonstrated that a mislocation of an anatomical landmark, in this case the GH, would have minimal impact on the whole-body centre of mass location and the orientation angle.

The final section of the chapter applied the ideas of the first two sections to a real climbing situation. The first pilot study validated the movement problem as being suitable for investigating reaching task performance with different ipsilateral foot orientations. There were also indications that the ipsilateral foot orientation impacted on the way the reaching task was made and the performance of the task. However the study also highlighted a number of methodological problems. Firstly a consistent start position requirement was identified. Secondly the reaching task has to be broken down into discrete phases. Thirdly, there was an issue with the quality of data. The problem of the quality of the data was solved by modifications to the camera layout, capture frame rate and the arrangement of the technical markers on the leg (Pilot Study 3).

In conclusion, the work in this chapter has established that accurate, reliable and repeatable three-dimensional measures can be taken of a climber on an overhanging wall performing a reaching task.

The methodology established in this chapter can now be used in subsequent studies. In order to evaluate the impact of ipsilateral foot orientation on reaching tasks, the comparative studies must be interventionist, in that the participants are not free to choose start position and technique. Pilot study 2 (in this chapter) has already established for the given movement problem elite climbers will choose different foot orientations to perform the reaching task. To validly compare the impact of different foot orientations on the reaching task, all the participants must perform all the techniques from a controlled set point. This is the focus of Chapters 5 and 6.

Chapter 5. Comparative Study 1 – Investigating the distinctness of the techniques

5.1. Introduction

Pilot Study 1 confirmed the existence of the Inside Edge (IE), Outside Edge (OE) and Toe Edge (TE) techniques (Chapter 3) in the performance of reaching movements. The pilot study in Chapter 4 demonstrated that within a group of five elite climbers all three techniques were voluntarily chosen in the successful performance of the same reaching task. A limited analysis, based upon centre of mass trajectory of each technique, suggested that the differences in the techniques would be worth further investigation. The purpose of this study was therefore to perform a controlled, detailed three-dimensional kinematic analysis of each technique, using the methodology established in Chapter 4. To our knowledge, no previous work has been performed involving such a comparison.

Although direct comparisons of technique have not been undertaken, important work has been published by Quaine and co-workers on balance maintenance in rock climbing and, in particular, on the specific roles of the arms and legs. Kinetic analyses have also studied the posturo-kinetic coordination in limb movement (Testa et al., 1999, 2003) and demonstrated postural constraint effects on the reaching and grasping movements (Bourdin et al., 1998, 1999). Despite the fact that these studies increased our understanding of posture in rock climbing, they did not analyse the way the climbers organised their bodies to apply the forces to the supports. The way in which climbers move their limbs has had limited research attention. Kinematic analyses have focussed on the whole body centre of mass (Cordier et al., 1994; Werner et al., 2000). To our knowledge, only the study of Bursnall & Messenger (2000) has attempted to look at the joint kinematic characteristics of making a reaching movement.

The centre of mass has experienced previous research interest as a measure characterising the movements of rock climbers (Cordier et al., 1994; Werner et al, 2000) and as a control variable for balance maintenance (Testa et al., 1999; Quaine et al.1997a). The need to use three dimensions in the analysis of rock climbing tasks has been confirmed by several authors (Quaine et al., 1997a, b; Quaine & Martin, 1999; Noé et al., 2001; Testa et al., 2003).

Determination of whether different ipsilateral foot orientations are to be characterised as distinctly different techniques, will be performed through analyses of the resulting coordinative structures (Chapter 2.5). The concept of coordinative structures has been previously used to characterise movements associated with a particular task (Steenbergen et al., 1995; Sugden & Utley, 1995; Temprado et al., 1997; Vereijken et al., 1997; Newell & van Emmerik, 1989). Coordinative structures are self-organised functional ensembles of degrees of freedom (Turvey, 1990), which at a behavioural level are the peripheral mechanical and physiological component degrees of freedom defining the joint configuration of the system (Newell & Vaillancourt, 2001). Analyses of the joint activation patterns, such as proximal-distal sequencing (Bobbert & van Ingen Schenau, 1988), and three-dimensional analysis of joint angular changes will permit the characterisation of the coordinative structure associated with a particular ipsilateral foot orientation. The level of complexity in coordination within each technique is characterised through analyses of the number of joint displacement reversals, both in total and in the upper and lower limbs.

The aims of this chapter are, therefore, to determine where the differences and similarities lie between the three techniques, in terms of centre of mass displacement and velocity, and organisation of the joint rotations.

5.2. Participants

Seven male rock climbers (mean age: 28(±5.1) years, mean height: 1.81(±0.63)m, mean weight: 72.9(±6.3)kg, arm span: 184±4cm) participated in the study. All the participants had previously climbed, onsight, at a level of F7a or above.
Informed consent was given by all participants in the study.

5.3. Equipment and Set-up

5.3.1. Climbing Holds Layout on the Wall

The climbing wall was tilted to an angle of 9°±0.3° past the vertical. Five climbing holds (flat edge: 12cm wide, 2.5cm deep) were attached to the wall as in Chapter 4.5.

5.3.2. Camera Layout

Seven ProReflex Motion Capture Units were placed around the climbing wall in a semi-circular fashion (Figure 5-1).

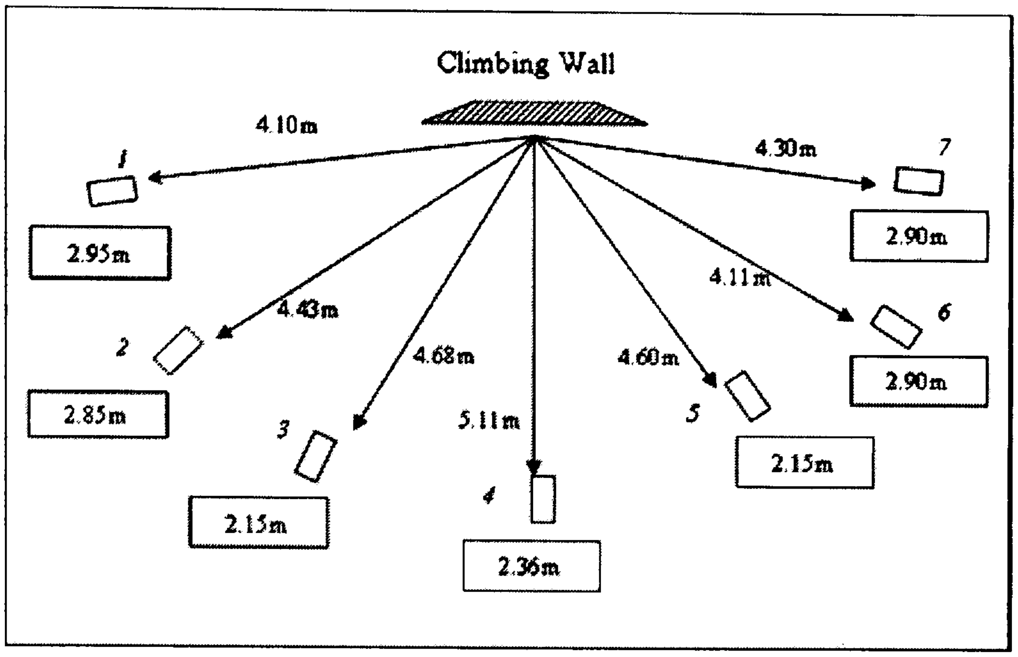


Figure 5-1 ProReflex motion capture unit (MCU) layout with distances from the wall and height above the ground (in boxes). The number of the MCU is in italics.

5.4. Calibration

The movement space was calibrated using the Qualysis Wand and calibration unit.
The calibration unit defined the horizontal axes X (positive away from the wall towards camera four) and Y (positive to the right). The wand was waved around the test volume in order to calibrate the Z axis.

5.5. Data Validation

A number of validation tests were performed prior to each data acquisition session. These tests consisted of: a ball throw through the test volume of space, the movement of three markers fixed to a rigid wooden arm model and the placement of markers on the climbing holds. The results of these tests are reported in Chapter 4.2.2.

5.6. Global Reference Frames

The global reference frame was orientated parallel to the ProReflex Calibration reference frame, with the origin at the left end of the left foothold (Figure 5-2). The global reference frame was referred to as the Gravitational Reference System (GRS), as the Z axis pointed positively in a vertical direction, and was thus taken as parallel to the direction of the force of gravity.

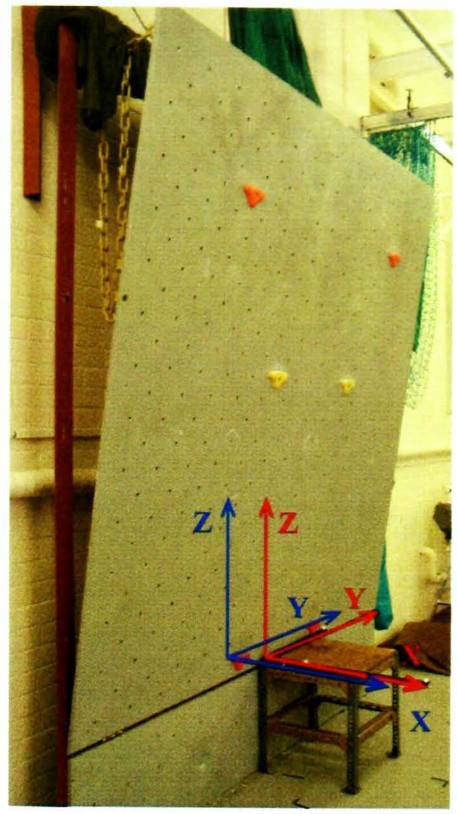


Figure 5-2 ProReflex global coordinate system (red) and the gravitational reference system (blue)

5.7. Technical Marker Placement

Technical markers were placed on the participants, as in Chapter 4.3.3, with the modifications to the leg markers as in Chapter 4.6.1.

5.8. Methods

The participants were asked to step onto the starting footholds (holds 5 and 6) whilst holding the starting handholds (holds 3 and 4) (see Figure 4-16 in Chapter 4.5.2) and then attain the set start position. The start position required the climber to place the left foot on the leftmost foothold, using the inside edge of the shoe, while the right foot was placed on the other foothold, using the front toe of the shoe, so that the foot was perpendicular to the wall. The handholds were gripped using a crimp grip style on the top edge of the holds. At no point were the climbers allowed to use the sides of the handhold.

Once the set position had been obtained, the participant held the position for two seconds and then performed one of three tasks. Two of the tasks involved moving the right foot and then making a hand reach for a target hold; the third task just involved making the hand reach from the starting set position. In the first task, the climber had to move the right foot so that the inside edge of the foot was placed on the hold; the second task required the foothold to be utilized by the outside edge of the right foot. In both tasks, where the right foot had to change position, the participants were asked to make a definite movement and placement of the foot and then to make to hand reach. In all three tasks the hand reach was performed by the right hand.

Each task was performed five times, giving a total of fifteen trials, in a randomized sequence. From the five trials, three were chosen to be averaged, to provide a representative data set for each participant performing each technique (see Chapter 5.10). Previous work had demonstrated that three trials were sufficient to produce a representative measure of a climber's performance (Chapter 4.4.1), a finding which was also in line with the recommendations of Mullineaux et al. (2001).

5.8.1. Static Trials

Post experimental static trials were performed to establish the position of the anatomical landmarks within the technical coordinate systems. Anatomical markers were attached to the participants, as in Chapter 4.3.2. To determine the shoulder joint centre, participants performed an abduction/adduction movement followed by a flexion/extension motion. Only data from the adduction and extension movements were used to find the shoulder joint centre (Chapter 4.3.7). The shoulder joint centre and hip joint centre were found using the methodology described in Chapter 4.3.7 and 4.3.8.

5.9. Data Analysis

5.9.1. Static Trials

The three-dimensional coordinates of the anatomical and technical landmarks within the ProReflex GCS were reconstructed in Qualysis Tracking Manager (QTM). The data was optimally processed within QTM and the coordinate data exported into Matlab. The coordinate data was smoothed using the GCVSPL program at the GCV criterion. The anatomical landmarks were then defined within the relevant technical coordinate system by a local vector.

5.9.2. Global Reference Systems

The coordinates of the markers placed on the climbing wall were optimally reconstructed within QTM and exported into Matlab. The GRS was defined as a time invariant local vector [L_G] with respect to the ProReflex GCS.

5.9.3. Climbing Trials

The distance between the climbing supports was scaled to the anthropometry of the individual participants as in Chapter 4.5.5.1.

The three-dimensional coordinates of the technical markers were optimally reconstructed in QTM and exported into Matlab. The technical marker coordinates were initially smoothed using GCVSPL program using the GCV criterion. Subsequently, the anatomical landmarks and thus the centre of mass displacement and velocity could be calculated, as described below. The amount of smoothing applied to the technical marker data was then adjusted according to the centre of mass velocity profile.

The locations of the anatomical landmarks were reconstructed using the technical marker coordinate systems and the time invariant anatomical local vectors, defined in the static trials, as described in Chapter 4.2.3. Initially, the coordinates of the anatomical landmarks were defined in the ProReflex GCS. These coordinates were converted to the GRS by pre-multiplying the anatomical landmark vector by $[L_G]$. Anatomical coordinate systems were then attached to each body segment, with the origin defined at the segmental centre of mass (Chapter 4.3.2).

5.9.4. Centre of Mass

Whole body three-dimensional centre of mass location was calculated from the segmental centre of mass locations (Chapter 4.3.5). Centre of mass velocities were calculated using the double finite difference technique.

5.9.5. Joint Orientation Angles

The joint orientation angles were calculated through the relative position of the distal segment with respect to the proximal segment. The resulting orientation matrix was parameterised using the Cardan sequence Zx'y'' in all the joints, except the shoulder, where the Euler sequence Yx'y'' was used (Wu et al., 2002, 2005) (Chapter 4.3.6).

In order to study joint sequencing, initiation of joint rotation was defined as the point where a 5% angular change from the initial value had occurred (Haguenauer et al., in press). A cessation of joint rotation was defined as three sequential gaps of zero angular change in displacement.

5.9.6. Movement Phases

Analysis of the movement was broken down into discrete time phases. For the OE and IE techniques, the movement was split into 5 phases; for the TE technique, the movement consisted of 3 phases.

Phase 1 was defined as the time period from the start of the whole body centre of mass movement to the initiation of right foot movement. Centre of mass initiation was defined as three sequentially bigger gaps of at least 1mm. Foot movement was determined by analyzing the right foot centre of mass movement in the x direction only. When the change in x data between two frames exceeded 1mm and the next two subsequent gaps were equal or greater in amplitude than the initial gap, then the foot was determined to have started moving.

Phase 2 was defined as the time period from the start of foot movement to the end of foot movement in the x direction. End of foot movement was determined by the gap in frames being less than 1mm and the two subsequent frames being equal or smaller in magnitude than the initial gap.

Phase 3 was defined as the time period from the end of foot movement to the start of the right hand movement. Hand movement initiation was determined in the same way as at the foot, but instead of the movement occurring in the x direction, the movement was studied in the z direction.

Phase 4 was defined as the time period from the start of the right movement from the starting hold to the end of the hand movement on the target hold. The end of the hand movement was defined in a similar fashion to the end of the foot movement, but in the z direction.

Phase 5 was defined as the time period from the end of the hand movement to the end of centre of mass movement. The end of centre of mass movement in a single direction was defined as three consecutive displacements of less than 0.1mm. The latest time point in the x, y and z directions was taken as the end of total centre of mass movement.

The TE technique did not have a pre-movement of the foot prior to hand movement; thus phases 1 and 2 do not exist for this technique. Phase 3 definition cannot be applied to the TE technique either. So, for TE technique, phase 3 is defined as the time from the start of whole body centre of mass movement to the start of the hand movement. Phases 4 and 5 are applied as in the OE and IE techniques.

5.10. Data Reduction

Three representative trials of each technique were selected for each participant. Each dependant variable data set was split into the five movement phases. Each movement phase was time normalised to 101 time-points. The average of the three time-normalised movement phases was taken to produce a single data set. The five mean movement phases were then recombined to produce one data set representing the whole movement of the participant for that particular technique. In this way, the data for each measured variable was reduced, so that for each participant, there was a single set of data for each variable, associated with each technique. The participants' data was conflated to produce mean data sets corresponding to each technique. Thus for each dependent variable there was one mean set of data per technique, to allow comparisons to be made.

5.11. Statistical Analysis

The effect of technique on the dependant measures was analysed through the use of Repeated Measures ANOVA for phases 3 to 5 and by a Within Subjects T-Test in phases 1 and 2. The statistical tests were used to analyse key moments in the climbing task.

The Repeated Measures ANOVA and Within Subjects T-Test both make particular assumptions about the data, which need to be met for these tests to be valid. Firstly, the data must be at least interval data; the dependant variables in this study are all at a ratio level. A common assumption of both tests is that the data is normally distributed. This assumption was tested objectively using the Shapiro-Wilks Test. A third major assumption of the Repeated Measures ANOVA is that of sphericity, formally tested using Mauchley's Test of Sphericity. Sphericity requires that the variance and covariance of the data are homogenous (Mullineaux & Bartlett, 1997). If sphericity was not demonstrated, then the Greenhouse-Geiser adjustment was made to the data.

The sample size for this study is small (n = 7). Thus there is a lack of statistical power in the Repeated Measures ANOVA and the Within Subjects T-Test (Mullineaux et al.,2001). The lack of statistical power is partially offset by the data reduction technique, whereby increased statistical power is achieved through averaging the multiple trials (Mullineaux et al., 2001); however, the low level of statistical power means that the statistical analysis may find non-significant findings for differences in the dependant measures in terms of technique, that is to say, there is an increased chance of type II errors occurring (Mullineaux et al., 2001).

In order to avoid misleading statistical results, the magnitude of effect (effect size: ES) will be reported (Mullineauux & Bartlett, 1997; Mullineaux et al., 2001), as ES can be used as a quantifiable measure of the association between data sets (Mullineaux et al., 2001). Magnitudes of ES <0.2 represent small/minor differences, 0.5 medium/moderate differences and >0.8 large/major differences (Cohen, 1988). In this study the ES will be used as a descriptive statistic to provide support for accepting or rejecting the null hypothesis (Mullineaux et al., 2001). ES will be reported as a partial eta-squared value, ranging in value from 0 to 1. Formally, partial eta-squared is defined as the proportion of total variance credited to the experimental factor, excluding other factors from the total non-error variation (Cohen, 1973; Haase, 1983 both in Pierce et al., 2004):

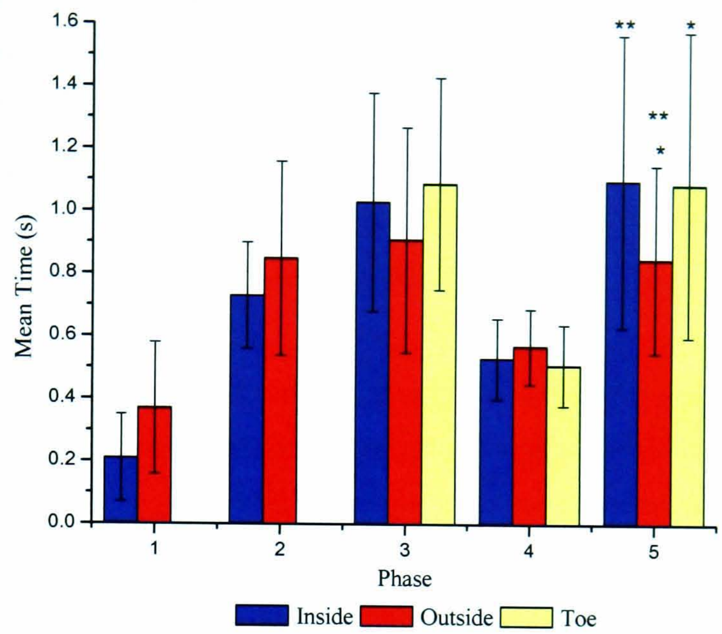
$$\text{partial}\,\eta^2 = SS_{factor} / (SS_{factor} + SS_{error}) \qquad \textbf{Equation 5-1}$$

where SS_{factor} is variation ascribed to the experimental factor and SS_{error} is the error variation.

As the Repeated Measures ANOVA is a one-way analysis of the effect of technique on the dependent variable, $SS_{total} = SS_{factor} + SS_{error}$, partial eta-squared becomes equivalent to classical eta-squared (Pierce et al., 2004). Partial eta-squared is, therefore, a measure of the unique variation in the dependent variable and as such can be used as a descriptive index of association between the experimental factor (technique) and the dependent variable (Pierce et al., 2004).

5.12. Results

5.12.1. Timings of the Phases



$$\left.\begin{aligned} {**}p &= 0.015 \\ {*}p &= 0.060 \end{aligned}\right\} ES = 0.64$$

Figure 5-3 Mean and standard deviation for duration of each movement phase with each foot orientation

The first two phases of movement demonstrated a longer mean time associated with the OE technique and greater variation within the group, denoted by the standard deviations. In phase 1, the mean times were not significantly different (p = 0.094, ES = 0.40), despite the outside edge (OE) technique demonstrating a mean length of time almost twice that of the inside edge (IE) technique. The OE technique also had a greater duration of time for reorganisation of the right leg geometry. No significant differences were found, however, between the techniques (p = 0.218, ES = 0.24), but the standard deviation between the participants in the IE technique (±17s) was nearly half of that associated with the OE (±31s).

Phase 3 was the preparation period for the onset of right hand movement from the initial hold, which for the IE and OE techniques constituted the mean time from the end of foot movement to the onset of vertical hand movement. The third phase was defined for the TE technique as the time from the centre of mass starting to move to the onset of right hand movement in the vertical direction. Phase 3 was the longest of the 5 phases for the OE technique (0.9±0.36s). For the IE and TE techniques, phase 3 duration was similar in magnitude to the fifth phase (1.03±0.35s and 1.09±0.34s, compared with 1.04±0.42s and 1.10±0.49s, respectively). The OE technique had the lowest mean time for phase 3 of all the techniques; however, no significant differences were found to exist between techniques (p = 0.256, ES = 0.20). The variability in the length of phase 3 between the participants was consistently around 0.35 seconds for all three techniques.

The fourth phase consisted of the movement of the right hand from the starting hold to the target hold. The timings for all three techniques within phase 4 were the least variable for all the phases of movement (standard deviations of 0.13s, 0.12s and 0.13s for IE, OE and TE respectively). The mean lengths of time were also the most closely comparable, with a difference of only 0.06 seconds between the OE and TE techniques. Again, no significant differences were found between techniques ($p = 0.167$, $ES = 0.30$).

Phase 5 constituted the time from the end of the hand movement to the end of centre of mass movement, which could be viewed as the post hand movement adjustment phase. The OE had the shortest mean time for phase 5 (0.84±0.3s), which was shown to be significantly different from the IE technique. The difference between the OE and TE techniques was even greater than the difference between the OE and IE. The TE technique had a greater standard deviation, which probably led to significance just being missed. Both the IE and TE techniques had similar mean lengths of time and standard deviations: 1.04±0.42 seconds and 1.10±0.49 seconds, respectively.

5.12.2. Mean Whole Body Centre of Mass

5.12.2.1. Intra- and Inter-participant Coefficients of Variation

The coefficients of variation (CV) for the mean centre of mass trajectories in each phase, within each participant, for each of the three techniques were below 10% in all but two cases. Participants 1 and 5 had CVs of 11.9% and 11.7% respectively for the centre of mass data in the x direction during phase 5. The CV for the mean centre of mass trajectories between each participant for each technique was below 10% in each of the x, y and z directions. The CV values mean that the participant group was homogenous both within and between participants.

5.12.3. Centre of Mass Displacement in Relation to the Base of Support

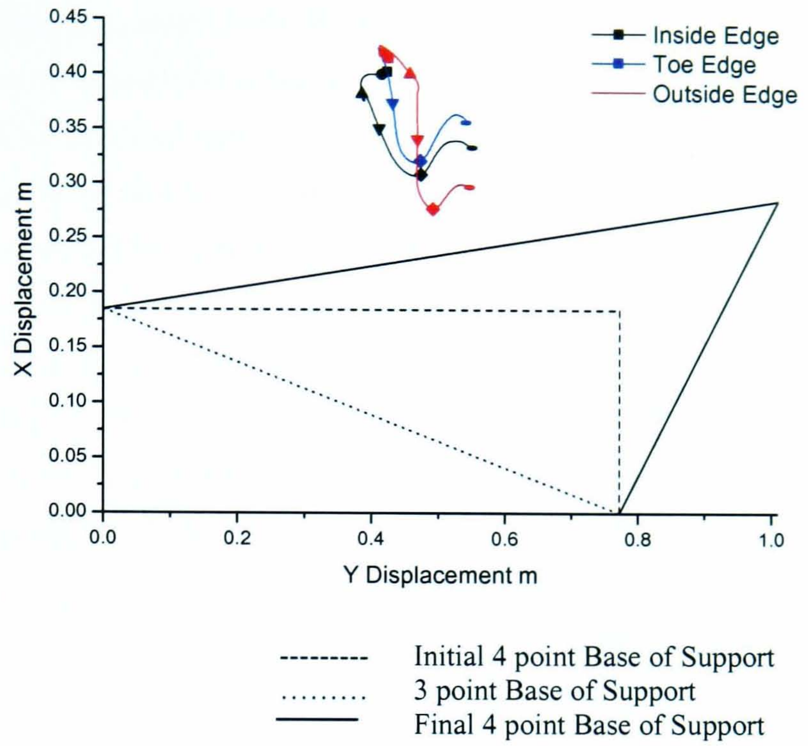


Figure 5-4 Centre of mass displacement in the XY plane with respect to the changing functional base of support

The base of support (BoS) is traditionally thought of as the supporting area in which resultant reaction forces can be applied (Pai & Patton, 1997). Static stability exists when the vertical projection of the centre of mass lies within the base of support (Karcnik & Kralj, 1999). Three main BoS existed for the movement under consideration (Figure 5-4). Initially a rectangular BoS existed for the four starting holds. Once the right hand started to move, the BoS decreased to a triangular shape, comprising the two footholds and the left handhold. When the right hand grasped the target hold, the BoS returned to a quadrilateral shape. The final BoS had the greatest area of the three. At no stage in the movement studied did any one technique displace the centre of mass into a functional base of support.

5.12.4. Initial Postures

The joint angular values for the starting position in each technique are given in Table 5-1. The participants adopted a position in which the ankles were both flexed, in inversion and internally rotated. The left ankle was more flexed, but with less internal rotation and inversion. Significant differences were demonstrated between the techniques, specifically the IE and TE were shown to be significantly different. However, in real terms the two techniques only differed by 3°. The left knee was slightly more flexed than the right knee in all three techniques. Significant differences were found to exist between the techniques in terms of left knee flexion, but the Bonferroni test was unable to show where the differences lay. The mean values showed the OE technique involved less flexion than the IE and TE, which both had similar magnitudes. All three techniques showed similar levels of abduction within each knee. Both knees were externally rotated with respect to the thigh, the left more so. The left hip started in a more flexed position than the right hip. The left hip was over twice as abducted and externally rotated. Significant differences were found between the OE and TE techniques in left hip abduction, but again the magnitude of the difference was only 3°. The right hip essentially had no internal or external rotation at the start of movement. The left and right arms had similar levels of elevation and external rotation at the shoulders. Significant differences were found to exist between the techniques in the external rotation in the left shoulder, but the location of the differences could not be shown. The mean values showed that the IE and TE had the same magnitude of external rotation but the OE had greater levels. The IE and TE techniques had the right arm orientated slightly further in front of the torso than the left arm, whereas the opposite trend was shown in the OE technique. In the OE, the left upper arm was orientated significantly further in front of the torso, compared with the IE and TE techniques. Both the elbows are similarly flexed in the IE and TE techniques, but in the OE technique the right elbow was slightly more flexed. Both elbows were pronated in all three techniques, but the right arm was consistently more so. The wrists were both hyper-extended, and in abduction with the right wrist more abducted and hyper-extended. Significant differences were shown to exist between the three techniques in the amount of flexion in the left arm, but the location of these differences could not be found. The OE technique had the least flexion and the TE had the most.

The significant differences in the starting data, though small in magnitude, may have been due to an anticipation of the forthcoming limb movement, as the participants did have prior knowledge of which technique to perform before adopting the set start position. The OE had significantly more adduction in the left hip, more extension in the knee, greater plane of elevation angle, greater external rotation at the shoulder and more elbow extension. This placed the body in a slightly better position from which to move the hips away from the wall, to allow the right thigh to adduct without hitting the wall. A detailed description of joint sequencing is now considered.

Table 5-1 Mean joint rotation angular values, P values between the three techniques and the effect size for the twelve joints at the start of movement

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P values	Effect Size
lankle	Z	25	9	24	10	25	7	0.425	0.12
	x	16[a]	10	17	10	19[a]	10	0.024	0.46
	y	6	6	6	5	7	6	0.088	0.33
lknee	Z	-84	12	-80[*]	13	-85[*]	11	0.044	0.41
	x	9	4	9	3	9	2	0.802	0.04
	y	-25	13	-27	13	-26	14	0.080	0.34
lhip	Z	53	18	54	15	54	16	0.858	0.03
	x	-43	11	-41[a]	11	-44[a]	11	0.007	0.57
	y	-19	23	-18	22	-17	22	0.958	0.01
lshoulder	Y	21[a]	28	26[a,b]	26	21[b]	27	0.021	0.48
	x	-62	8	-61	7	-58	10	0.272	0.23
	y	-68[*]	10	-71[*]	8	-68[*]	9	0.024	0.46
lelbow	Z	109	13	107[*]	14	111[*]	15	0.047	0.49
	y	98	16	100	17	99	16	0.127	0.29
lwrist	Z	-22	17	-21	16	-23	19	0.572	0.09
	x	-12	13	-13	13	-13	13	0.373	0.15
rankle	Z	10	9	8	10	7	11	0.479	0.17
	x	40	8	42	8	41	9	0.455	0.12
	y	34	12	35	14	36	13	0.395	0.14
rknee	Z	-82	11	-78	12	-81	12	0.109	0.36
	x	11	9	8	10	9	10	0.073	0.35
	y	-20	13	-20	12	-19	14	0.281	0.23
rhip	Z	49	6	49	8	48	7	0.847	0.03
	x	-19	14	-15	11	-17	13	0.208	0.23
	y	-1	14	1	14	0	14	0.237	0.21
rshoulder	Y	24	15	29	11	24	16	0.074	0.35
	x	-63	13	-64	12	-60	14	0.231	0.31
	y	-69	12	-70	8	-67	12	0.267	0.23
relbow	Z	111	16	110	16	111	17	0.653	0.07
	y	106	9	105	10	106	10	0.884	0.02
rwrist	Z	-25	13	-25	11	-24	11	0.956	0.01
	x	-7	7	-8	7	-8	7	0.595	0.08

5.12.5. Phases 1 and 2 Reorientation of the Right Foot

The purpose of phase 1 was to move the body in preparation for the movement of the right foot, which defined phase 2. The patterns of joint angular change and the motion of the centre of mass are shown in Figure 5-5 and Figure 5-6 for the Inside Edge (IE) and Outside Edge (OE) respectively. In the IE technique the centre of mass was only displaced upwards and to the left through phase 1. This was primarily achieved through right foot extension and right hip abduction. As the centre of mass moved to the left, the left upper arm started to rotate forwards relative to the torso and the left ankle started to flex. The vertical motion was accommodated through an increase in hyper-extension in the right wrist.

The OE technique showed similar upward and leftward displacement of the centre of mass in the z and y directions but also demonstrated a displacement away from the wall. At the end of phase 1, the OE was significantly further from the wall. As with the IE technique, the right leg was the main instigator of centre of mass displacement in the OE. However, in the OE the right hip adducted, as opposed to abducted, causing the hips to move backwards and, as the right foot was fixed, the right knee to abduct and externally rotate. Extension of the right ankle displaced the centre of mass vertically upwards and to the left. The upward and leftward movement of the centre of mass was accommodated by the plane of elevation in the right shoulder decreasing and hyper-extension in the right wrist. Near the end of phase 1 the knees started to extend (89-90%PMT), which increased the velocity of the centre of mass upwards. But the right hip was less adducted than the left hip, despite the adduction motion at the right hip, so the extension of the left knee reduced the velocity of the centre of mass in the leftward direction created by the right knee and ankle extensions. The result was that at the end of phase 1, there was a negative velocity peak in the y direction. The combined effect of the knees, along with right hip adduction, acted to push the hips away from the wall.

At the end of phase 1, the two techniques showed significant differences in centre of mass displacement and velocity. In terms of posture, the OE showed significantly more extension in the knees and left ankle. The right knee had significantly more external rotation and abduction. The right ankle had significantly more inversion in the OE and the right hip was more adducted and internally rotated. In the upper limbs, significant differences were only shown in the left arm. The plane of elevation was significantly greater, with greater external rotation in the shoulder in the OE technique, and the elbow significantly more pronated.

The reorientation of the right foot in the IE required the right foot to be rotated, from a position of the toe being in contact with the foothold, to a position where the inside edge of the foot was used on the foot support by the end of phase 2. This was achieved initially through abduction in the right hip and adduction in the right knee and then by external rotation at the knee and foot. Eversion at the right ankle early in phase 2 suggested the right foot being unweighted. This was supported by the observation of the right knee extending, with the tibia having already been placed into external rotation. If the foot had been weighted then the tibia would have been expected to internally rotate. During the right foot movement, the centre of mass continued to be displaced vertically upwards and to the left. This motion was accommodated by the right leg, initially through continued ankle extension and then by extension of the knee coupled to flexion in the ankle.

The OE technique involved rotating the right foot so that the outside edge of the foot was in contact with the foothold. At the start of the phase, the right foot movement was primarily due to adduction in the right hip. Early in phase 2 the foot was helped to rotate by internal rotation in the knee and eversion in the ankle. These actions were closely followed by flexion in the right ankle, which helped to swing the rear of the foot round. At 28% of phase 2, the right thigh moved into a position of adduction. The rotation of the foot started to be opposed by the right ankle midway through the phase, through inversion in the ankle. This inversion action helped to stabilise the right foot, as the right knee began to flex. The right knee then stopped internally rotating and began to rotate externally. Thus the rotation of the foot was now due to the right hip internally rotating and adducting. Right ankle support further solidified by internal rotation, which also helped to rotate the foot into the wall. The internal rotation in the hip joint plateaued at 78%, so for the remainder of the phase the foot was rotated in by hip adduction and ankle internal rotation. The last 20% of the phase, the right ankle started to extend, which solidified support on the right foot, and helped lift the heel in towards the wall as the right knee was flexing.

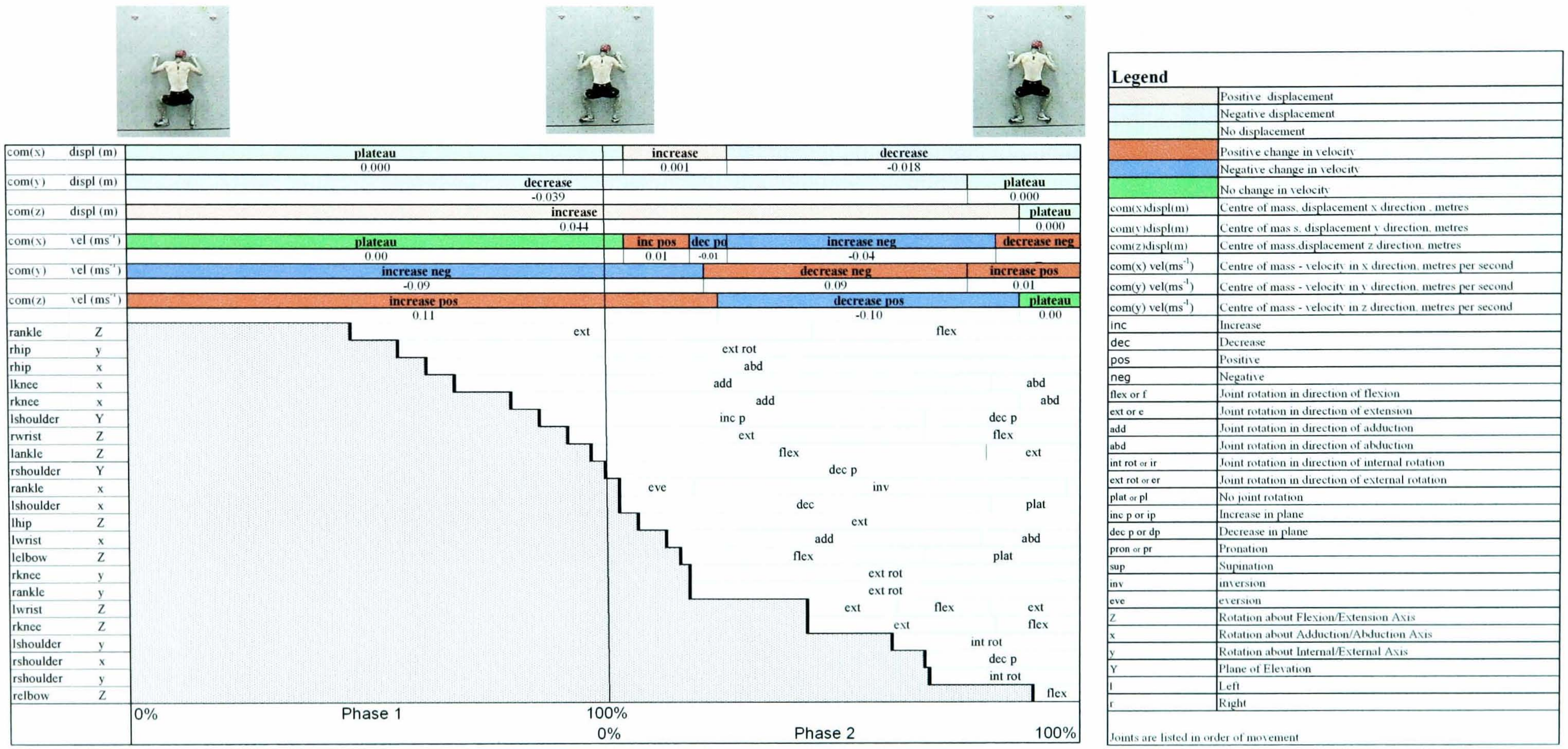
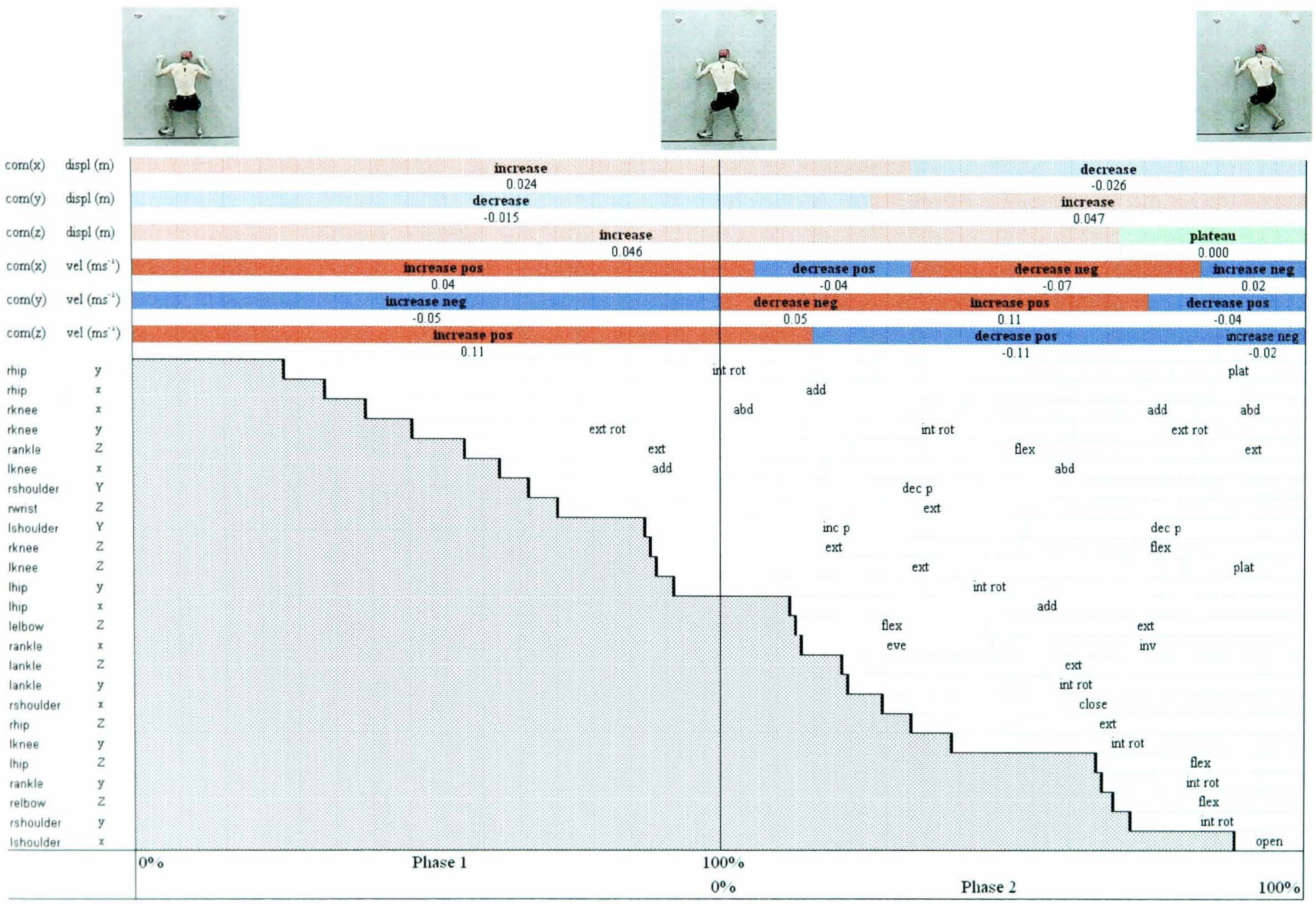


Figure 5-5 Inside edge phase 1 and 2: patterns of joint angular changes and centre of mass displacement and velocity changes



Legend

	Positive displacement
	Negative displacement
	No displacement
	Positive change in velocity
	Negative change in velocity
	No change in velocity
com(x)displ(m)	Centre of mass, displacement x direction , metres
com(y)displ(m)	Centre of mas s, displacement y direction, metres
com(z)displ(m)	Centre of mass,displacement z direction, metres
com(x) vel(ms^{-1})	Centre of mass - velocity in x direction, metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in y direction, metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in z direction, metres per second
inc	Increase
dec	Decrease
pos	Positive
neg	Negative
flex or f	Joint rotation in direction of flexion
ext or e	Joint rotation in direction of extension
add	Joint rotation in direction of adduction
abd	Joint rotation in direction of abduction
int rot or ir	Joint rotation in direction of internal rotation
ext rot or er	Joint rotation in direction of external rotation
plat or pl	No joint rotation
inc p or ip	Increase in plane
dec p or dp	Decrease in plane
pron or pr	Pronation
sup	Supination
inv	inversion
eve	eversion
Z	Rotation about Flexion/Extension Axis
x	Rotation about Adduction/Abduction Axis
y	Rotation about Internal/External Axis
Y	Plane of Elevation
l	Left
r	Right

Joints are listed in order of movement

Figure 5-6 Outside edge phases 1 and 2: patterns of joint angular changes and centre of mass displacement and velocity changes

The onset of centre of mass displacement in the x direction in the IE technique occurred just inside phase 2. The displacement was initially away from the wall until 26% PMT, when the centre of mass changed direction and acquired a negative velocity. The initial positive velocity in the x direction was small and probably due to the increasing plane of elevation in the left shoulder. However, the decrease in elevation in the shoulder and the elbow flexion acted to displace the centre of mass in a negative x direction towards the wall. The displacement in the y and z directions continued as in phase 1, until 88% PMT when there was a plateauing. However, the velocities in the y and z directions showed peaks after approximately a quarter of the phase (21% and 25% PMT respectively). Leftward displacement in the y direction occurred through decreasing plane of elevation in the right shoulder, with increasing plane of elevation in the left shoulder, decreasing elevation in the shoulder and flexion in the left elbow. The left ankle continued to flex, but the left hip also started to extend. Extension in the hip opposed the displacement of the centre of mass to the left, thus creating the peak in velocity. The unweighting of the right foot meant that the displacement of the centre of mass in z direction occurred through the left hip extension, reduction in the left shoulder elevation and left elbow flexion. However, the changes in the planes of elevation in the shoulders meant that these actions moved the centre of mass laterally, as well as upwards, so the velocity in the z direction decreased. The right arm remained essentially fixed, apart from the plane of elevation, so the vertical displacement was accommodated through hyper-extension in the right wrist.

At two-thirds of phase 2 movement time, the angular motions in the left arm changed. The left upper arm started to rotate internally and the wrist started to flex. The plane of elevation stopped increasing and reversed direction, as the elbow fixated. In the right arm, the angle of elevation started to decrease, there was internal rotation at the shoulder joint and the wrist ceased further hyper-extension. These actions reduced the velocity of the centre of mass in the left and upward directions, with resulting plateaus in displacement in these directions. The displacement plateau in the z direction was reinforced by left ankle extension with a plateauing in the left shoulder angle of elevation. Right knee flexion in the last 20% of the phase followed by flexion in the right elbow reinforced the plateau in the y direction. The centre of mass continued to displace towards the wall through the decreasing planes of elevation in the shoulders and abduction in the right hip. At the end of phase 2, the right ankle started inversion, indicating the onset of re-weighting of the right foot.

In the OE, the centre of mass displacement showed similar patterns of change in the x and z directions. The centre of mass continued to move in a direction away from the wall for the first third of phase 2, after which the direction of displacement reversed. In the z direction, the centre of mass increased in height, until plateauing in the last part of the phase. The plateau occurred earlier in the OE technique than in the IE. In the y direction, however, the centre of mass reversed direction after a quarter of the phase, showing a substantial displacement to the right. The change in velocity in the y direction occurred at the onset of phase 2. This is attributed to the knee extension of the left leg, which was in greater degree of adduction at the hip than the right leg, also extending at the knee and ankle. The left knee extension reduced the negative velocity of the centre of mass in the y direction. The extensions at the knees and right ankle served to increase the upward displacement in the z direction. The velocity in the z direction peaked at 16% PMT, just after the right foot started eversion. This suggests that the right leg played an active role initially in phase 2 on the centre of mass. The onset of eversion indicated the right foot becoming unweighted. This means that the z displacement was primarily due to left knee extension. At the same time as the right ankle started eversion, the left hip began to adduct, thus helping direct the knee extension in a more lateral direction and less in a positive x direction. The angular changes in the left leg effectively slowed and reversed the lateral movement of the body and displaced the hips away from the wall.

Prior to phase 2, the left shoulder plane of elevation started to increase. At the same time, the right shoulder plane of elevation was decreasing. These actions acted to rotate the torso towards the left arm. There were no other joint angular changes in the arms; thus to accommodate the vertical displacement of the body, the right shoulder was elevated as the torso twisted and the right wrist hyper-extended. At the same time as the right ankle performed eversion and the left hip adducted, the left elbow started to flex. This had the effect of moving the torso towards the climbing wall. So the actions of the upper body were to move the torso towards the left arm, reinforcing support on that arm, while the left leg tried to push the hips in the opposite direction, in order for there to be space to bring the right knee in front of the body.

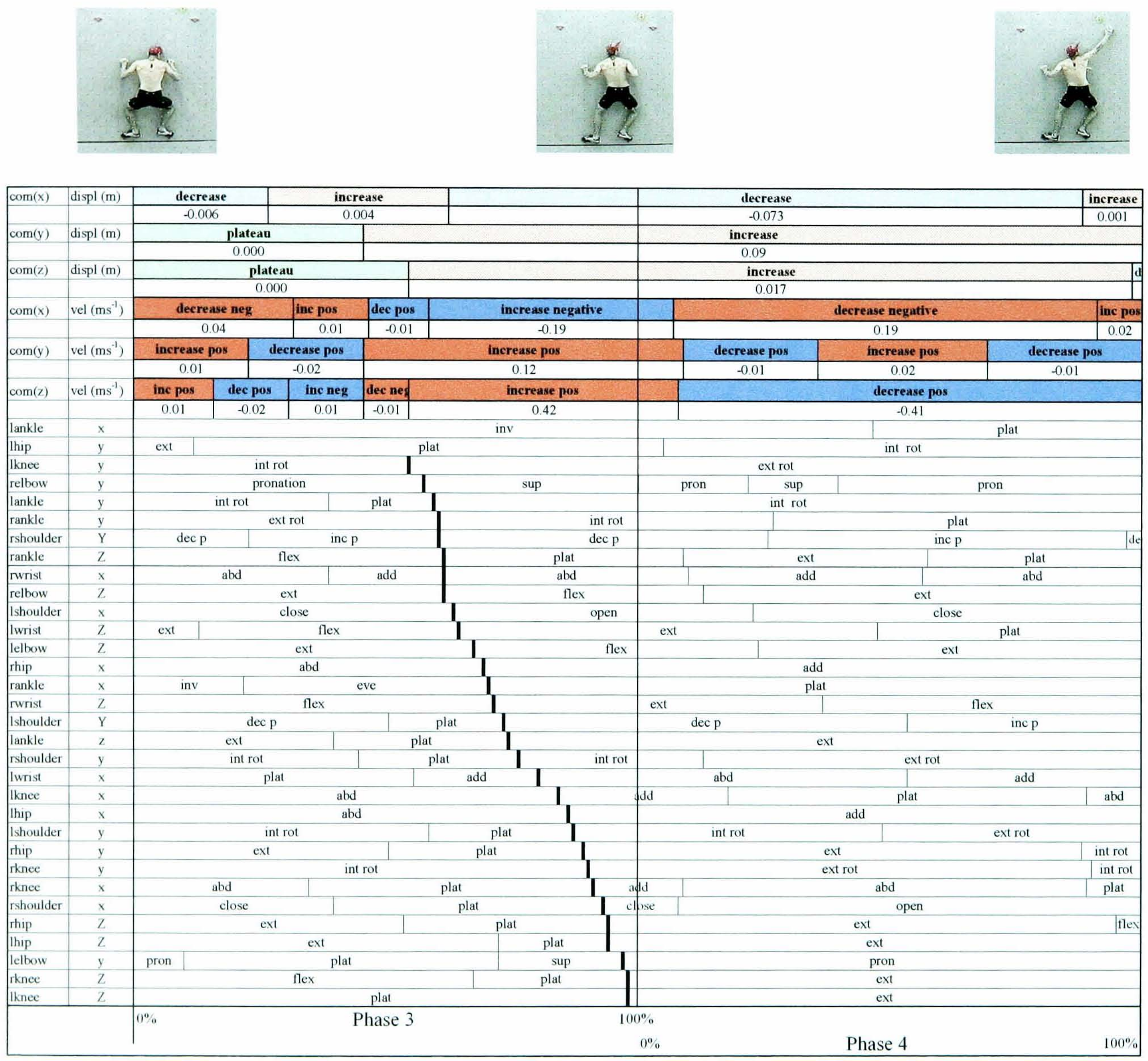
Once the right thigh moved into a position of adduction, the strategy changed. The centre of mass moved to the right and towards the wall. The right hip continued to adduct and internally rotate but also started to extend. The left ankle started to extend and internally rotate just prior to the right thigh moving into an adducted position and the knee was still extending. These angular changes acted to rotate the hip towards the left leg, meaning that the left hip eventually had to flex. The rotation of the hip helped the already rotated trunk. However, the trunk started to move to the right by a closure in the angle of elevation of the right humerus, combined with a continued decrease in the plane of elevation at the right shoulder. The left elbow started to extend, followed by decrease in left humerus plane of elevation. These actions meant that the trunk bent back towards the right arm, while remaining rotated towards the left arm. Thus the right side of the trunk was elevated. The rise in the vertical direction of the centre of mass was reduced by the flexion of the right knee, as the centre of mass moved back over the right foot. The right foot was progressively weighted, as the ankle sequentially inverted, internally rotated and extended. As the centre of mass moved further to the right, the right shoulder internally rotated and the right elbow flexed, as the angle of elevation in the left shoulder increased.

The result of the right foot orientation was that the centre of mass in the OE technique was significantly more displaced to the right, but in similar positions in the x and z direction compared with the IE technique. Both techniques had negative velocities in the x direction, with OE having the greater. In the y direction the OE had significantly greater positive y velocity than the IE, which also had a positive velocity. The IE had a positive velocity in the z direction at the end of the phase, whereas the OE had a negative velocity; the differences were not, however, significant.

The re-orientation of the foot produced major differences in the body geometry of the climber (Appendix C). The right leg was obviously significantly more adducted in the hip. There were significant differences in the internal rotation in all three joints and in abduction in the knee and inversion in the ankle. However, the amount of flexion in the hip, knee or ankle was not significantly different in the two techniques. The end posture of the left leg showed the OE technique to have greater extension in the knee and ankle but more flexion in the hip (all differences significant). The left ankle and hip were significantly more internally rotated, while the knee had significantly greater abduction in the OE technique. In the upper limbs the OE technique showed the angle of elevation in the shoulders to be significantly less in the right shoulder and significantly more in the left. The only significant differences in the right arm, apart from shoulder elevation, were in the wrist, where there was more hyper-extension and abduction associated with the OE technique. In contrast, the left arm showed significantly more extension and pronation in the elbow, along with significantly more external rotation in the shoulder and less hyper-extension in the wrist.

5.12.6. Phases 3 and 4 Reaching Movement of the Right Hand

Phase 3 consisted of angular changes post foot re-orientation and preparatory movements for the hand reaching movement. The purpose of phase 4 was to make a hand reaching movement for the target hold. The intra-limb coordination in the right arm is considered in detail further in the text. In this section, it is the angular changes in preparation for the hand reach (phase 3) and the angular changes in the rest of the body during the hand reach (phase 4) that are of interest. The angular changes and the centre of mass movement variables are presented for the IE, OE and Toe Edge (TE) techniques in Figure 5-7, Figure 5-8 and Figure 5-9 respectively.



Legend	
	Positive displacement
	Negative displacement
	No displacement
	Positive change in velocity
	Negative change in velocity
	No change in velocity
com(x)displ(m)	Centre of mass, displacement x direction , metres
com(y)displ(m)	Centre of mas s, displacement y direction, metres
com(z)displ(m)	Centre of mass,displacement z direction, metres
com(x) vel(ms-1)	Centre of mass - velocity in x direction, metres per second
com(y) vel(ms-1)	Centre of mass - velocity in y direction, metres per second
com(y) vel(ms-1)	Centre of mass - velocity in z direction, metres per second
inc	Increase
dec	Decrease
pos	Positive
neg	Negative
flex or f	Joint rotation in direction of flexion
ext or e	Joint rotation in direction of extension
add	Joint rotation in direction of adduction
abd	Joint rotation in direction of abduction
int rot or ir	Joint rotation in direction of internal rotation
ext rot or er	Joint rotation in direction of external rotation
plat or pl	No joint rotation
inc p or ip	Increase in plane
dec p or dp	Decrease in plane
pron or pr	Pronation
sup	Supination
inv	inversion
eve	eversion
Z	Rotation about Flexion/Extension Axis
x	Rotation about Adduction/Abduction Axis
y	Rotation about Internal/External Axis
Y	Plane of Elevation
l	Left
r	Right

Joints are listed in order of movement

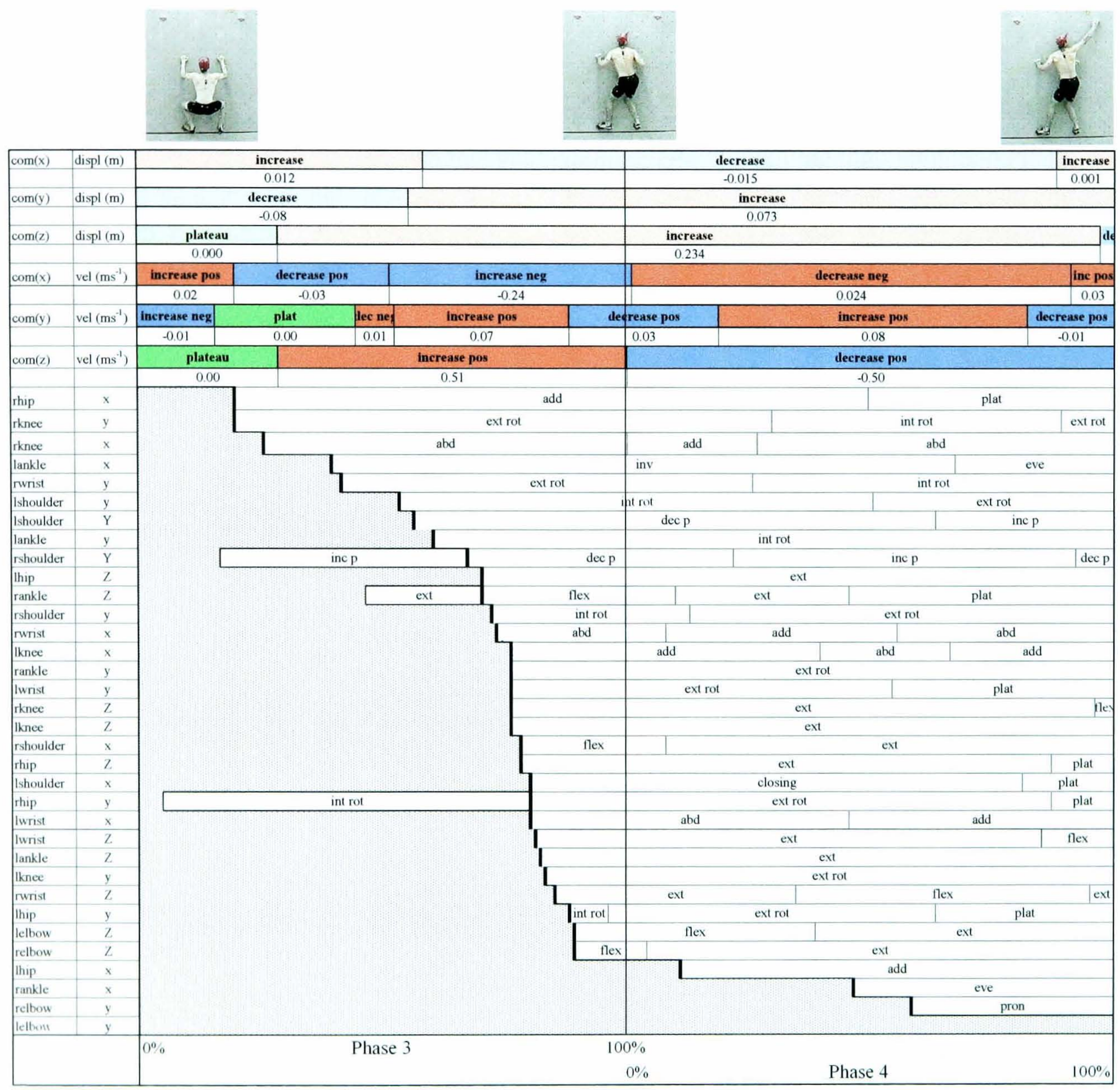
Figure 5-7 Inside edge phase 3 and 4: patterns of joint angular changes and centre of mass displacement and velocity changes

		Phase 3 (0%–100%)	Phase 4 (0%–100%)
com(x)	displ (m)	decrease -0.012	decrease -0.111
com(y)	displ (m)	increase 0.012; plateau 0.000	increase 0.022
com(z)	displ (m)	plateau 0.000	increase 0.152
com(x)	vel (ms^{-1})	decrease neg 0.02; increase neg -0.01; plateau 0.00; increase neg -0.29	decrease neg 0.24
com(y)	vel (ms^{-1})	decrease pos -0.07; increase -0.01; dec neg 0.01; inc pos 0.01; dec pos -0.01	inc neg _; dec ne _; increase pos 0.08; dec pos 0.01
com(z)	vel (ms^{-1})	dec neg 0.01; inc neg -0.01; decrease neg 0.02; increase pos 0.32	decrease pos 0.28
lankle	x	inv	plat
lankle	y	int rot	
lhip	y	int rot	ext rot
lshoulder	Y	dec	inc
rknee	y	ext rot	
rhip	Z	ext	
rhip	x	add	abd
rshoulder	y	int rot	ext rot
lshoulder	y	plat; int rot	ext rot
lhip	x	add; plat	add
lknee	y	int rot	ext rot
lelbow	Z	ext; flex	ext
lshoulder	x	elevating; closing	closing
rwrist	Z	flex; ext	flex
rshoulder	Y	inc p; dec p	inc p; dec
relbow	Z	flex; ext; flex	ext
lelbow	y	int rot; ext rot	int rot
lankle	Z	ext; flex	ext
rhip	y	ext rot; int rot	ext rot
lknee	Z	flex	ext
lknee	x	abd	add; abd
lwrist	Z	flex	ext; flex
rankle	y	int rot	ext rot; int rot
rwrist	x	abd; add; abd	add; abd
rankle	Z	flex; ext; plat; ext; flex	ext; flex; ext
lhip	Z	flex; ext	ext
rshoulder	x	close; plat; close	open
rknee	Z	flex	ext
lwrist	x	abd	add; plat
rknee	x	abd; add; abd; add	abd
rankle	x	inv	eve
relbow	y	sup; pron; sup	pron; sup; pron

Legend	
(light pink)	Positive displacement
(light blue)	Negative displacement
(white)	No displacement
(orange)	Positive change in velocity
(blue)	Negative change in velocity
(green)	No change in velocity
com(x)displ(m)	Centre of mass. displacement x direction . metres
com(y)displ(m)	Centre of mas s. displacement y direction. metres
com(z)displ(m)	Centre of mass.displacement z direction. metres
com(x) vel(ms^{-1})	Centre of mass - velocity in x direction. metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in y direction. metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in z direction. metres per second
inc	Increase
dec	Decrease
pos	Positive
neg	Negative
flex or f	Joint rotation in direction of flexion
ext or e	Joint rotation in direction of extension
add	Joint rotation in direction of adduction
abd	Joint rotation in direction of abduction
int rot or ir	Joint rotation in direction of internal rotation
ext rot or er	Joint rotation in direction of external rotation
plat or pl	No joint rotation
inc p or ip	Increase in plane
dec p or dp	Decrease in plane
pron or pr	Pronation
sup	Supination
inv	inversion
eve	eversion
Z	Rotation about Flexion/Extension Axis
x	Rotation about Adduction/Abduction Axis
y	Rotation about Internal/External Axis
Y	Plane of Elevation
l	Left
r	Right

Joints are listed in order of movement

Figure 5-8 Outside Edge Phases 3 and 4 : Patterns of Joint Angular Changes and Centre of Mass Displacement and Velocity Changes



Legend

	Positive displacement
	Negative displacement
	No displacement
	Positive change in velocity
	Negative change in velocity
	No change in velocity
com(x)displ(m)	Centre of mass. displacement x direction . metres
com(y)displ(m)	Centre of mas s, displacement y direction, metres
com(z)displ(m)	Centre of mass.displacement z direction. metres
com(x) vel(ms^{-1})	Centre of mass - velocity in x direction. metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in y direction. metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in z direction. metres per second
inc	Increase
dec	Decrease
pos	Positive
neg	Negative
flex or f	Joint rotation in direction of flexion
ext or e	Joint rotation in direction of extension
add	Joint rotation in direction of adduction
abd	Joint rotation in direction of abduction
int rot or ir	Joint rotation in direction of internal rotation
ext rot or er	Joint rotation in direction of external rotation
plat or pl	No joint rotation
inc p or ip	Increase in plane
dec p or dp	Decrease in plane
pron or pr	Pronation
sup	Supination
inv	inversion
eve	eversion
Z	Rotation about Flexion/Extension Axis
x	Rotation about Adduction/Abduction Axis
y	Rotation about Internal/External Axis
Y	Plane of Elevation
l	Left
r	Right
Joints are listed in order of movement	

Figure 5-9 Toe edge phases 3 and 4: patterns of joint angular changes and centre of mass displacement and velocity changes

Preparatory movements of the centre of mass for the prehension task began at 47% of phase 3 in the IE technique, with the centre of mass being displaced to the right. The vertical displacement of the centre of mass occurred at 55% of phase 3 movement time. In the x direction, the centre of mass was displaced away from the wall until 63% PMT, after which the centre of mass moved towards the climbing wall.

In contrast, the OE technique showed centre of mass displacement towards the wall and to the right from the start. As with the IE technique, the OE started phase 3 with the no displacement in the z direction. Although the centre of mass was displaced towards the climbing wall, the velocity profile showed that the movement was limited for the first half of phase 3. After 53% PMT, the velocity of the centre of mass in the negative x direction increased markedly. The centre of mass started to move in the z direction at 47 % of phase 3, while the y displacement ceased at 56% PMT and remained so for the rest of the phase.

The TE technique differed from the IE and OE techniques in that there were no phases 1 and 2. Thus the TE technique started from the initial starting position. Although this was consistent with the starting posture in the IE and OE techniques, it meant that at the start of phase 3, the centre of mass in the TE was in a position further from the wall and vertically lower, compared with the other techniques. In the y direction the centre of mass was further to the right than in the IE, but left of the OE position. The pattern of centre of mass movement in phase 3 consisted of initial movement outwards and to the left only. At 29% PMT the centre of mass started to move upwards. Subsequently, the centre of mass reversed direction in the x and y directions, moving to the right (56%) and towards the wall (59%).

In the IE technique, the action of the legs served to reweight the right foot. This was achieved through flexion in the right knee and ankle, and extension in the left ankle, while the left knee remained fixated in terms of flexion. The lack of movement of the whole body centre of mass in the y direction was due to the conflicting extensions in the hip joints, combined with the external rotation in the right hip. The action of the hips brings the hips in towards the wall. In the shoulder joints there is a reduction in the plane of elevation, decrease in angle of elevation and internal rotation. The effect of these actions is to displace the centre of mass inwards. However the pronation in the right elbow and extension of both elbows acts to resist the negative movement of the centre of mass in the x direction. These resistive motions combine with the increase in plane of elevation in the right shoulder at 23% PMT to rotate the trunk towards the right arm, pushing the right shoulder backwards. As the hips continue to extend, the right shoulder is pushed further backwards, reversing the motion of the centre of mass in the x direction and maintaining the constant position in the vertical direction.

Movement of the centre of mass rightwards is initiated primarily through the right hip ceasing to extend, while the left hip continues to extend and the right knee and ankle flex. Precursors for the angular change in the hip, are eversion of the right ankle, with increase in the plane of elevation in the right shoulder, followed by fixation in the angle of elevation and internal rotation in the right shoulder and fixation in left ankle extension and internal rotation. Thus the action in the left leg changes from ankle and hip extension to just hip extension. The angular changes in the right leg and arm allow the centre of mass to move to the right. The vertical displacement of the centre of mass is initiated through extension in the left hip.

The trunk rotates back towards the left arm through angular changes in both arms. The left wrist starts to adduct while the left shoulder stops internally rotating. In the right arm the elbow ceases to pronate and begins supinating, followed by the plane of elevation in the right shoulder starting to decrease again. The right elbow flexes and the right wrist abducts. The effect of these angular changes is to move the centre of mass to the right and reverse the motion of the centre of mass in the x direction, which occurs at 63%PMT.

As the centre of mass moves to the right, the right ankle ceases to flex and starts to internally rotate. Subsequently the right knee stops flexing, suggesting a sequential re-weighting of the right leg and opposition to movement of the centre of mass to the right. At this point the left leg reverts to an ankle extension strategy to keep the centre of mass displacement in the positive y direction.

In the left arm there is flexion in the elbow and opening in the shoulder elevation angle. The right elbow is also flexing with the plane of elevation in the right shoulder decreasing. In both arms there is hyper-extension of the wrists, indicating a movement of the elbows outwards.

The change in strategy in the left leg is accompanied by angular changes in the arms. The plane of elevation in the left arm starts to decrease, helping to move the centre of mass towards the wall and rightwards and there is internal rotation in the right shoulder, indicating a more active pull by the right hand. The left shoulder also starts to internally rotate, while the elbow flexes and the shoulder elevation increases, indicating a pressing action in the left arm. At the end of phase 3 there is hip extension followed by knee extension. This coordination serves to increase the z displacement of the centre of mass however the right leg extensions are greater by the end of the phase than the left leg extensions, so the result is an opposition to the centre of mass movement in the y direction.

At the start of phase 3, the left leg is acting to push the body over the right foot, in the OE technique. This is primarily achieved through left and right knee and left hip flexion. The right ankle essentially remains fixed for the entire phase in terms of flexion and extension. The right ankle is still internally rotating and inverting, thus the ankle is acting to resist vertical collapse by the body moving over the right foot. The major movement in the right hip is in extension and adduction. The combined action of the legs moves the centre of mass rightwards. The continued adduction in the right hip, acts to rotate the pelvis towards the left leg, helping to displace the centre of mass in a negative x direction.

The action of the arms is also to move the centre of mass to the right. In the left shoulder the plane of elevation continues to decrease and the angle of elevation increases, while the elbow extends. The action of the left wrist suggests that the role of the left arm is to control the displacement to the right. In the right arm the greatest movement occurs in the shoulder joint, the elbow does not start to flex until 60%PMT. So the movement of the body centre of mass in the positive y direction is achieved through musculature at the shoulder and wrist. Specifically at the shoulder the movement pattern is of increase in plane of elevation as the angle of elevation decreases and the upper arm internally rotates. The angular changes of the shoulder joint helps maintain the vertical displacement of the body. The kinematics of the left and right shoulders shows that the torso rotates back towards the right hand as well as moving to the right. The plane of elevation in the left shoulder continues to decrease for the whole of phase 3, thus helping to move the centre of mass towards the wall for the whole of the phase duration.

At 22% of phase 3 the right elbow starts to pronate, which suggests a resistance to the motion of the centre of mass in the positive y direction. Further decrease in velocity in the positive y direction of the centre of mass occurs through flexion in the left ankle, which combined with the flexion at the left knee acts to pull the hips back towards the left. The movements in the left arm, elbow flexion with decreasing plane of elevation in the shoulder, now act to bring the centre of mass back leftwards. Combined with the extension of both hips, the left arm also acts to move the centre of mass vertically upwards. The adduction and hyper-extension movements in the right wrist occur with the elbow fixed in flexion and pronated, thus the distal musculature is acting to repel further movement to the right. These actions are accompanied by the right shoulder plane of elevation ceasing to increase and starting to decrease at 56% PMT, which also acts to increase the velocity of the centre of mass towards the wall.

The leftwards centre of mass displacement plateaus at 56% and remains fixed until 19% of phase 4 movement time. At this point the centre of mass velocity is increasing in the negative x and positive z direction and continues to do so until the right hand starts to move. These increases in centre of mass velocity are achieved through a number of joint angular changes.

The angular changes in the legs, specifically right hip adduction and knee flexion, act to displace the hips to the right, which is counteracted by the left arm primarily. Supination of the left elbow acts to consolidate support on the left hand hold as the left shoulder is decreasing in elevation and the left elbow flexing. The action of the left arm is aided when the right shoulder angle of elevation plateaus, which combined with the plane of elevation decreasing acts to move the trunk leftwards.

At 66%PMT the left ankle starts to extend, closely followed by extension and adduction in the left knee. The extension in the left leg has the effect of increasing displacement upwards. However the actions of the left leg also try to displace the centre of mass rightwards. The plateau in the angle of elevation in the right shoulder counteracts the actions of the left leg in this respect. As the angle of elevation in the right shoulder is fixed, the decrease in the plane of elevation and the internal rotation of the upper arm act to redirect the movements of the left leg in the y direction into movement in the z direction.

At 82%PMT the right shoulder angle of elevation begins to decrease, which coincides with the right knee starting to extend. This confirms the role of the right shoulder in preventing the displacement to the right from the actions of the left leg. The right knee extension now counteracts the lateral effect on the whole body centre of mass of extending the left leg. Similarly the extension in the left leg counters the effect of the right knee extension in trying to displace the centre of mass leftwards. At the same time the right knee starts to extend the left wrist starts to adduct, presumably to help counter the action of the right knee.

The initial movement of the whole body centre of mass to the left in the TE technique, is due to the right hip internally rotating and adducting from its initial abducted position. The right shoulder plane of elevation increases in angle, which counters the effect of the hip movement at moving the centre of mass in a negative y direction. The combined effect of the shoulder and hip joints is to move the centre of mass away from the wall. As the thigh segment is not at right angles to the pelvis, the adduction motion of the thigh will also start to move the centre of mass upwards.

At 40% PMT there is an increase in the degree of inversion in the left ankle, indicating opposition to the centre of mass displacement to the left and away from the wall. Right ankle extension and internal rotation in the left shoulder with a decrease in the plane of elevation displace the centre of mass to the right (at 56% PMT) and inwards towards the wall (at 59% PMT).

Displacement of the centre of mass inwards is enhanced by the plane of elevation at the right arm ceasing to increase and starting to decrease at 68% PMT. Following the change in direction of the plane of elevation in the right arm, the right ankle stops extending and starts flexing as the left hip starts to extend. The extension of the hip maintains the displacement of the centre of mass in the z direction and increases the displacement in the y direction. However the movement of the centre of mass in the y direction by the left hip is moderated by the movement at the right shoulder. As the right upper arm rotates back relative to the trunk, the arm starts to internally rotate and the wrist abducts.

At 77%PMT the right ankle externally rotates and both knees start to extend. The angle of elevation in the right shoulder now starts to decrease, as the body is moved upwards and to the right. At the same time the right hip is recruited in extension. The left shoulder elevation angle starts to decrease and the left wrist begins abduction and hyper-extension. The left ankle now extends.

At 89%PMT the centre of mass velocity in the y direction reaches a peak. The movement of the centre of mass in the y direction seems to be mainly due to the actions of the left leg. The arms are characterised by angular changes at the shoulders, the elbows remain fixated until the end of phase 3. The role of the arms appears to be moving the centre of mass towards the wall, through the decrease in plane of elevation, and vertically upwards through the decrease in the angle of elevation.

Phase 4 is characterised by the reaching movement of the right hand. As such the climber now has a tripedal support posture with which to control the centre of mass. The coordination of the reaching arm is discussed in detail later (section 5.12.8). In this section the movements of the limbs in contact with the wall will be considered in relation to the centre of mass motion.

All the techniques demonstrate similar centre of mass motion, upwards and inwards during phase 4. Due to the loss of support by the right hand, the velocities in the upwards and inwards directions decrease throughout the phase. In the IE and TE the x velocity becomes positive late in the phase, thus the centre of mass starts to move away from the wall in these techniques.

All three techniques move the centre of mass to the right in phase 4, however, the OE technique delays the movement until 19%PMT. In the TE the velocity in y direction decreases just prior to removal of the right hand and in the IE technique the y velocity essentially plateaus at an elevated level for the whole phase. This suggests that the right hand played a role in moving the centre of mass laterally in the TE and IE techniques, prior to hand movement. The velocity data in the OE technique demonstrates that the right hand did not influence the lateral centre of mass movement in the later stages of phase 3, supporting the notion that the left leg extensions are counteracted by the extension of the right knee, as described earlier.

When the right hand starts to move in the IE technique, the left leg has the ankle extending, internally rotating and inverting, the knee is externally rotating, adducting and extending while the hip is adducting and extending. The left leg is pushing the body upwards, to the right and in towards the wall. The right leg, however, acts to oppose the actions of the left leg by pushing the body leftwards. The right ankle remains invariant in flexion and inversion, only internally rotating. The right knee is externally rotating, adducting and extending while the right hip extends, adducts and externally rotates. The actions of the right leg cooperate with the left to move the centre of mass up and inwards.

At the onset of phase 4 the left shoulder shows a decrease in the plane of elevation, an increase in the magnitude of elevation and internal rotation. The left elbow is pronating and flexing with the wrist hyper-extending and abducting. So the actions of the left arm are move the elbow up and away from the wall and pull the body inwards. The abduction in the wrist with the pronation in the elbow and opening of the shoulder joint suggest the left arm is also acting to oppose the movement of the torso in a negative y direction but is not actively pushing the torso to the left. The plane of elevation in the left shoulder is negative at the start of phase 4, and becomes increasingly so until 54%PMT, so the increasing elevation in the shoulder joint acts to move the elbow up and back, not move the torso rightwards.

In phase 4 a number of joint rotations change continuously throughout the phase. In the left leg, the ankle extends and internally rotates while the left knee extends and externally rotates and the hip adducts and extends. In the right leg, the right hip adducts and the knee extends. The right hip extends for the majority of phase 4, only starting to flex at 96%PMT. The right ankle stays in a constant position of inversion for the whole of phase 4. The left elbow also pronates for entire phase. Initially the extensions of the right hip and knee, from onset to the start of phase 4, are greater than the extensions of left leg. Thus the actions of the right knee act to slow the movement of the centre of mass in the y direction. The decrease in velocity is evidenced at 9% of phase 4. To counteract the action of the right leg the left hip starts to internally rotate at 5% of phase 4. The effect of the left hip internal rotation is to increase the velocity to the right at 36%PMT. The internal rotation of the left hip is moderated by the right ankle starting to extend at 9%PMT. At the same time the right arm is moving towards the target hold through increased elevation in the right shoulder and extension of the right elbow.

The knees both stop adducting early into phase 4 but remain essentially unchanged throughout the phase. After a quarter of phase 4's total movement time, the action of the left arm changes.

The elbow starts to extend while the angle of elevation in the shoulder decreases. This acts to push the torso rightwards. The change in the arm function occurs as the plane of elevation in the right shoulder starts to increase.

Mid-way through phase 4 the left arm makes further angular changes, the wrist stops hyper-extending and starts adducting while the shoulder joint shows external rotation and increase in the plane of elevation. At the end of phase 4 the centre of mass starts to move away from the wall. This movement is probably caused by the increase in plane of elevation in the left shoulder joint initially, followed by the right hip and knee stopping externally rotating. The right hip stops extending late in the phase, which accounts for the z displacement peak of the centre of mass at 99% of phase 4.

At the start of phase 4, in the OE technique, the left ankle is inverting, internally rotating and extending, providing a solid support for the left leg to apply forces to the foot hold. The left hip extends and internally rotates but is fixed in adduction until 10%PMT. The actions at the hip and ankle mean that the knee has to externally rotate and adduct while extending.

In the right leg, the ankle is externally rotating, everting and fixed in terms of flexion. At first this would not appear to constitute a firm base for the right leg to apply forces, but the right foot is now orientated so that the outside edge of the foot is on the foothold. So the right foot has to roll onto the outside of the foot, through externally rotating and everting. In order to provide a stable support the right foot has to lock in flexion/extension. It is therefore left to the right hip and knee to extend. The right hip initially externally rotates and adducts but quickly starts to abduct, at 3% PMT. The right knee also abducts and externally rotates.

The extensions in the hips and knees and left ankle continue throughout the whole of phase 4 as does the left ankle internal rotation, left knee external rotation, right ankle eversion, right knee abduction and right hip external rotation. The actions of the legs act to elevate the whole body centre of mass throughout phase 4 and rotate the pelvis counter-clockwise, so that the hips turn to face the wall.

In the left arm the wrist is hyper-extending and adducting, the elbow is flexing and supinating while the plane of elevation in the shoulder continues to decrease. The elevation angle between the upper arm and the trunk decreases and the upper arm continues to internally rotate. The action of the left arm is therefore to keep moving the centre of mass towards the wall and help the right leg to counteract the lateral movement effect of the left leg extension.

At 19% PMT the centre of mass begins to displace rightwards again. However, the main angular changes only occur in the right arm. It may be that the right leg and left arm can not compensate for the action of the left leg and thus the extensions in the joints in the left leg now initiate the movement of the centre of mass. Certainly the angular changes in the left leg are greater than in the right; the left knee has an angular change in extension of 25° whereas the right knee only extends 15° and the left hip undergoes greater hip extension than the right, 15° and 9° respectively. The displacement of the right arm mass will also help to move the whole body centre of mass in the positive y direction.

At 38%PMT the left elbow starts to pronate and then extend as the plane of elevation in the left shoulder beginning to increase again. The action of the left arm is now to slow the movement of the centre of mass inwards towards the wall and increase the movement to the right. At the same time the left ankle plateaus in terms of inversion/eversion. This could indicate a decrease in the role of the leg in lateral centre of mass movement.

Towards the end of phase 4 there is fixation of movement in the left wrist and in the left shoulder in terms of internal rotation. The left knee also starts to abduct and the right ankle to internally rotate. At the same time the velocity of the centre of mass in the y direction decreases.

The right ankle is fixed in eversion/inversion at the start of phase 4 in the TE technique. The left hip is fixed in adduction and both the elbows are fixed in pronation. The left elbow remains fixed for the whole phase. The left hip, knee and ankle extend for the whole of the phase with the ankle internally rotating and the knee externally rotating. The right knee and hip also extend for most of the phase while the right ankle externally rotates for the entire phase. The right hip continues to adduct until the middle of the phase. Thus the right knee counteracts the movement to the right from the left leg actions.

The left arm shows a decrease in plane of elevation, internal rotation and a closing of the elevation angle at the shoulder in to phase 4. The elbow is flexing and the wrist is hyper-extending and abducting.

Early in the phase the right ankle starts to extend and the left hip starts to adduct. At a quarter of the phase duration the right knee starts to show adduction and internal rotation, in response to the extension and internal rotation of the right ankle. After approximately 40% of the movement phase the left elbow changes from flexing to extending, helping the centre of mass to move to the left. Shortly after, the right ankle stops extending and remains fixed for the duration of the reach. From this point onwards the left knee remains also essentially fixed. The left wrist starts to adduct to accompany the movement of the elbow.

In the middle of the phase, three changes occur, the left ankle starts to move in eversion, the right hip stops adducting and the left shoulder starts externally rotating. The external rotation combines with the increase in shoulder plane of elevation, that begins shortly after, to slow the centre of mass movement inwards. At the same time the left hip stops externally rotating and plateaus and the left ankle starts to move in eversion, which suggests a decrease in the action of the ankle to push the body to the right.

In the last fifth of the phase the velocity of the centre of mass to the right peaks as the left shoulder stops increasing the angle of elevation. The left wrist starts to flex and the right hip stops extending. The right hip also plateaus in external rotation and the knee begins to externally rotate. In the last 10% of the phase, the centre of mass starts to move away from the wall and the right knee starts to flex.

At the end of phase 4 the OE technique has the centre of mass significantly closer to the wall, with a velocity in the direction of the wall. The IE and TE are both moving away from the wall, thus the velocities for these two techniques are significantly greater. Significant differences were demonstrated in the y velocities between the techniques but the exact location of the differences was not detected. Both IE and TE have the same mean velocity, which is greater than the OE velocity. No significant differences were found in the centre of mass position in the y direction at the end of the phase. No significant differences existed between the techniques in terms of vertical velocity. The TE technique did finish the phase significantly higher than both the IE and OE techniques. The OE technique had the lowest vertical centre of mass position.

The grasping of the target hold by the right hand denotes the end of phase 4. The joint rotations in the right arm only differ with technique in the right shoulder elevation, where the IE has greater elevation than the OE technique. The TE technique has an angular value in the middle of the other two techniques value and is not significantly different to either.

The three techniques still significantly differ in the right hip abduction/adduction, hip internal/external rotation and knee adduction/abduction joint rotations. The OE technique has the greatest knee flexion angle of the three techniques, which was shown to be significantly greater than the TE flexion angle and just missed significance with the IE technique. In the IE technique, the right ankle is still in significantly less inversion compared to the other two techniques. The ankle is significantly more internally rotated in the OE compared to the IE but the TE value is not significantly different to either IE nor OE.

In the left leg the hip adduction/abduction joint rotation does not show significant differences between the techniques but the OE technique still has a less abducted angle than the other two techniques. The OE is significantly more flexed and internally rotated at the hip compared to the IE and TE techniques. In contrast to the end of phase 3 the IE and TE techniques are no longer significantly different in terms of hip flexion or internal rotation. In the left knee significant differences exist in the external/internal rotation and flexion/extension joint rotations. The OE technique shows significantly less external rotation than the TE but not the IE. As the mean external rotation value for the IE is greater than the value for the TE, it is suggested that a type II error has occurred and that the OE technique has a significantly lower amount of external rotation compared to both the TE and IE techniques. In the knee flexion values, significant differences were found to exist between the three techniques but the location of these differences could not be found. The OE and TE techniques have the same mean value for knee flexion, whereas the IE has a greater mean value. Therefore it is proposed that the IE has significantly greater knee flexion than the OE or TE techniques. No significant differences between the techniques were shown in the knee abduction/adduction movement range but again the statistical significance effect was only just missed with a reasonable effect size. The pattern of differences between the three techniques is the same as at the end of phase 3, with the OE technique having the least adduction and the IE having the most.

The left ankle only showed significant differences in the amount of inversion/eversion in the joint. The IE technique had the ankle in significantly greater inversion than the OE but the TE was not significantly different to either the OE or the IE. Although not significantly different the IE technique has the least amount of left ankle extension at the end of phase 4.

In the left arm significant differences are shown to exist between the techniques in all the joint rotations except the elbow flexion angle and wrist adduction/abduction angle. In the shoulder joint the IE and TE are not significantly different in any of the joint rotations, it is only the OE technique which differs significantly. Specifically, the OE technique has significantly lower plane of elevation, more elevation and less internal rotation. Significant differences were shown to exist in the elbow int/ext rotation joint but the exact location of these differences could not be ascertained. From the data it would seem that the OE technique has significantly less pronation in the elbow than the other two techniques. The OE also shows significantly less hyper extension in the wrist joint compared to the other two techniques, which do not differ from each other.

5.12.7. Phase 5 Post Reach Adjustment

The purpose of Phase 5 was to maintain the posture having successfully completed the reaching task.

The angular changes and centre of mass motions are described in Figure 5-10, Figure 5-11 and Figure 5-12 for the IE, OE and TE techniques respectively. In phase 5 all three techniques show similar trends in the centre of mass movement. The centre of mass initially moves away from the wall, the least movement being in the OE technique and most in the TE. In the latter two techniques the centre of mass plateaus but in the IE starts to move back towards the wall again. All three techniques continue to displace to the right with the greatest displacement in the IE and least in the OE. The centre of mass also drops at the start of phase 5, except for the OE technique which shows little drop and then plateaus. The IE and OE both increase the centre of mass height again. The greatest velocities in the x and y direction are associated with the TE technique. Vertically the OE technique has the least velocity.

All three techniques show similarities in the joints that continue to move through phase 5. All three techniques show the left elbow extending and the left hip extending. As all three techniques show a shift of the centre of mass to the right, then these joint movements are probably responsible.

In the IE the right arm starts to flex early in the phase slowing the centre of mass velocity away from the wall. As the centre of mass moves to the right the right hip starts to adduct, as the right shoulder plane of elevation increases and the left knee extends. The left knee extension helps to move the centre of mass back upwards. In the middle of the phase there are number of joints that plateau at the same time as the centre of mass stops moving away from the wall.

Early in phase 5, in the OE technique there are a number of joint angle changes which occur closely. The right elbow starts to supinate and flex as the right shoulder internally rotates. The left shoulder angle of elevation increases as the right hip stops flexing. These actions slow the centre of mass movement downwards. A second sequence of changes occurs in the first half of the phase, where the right shoulder angle of elevation decreases and the left ankle starts to extend and evert. These actions help to stop the centre of mass moving away from the wall and downwards. A third sequence occurs at the end of the phase, with the majority of the joint angles plateauing.

In the TE technique there is less grouping of the joint angular changes, with a more continuous change across the phase. The right elbow flexs and supinates early in the phase. The right hip starts to flex while the left knee extends and the right knee flexes. So the centre of mass moves over to the right but moves downwards through the actions of the right leg. Shortly afterwards the right hip starts to extend and oppose this motion. During the first half of the phase the shoulder joints increase the plane of elevation, which contributes to the movement of the centre of mass away from the wall. The second half of the phase is characterised by a plateauing of the joints angular movement.

At the end of phase 5 the body geometries of the climbers continue to have significant differences (Appendix C). There are still significant differences between the three techniques in the right hip abduction/adduction and internal/external rotation and right knee abduction/adduction. The right ankle has significantly more inversion in the TE technique compared to the IE technique. As the OE technique has a greater value of inversion than the TE technique, it is suggested that a type II error might have occurred. The OE is significantly more internally rotated at the ankle than in the IE with the TE having a value between the other two techniques.

In the left leg, the OE has significantly greater flexion and external rotation at the hip than both the IE and the TE techniques. In the knee significant differences were found between the techniques in flexion and external rotation but the locations of the differences could not be found. The left ankle was significantly more extended in the OE technique compared to the IE technique but no significant differences existed with respect to the TE. Significant differences were demonstrated in the inversion of the ankle but again, the location of the differences could not be ascertained but the OE had the lowest value and the IE had the highest.

The OE had significantly greater angle of elevation in the left shoulder than both the IE and TE techniques. Differences in the techniques were shown to be significant in the plane of elevation at the shoulder but not where the differences lay. The OE was significantly less hyper-extended at the left wrist than either the IE or the TE, both of which had similar magnitudes. In the elbow significant differences existed in the pronation angle between the three techniques but the Bonferroni test could not determine where the differences lay.

The only significant differences in the right arm lay in the angle of elevation at the shoulder. The OE technique had significantly less elevation than the IE technique. Neither the OE or the IE were shown to be significantly different to the TE technique.

5.12.8. Right Arm Reaching Movement

Figure 5-13 describes the joint angular changes in the right arm during phases 3, 4 and 5. In phase 3 different magnitudes of joint rotation can be clearly seen between the three techniques. At the end of phase 3, significant differences were shown to be in the shoulder elevation angle, shoulder internal rotation and elbow flexion (Appendix C). More specifically, the IE has the greatest right arm elevation and external rotation. The OE has the least shoulder elevation and least external rotation but the most elbow flexion. Although not found to be significant the OE also has the most negative plane of elevation in the shoulder compared to the other two techniques, both of which have the right arm in a plane of virtually pure abduction.

During phase 4 the angular rotations in each technique converge, so that by the end of phase 4 the only significant differences lie in the elevation angle of the shoulder. Figure 5-13 clearly shows that the pattern of angular change in the right arm, during the arm reach is the same. The upper arm elevates and externally rotates, while the elbow extends and pronates. For the first fifth of phase 4 the upper arm rotates backwards relative to the torso. At this point, although remaining negative for the rest of the movement, the plane of elevation increases again. The movement of wrist is shows a specific coordination with the elbow and shoulder. Through the reaching motion the wrist movement changes its phase relationship with the other two joints. The first 10% of phase 4 the wrist hyper extends and abducts, the wrist then adducts and hyper extends until a third of the phase where the wrist starts to flex. The wrist continues to flex to the end of the reaching motion but just before 60%PMT the wrist begins to abduct again. The abduction movement of the wrist at the end of phase 4, rotates the hand so that the fingers will be above the target hold and thus able to grasp the hold.

com(x)	displ (m)	increase	decrease				
		0.032	-0.006				
com(y)	displ (m)	increase					
		0.074					
com(z)	displ (m)	decrease	increase				
		-0.02	0.01				
com(x)	vel (ms^{-1})	inc pos	decrease pos	inc neg	dec neg		
		0.03	-0.05	-0.02	-0.01		
com(y)	vel (ms^{-1})	decrease positive					
		-0.10					
com(z)	vel (ms^{-1})	inc ne	dec neg	inc pos	decrease pos		
		-0.05	0.06	0.01	-0.01		
lankle	Z	ext					
lhip	Z	ext					
rankle	x	plat					
rknee	x	plat					
rknee	y	int rot					
lelbow	Z	ext					
lshoulder	x	elevation					
lankle	y	i	ext rot				
lhip	y	i	ext rot				
relbow	Z	e	flex				
rwrist	x	ab	add				
lknee	x	abd	plat				
rhip	x	ad	abd	add			
lankle	x	plat	ever				
lknee	y	er	ir	plat			
rshoulder	Y	dec p	inc p				
lknee	Z	ext	flex	ext			
rankle	y	pl	ext rot	plat			
rankle	Z	flex	plat				
lwrist	Z	plat	flex	ext	plat		
lhip	x	add	abd	plat			
lelbow	y	int rot	plat				
lshoulder	y	ext rot	plat				
rknee	Z	flex	ext	flex	ext	flex	
rwrist	Z	f	ext	flex			
rhip	y	int rot	ext rot	plat			
rshoulder	x	open	close	plat			
rhip	Z	flex	ext	flex			
lshoulder	Y	inc p	dec p	ip			
relbow	y	pn	sup	pl			
rshoulder	y	er	int rot	pl			
lwrist	x	add	abd	add	abd	add	pl
		0%	Phase 5	100%			

Legend	
	Positive displacement
	Negative displacement
	No displacement
	Positive change in velocity
	Negative change in velocity
	No change in velocity
com(x)displ(m)	Centre of mass, displacement x direction , metres
com(y)displ(m)	Centre of mas s, displacement y direction, metres
com(z)displ(m)	Centre of mass,displacement z direction, metres
com(x) vel(ms^{-1})	Centre of mass - velocity in x direction, metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in y direction, metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in z direction, metres per second
inc	Increase
dec	Decrease
pos	Positive
neg	Negative
flex or f	Joint rotation in direction of flexion
ext or e	Joint rotation in direction of extension
add	Joint rotation in direction of adduction
abd	Joint rotation in direction of abduction
int rot or ir	Joint rotation in direction of internal rotation
ext rot or er	Joint rotation in direction of external rotation
plat or pl	No joint rotation
inc p or ip	Increase in plane
dec p or dp	Decrease in plane
pron or pr	Pronation
sup	Supination
inv	inversion
eve	eversion
Z	Rotation about Flexion/Extension Axis
x	Rotation about Adduction/Abduction Axis
y	Rotation about Internal/External Axis
Y	Plane of Elevation
l	Left
r	Right
Joints are listed in order of movement	

Figure 5-10 Inside edge phase 5:
patterns of joint angular changes and centre of mass displacement and velocity changes


com(x)	displ (m)	increase	plateau			
		0.022	0.000			
com(y)	displ (m)	increase				
		0.054				
com(z)	displ (m)	decrease	plateau			
		-0.050	0.000			
com(x)	vel (ms^{-1})	inc pos	decrease pos			
		0.07	-0.07			
com(y)	vel (ms^{-1})	inc pos	decrease pos			
		0.01	-0.07			
com(z)	vel (ms^{-1})	d	inc neg	dec neg	increase pos	decrease pos
	-0.04	-0.03	0.03	0.01	-0.01	
relbow	Z	flex				
lknee	y	e	plateau			
rshoulder	y	er	int rot			
relbow	y	pr	sup			
lshoulder	x	cl	open			
rhip	Z	fle	plat			
lankle	y	ir	ext rot			
rknee	x	add	plat			
lankle	x	plat	eve			
lankle	Z	plat	ext			
rknee	y	ext rot	int	plat		
lknee	x	abd	add	plat		
rshoulder	x	open	close			
lwrist	Z	flex	ext	flex	plat	
lhip	x	add	abd	plat		
rshoulder	Y	dec p	plat	ip	plat	
rankle	Z	ext	plat	flex		
rhip	y	er	int rot	ext rot	plat	
rankle	y	int rot	ext rot	plat		
rwrist	Z	ext	flex	ext	plat	
rhip	x	abd	plat	add		
rknee	Z	flex	ext	plat		
rankle	x	eve	plat			
lelbow	y	pron	sup	pr	pl	
rwrist	x	abd	add	pl		
lknee	Z	ext				
lhip	Z	ext				
lhip	y	ext				
lshoulder	Y	inc p				
lshoulder	y	ext rot				
lelbow	Z	ext				
lwrist	x	plat				
		0%	Phase 5	100%		

Legend

	Positive displacement
	Negative displacement
	No displacement
	Positive change in velocity
	Negative change in velocity
	No change in velocity
com(x)displ(m)	Centre of mass, displacement x direction , metres
com(y)displ(m)	Centre of mas s. displacement y direction. metres
com(z)displ(m)	Centre of mass.displacement z direction. metres
com(x) vel(ms^{-1})	Centre of mass - velocity in x direction. metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in y direction. metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in z direction. metres per second
inc	Increase
dec	Decrease
pos	Positive
neg	Negative
flex or f	Joint rotation in direction of flexion
ext or e	Joint rotation in direction of extension
add	Joint rotation in direction of adduction
abd	Joint rotation in direction of abduction
int rot or ir	Joint rotation in direction of internal rotation
ext rot or er	Joint rotation in direction of external rotation
plat or pl	No joint rotation
inc p or ip	Increase in plane
dec p or dp	Decrease in plane
pron or pr	Pronation
sup	Supination
inv	inversion
eve	eversion
Z	Rotation about Flexion/Extension Axis
x	Rotation about Adduction/Abduction Axis
y	Rotation about Internal/External Axis
Y	Plane of Elevation
l	Left
r	Right

Joints are listed in order of movement

Figure 5-11 Outside edge phase 5:
patterns of joint angular changes and centre of mass displacement and velocity changes

com(x)	displ (m)	increase	plateau				
		0.043	0.000				
com(y)	displ (m)	increase					
		0.069					
com(z)	displ (m)	decrease	increase				
		0.016	0.007				
com(x)	vel (ms^{-1})	inc pos	dec pos	inc neg	dec neg		
		0.1	-0.13	-0.02	0.01		
com(y)	vel (ms^{-1})		inc pos	decrease pos			
			0.01	-0.11			
com(z)	vel (ms^{-1})	inc neg	dec neg	inc pos	dec pos		
		-0.06	0.06	0.01	-0.01		
rshoulder	y	er	int rot				
relbow	y	pr	sup				
lankle	y	ir	ext rot				
lknee	y	ext rot	plat				
rknee	y	ext rot	int rot				
rankle	y	er	int rot	er	plat		
rhip	Z	plat	flex	ext			
rshoulder	x	open	close				
lknee	Z	ext	plat	ext			
rknee	Z	flex	ext	plat			
lwrist	x	add	abd	plat			
lshoulder	Y	inc p	pla	inc p			
rankle	x	eve	plat				
lhip	x	add	abd	plat			
lhip	y	ext rot	plat				
rwrist	x	abd	add	plat			
rankle	Z	flex	ext	plat	flex	plat	
rshoulder	Y	dec p	inc p	plat			
lwrist	Z	flex	ext	flex	ext	plat	
rknee	x	abd	plat	add	plat	ad	plat
rwrist	Z	ext	plat				
lankle	Z	ext	flex	ext	plat		
lankle	x	eve	plat				
lelbow	y	plat	pron	plat			
lknee	x	abd	add	abd	plat	abd	
rhip	y	pl	int rot	ext rot	plat		
lshoulder	x	plat	open	plat			
relbow	Z	x	flex	plat			
lhip	Z	ext					
rhip	x	plat					
lshoulder	y	ext rot					
lelbow	Z	ext					
		0%	Phase 5	100%			

Legend	
	Positive displacement
	Negative displacement
	No displacement
	Positive change in velocity
	Negative change in velocity
	No change in velocity
com(x)displ(m)	Centre of mass, displacement x direction , metres
com(y)displ(m)	Centre of mas s, displacement y direction, metres
com(z)displ(m)	Centre of mass,displacement z direction, metres
com(x) vel(ms^{-1})	Centre of mass - velocity in x direction, metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in y direction, metres per second
com(y) vel(ms^{-1})	Centre of mass - velocity in z direction, metres per second
inc	Increase
dec	Decrease
pos	Positive
neg	Negative
flex or f	Joint rotation in direction of flexion
ext or e	Joint rotation in direction of extension
add	Joint rotation in direction of adduction
abd	Joint rotation in direction of abduction
int rot or ir	Joint rotation in direction of internal rotation
ext rot or er	Joint rotation in direction of external rotation
plat or pl	No joint rotation
inc p or ip	Increase in plane
dec p or dp	Decrease in plane
pron or pr	Pronation
sup	Supination
inv	inversion
eve	eversion
Z	Rotation about Flexion Extension Axis
x	Rotation about Adduction Abduction Axis
y	Rotation about Internal External Axis
Y	Plane of Elevation
l	Left
r	Right
Joints are listed in order of movement	

Figure 5-12 Toe edge phases 5:
patterns of joint angular changes and centre of mass displacement and velocity changes

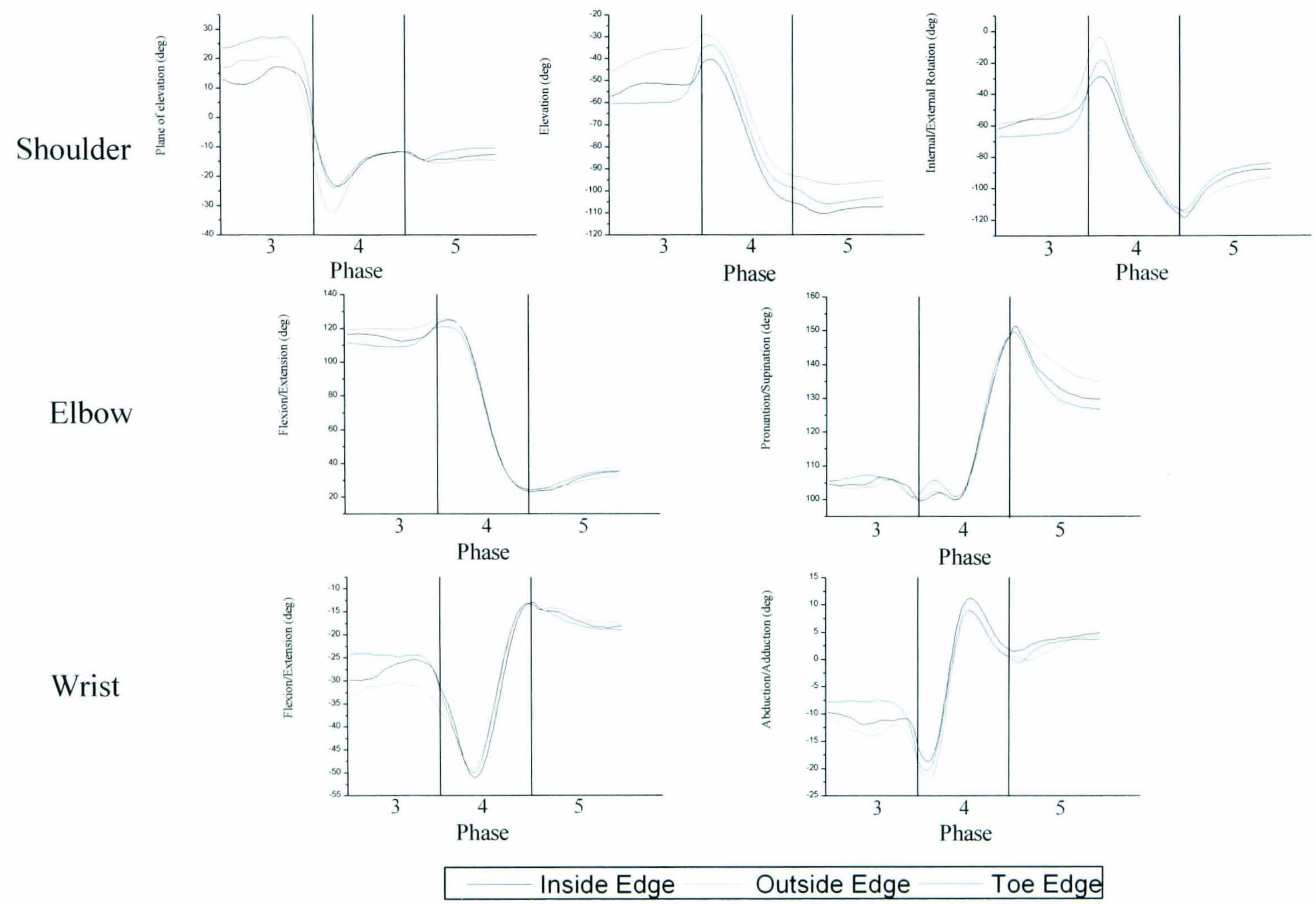


Figure 5-13 Joint angular changes in the right arm in each technique during phases 3, 4 and 5

There are initial differences in magnitude, particularly in the plane of elevation and internal rotation in the shoulder, early in the phase. Even when there are differences in magnitude of joint rotation, the temporal characteristics between the three techniques are very similar, for example in wrist abduction/adduction and shoulder elevation.

In phase 5 the joint rotations follow similar patterns within each technique. The greatest angular changes occur in external rotation of the upper arm and supination at the elbow joint. At the end of phase 5, only the shoulder angle of elevation is significantly different between the techniques. Figure 5-13 demonstrates that the different techniques move the right arm into different orientations prior to the start of the hand reach. However the techniques do not produce different final arm postures. More so, the use of a particular technique does not change the way in which the reaching arm coordinates the joint degrees of freedom (the coordinative structure) to perform the movement. As has been previously discussed, however, the use of a technique does change the joint rotations in the rest of the body, with the centre of mass in significantly different positions. These differences are accommodated by the coordinative structure in the reaching arm through the angle of elevation in the shoulder joint.

Previous work by Bourdin et al. (1998, 1999) found that postural constraints changed the organisation of the reaching arm. Therefore a possible conclusion from the results of this study is that the postural constraints are not changed with technique. This conclusion does not seem reasonable however. The techniques have been shown to imply different body geometry's on the climbers. The displacement of the limbs and the change in body geometry, perturb balance (Testa et al., 1999). The result of the changing body postures was significant differences between the techniques in terms of centre of mass displacement. The role of anticipatory postural adjustments in minimising the balance perturbations in rock climbing has been confirmed by the work of Testa et al. (1999, 2003). Thus one could postulate that the significant differences in centre of mass position resulting from different techniques will have different perturbations to the climbers balance and that therefore there will be different postural constraints associated with each technique. If this were the case, then the results of this study would seem to contradict the work of Bourdin et al. (1998, 1999). A comparison of the techniques in terms of postural requirements is needed to allow a fully understanding of the role of technique in organising arm reaches.

5.12.9. Joint Sequences in the Legs

Clear proximal-distal sequences were found in all three techniques in the joint extensions in the legs. In the IE technique both the left and right leg show extension of the hips prior to extension of the knees. The timing of the activation in the hip and knee joints were synchronised across the limbs. In the TE technique the left leg demonstrated a proximal-distal sequencing in joint extensions from the hip through to the ankle. In the right leg no proximal-distal sequencing was demonstrated, the right knee, however, did start to extend at the same time as the left knee. The OE technique showed proximal-distal sequencing in the right hip and knee for joint extensions. No proximal-distal sequencing was observed in adduction. Proximal-distal sequencing in external rotation was found in the left leg for both IE and OE techniques and in the right leg for the IE technique.

Table 5-2 Leg joint activations in phase 3 prior to the right hand reach

		% Phase Movement Time				% Phase Movement Time		
	Left	Z	x	y	Right	Z	x	y
	Hip	95	87	13	Hip	95	70	90
IE	Knee	99	85	55	Knee	99	92	91
	Ankle	75	-	60^{ir}	Ankle	62	-	61^{ir}
	Hip	81	25^{p}	0	Hip	0	0	67
OE	Knee	67	67	35	Knee	83	90^{ab}	0
	Ankle	66	-	0	Ankle	75^{f}	-	73
	Hip	71	111	97	Hip	108	20	81
TE	Knee	77	77	84	Knee	77	26^{ab}	20
	Ankle	83	-	61	Ankle	71^{f}	-	77

^{f} flexion ^{ir} internal rotation ^{p} plateau ^{ab} abduction

Proximal-distal coordination in joint angles in the legs has been observed in vertical jumping, where the goal is maximal vertical velocity on take-off (Bobbert & van Ingen Schenau, 1988). A consistent finding has been the initiation of the hip joint prior to the more distal joints (Bobbert & van Ingen Schenau, 1988; Rodacki et al., 2001; van Ingen Schenau, 1989). The complete proximal-distal sequencing of hip-knee-ankle is not such a robust finding, for instance a mixture of hip-knee-ankle and hip-ankle-knee strategies have been reported in studies of Rodacki et al. (2001) and Rodacki & Fowler (2001). The mechanism for proximal-distal sequencing has been shown to involve the activation of the biarticular muscles: rectus femoris, semitendinous and gastrocnemious lateralis (Bobbert & van Ingen Schenau, 1988; van Ingen Schenau, 1989; Jacobs et al., 1996; Prilutsky & Zatsiorsky, 1994, Rodacki et al., 2001). The action of the biarticular muscles allow efficient transfer of the rotational movements of the body segments into translational displacement of the centre of mass, through a proximal-distal transfer of power (Jacobs et al., 1996).

The results of this study showed that the TE technique produced the greatest vertical velocity, significantly greater than the OE technique, which produced the lowest peak vertical velocity at the end of phase 3. The vertical velocity in the TE technique is attributed to the use of a complete proximal-distal sequence through the left leg with synchronised extension in the right knee joint. The IE technique demonstrated a vertical velocity greater than the OE but less than the TE, although the differences were not significant. The lower vertical velocity in the IE technique is explained by the limited proximal-distal sequencing, just hip-knee, in the legs, even though temporal sequencing was synchronised in both legs.

In contrast to the other two techniques, the OE knee joints were not synchronised. In the OE technique the coordination appears to be a right knee-left hip synchronisation. The role of the right knee in counteracting the lateral movement effects of the left leg extensions has already been previously discussed.

5.12.10. Joint Reversals

The number of joint reversals associated with each technique in each phase of the movement are presented in Tables 5-3, 5-4 and 5-5.

The greatest number of joint rotations for whole-body over the entire reaching task were made in the IE technique. The least joint rotations occurred in the TE technique but in this technique phases 1 and 2 did not occur. Even though phase 3 existed for the TE technique, this phase consisted solely of preparation for the hand movement whereas in the IE and OE techniques phase 3 consisted of post foot re-orientation adjustments and preparatory movements. If the last two phases are considered then the TE actually had the highest total number of joint reversals.

Over the whole reaching task the majority of the joint reversals occurred in the legs for the OE and TE techniques. In contrast, in the IE technique, the greatest number of joint reversals were made in the upper limbs. Despite the differences in the numbers of joint reversals, the pattern of total joint reversals across the body was similar for both the IE and TE. In the upper limbs the most changes occurred in the wrist and shoulder; in the lower limbs the greatest changes were performed in the hip and ankle. The OE technique, on the other hand, shows a much more even spread of joint reversals across the joints in the upper arms and a more distal bias to the joint reversals in the lower limbs.

Table 5-3 Number of joint reversals in each phase of movement in the inside edge technique

		Phase 1	2	3	4	5	Total
Upper Limb	S	0	2	11	7	8	**28**
	E	0	1	6	4	4	**15**
	W	0	4	7	5	11	**27**
	Total	**0**	**7**	**24**	**16**	**23**	**70**
Lower Limb	H	0	0	8	3	9	**20**
	K	0	3	8	5	9	**25**
	A	0	4	8	4	5	**21**
	Total	**0**	**7**	**24**	**12**	**23**	**66**
Whole Body		**0**	**14**	**48**	**28**	**46**	**136**

Table 5-4 Number of joint reversals in each phase of movement in the outside edge technique

OE		Phase 1	2	3	4	5	Total
Upper Limb	S	0	1	5	7	6	**19**
	E	0	1	7	5	5	**18**
	W	0	0	5	5	8	**18**
	Total	**0**	**2**	**17**	**17**	**19**	**55**
Lower Limb	H	0	1	5	3	8	**17**
	K	0	7	7	1	8	**23**
	A	0	3	8	5	8	**24**
	Total	**0**	**11**	**21**	**9**	**24**	**64**
Whole Body		**0**	**13**	**38**	**26**	**43**	**119**

Table 5-5 Number of joint reversals in each phase of movement in the toe edge technique

TE		Phase 1	2	3	4	5	Total
Upper Limb	S			1	7	8	**16**
	E			0	2	5	**7**
	W			0	8	9	**17**
	Total			**1**	**17**	**22**	**40**
Lower Limb	H			2	4	8	**14**
	K			0	6	15	**21**
	A			1	3	13	**17**
	Total			**3**	**13**	**36**	**51**
Whole Body				**4**	**30**	**58**	92

In the preparatory phase for foot re-orientation no joint reversals occurred for either the IE or OE techniques. In phase 2 both techniques had similar whole-body values for joint rotations. However, in the IE the joint reversals were split between the arms and the legs whereas in the OE technique, the majority of the joint reversals were in the legs, particularly the knees. The greatest numbers of joint reversals in the IE technique occurred in the wrists and ankles.

The OE technique involved less joint reversals in phase 3 than the IE technique. The main differences lay at the shoulder and hip joints. As has already been discussed, phase 3 in the TE technique was solely a preparatory phase for the hand movement, which explains the much lower numbers of joint reversals.

In the reaching phase, all three techniques demonstrated similar amounts of joint reversals in the upper limbs. The majority of the changes occurred in the shoulder joint. In the lower limbs the OE technique involved less joint reversals than the IE and TE techniques. The latter two techniques not only had similar total values but demonstrated a similar pattern of change with the knee joint undergoing the greatest number of changes. In contrast, the knee joint showed the least number of changes in the OE technique. In the OE technique the joint reversals were shifted to the ankle joint.

In phase 5 the OE showed the lowest number of joint changes, with the TE demonstrating the most. The TE and IE had similar amounts of total joint change in the upper limbs. The OE had slightly fewer changes in joint opening in the upper limbs but all three techniques showed the wrists to undergo the greatest number of joint reversals. The TE had a much larger number of joint reversals in the lower limbs. The difference in the TE technique lay in the knees and ankles as the hip joints had comparative levels of joint change to the other two techniques.

Overall the IE technique was the most complex technique to coordinate, as shown by the total number of joint reversals. This technique appeared to be more difficult to control in the upper limbs compared to the other two techniques. The OE and TE show greater complexity in the lower limbs compared to the upper limbs within each technique, but the lower limb complexity is comparable to that of the IE technique. The OE technique was more complex to coordinate in the re-orientation of the foot. Once re-orientated though, the OE technique was less complex to control before, during and after the reaching movement. The OE technique did show patterns of more joint reversals in the ankle in phases 3, 4 and 5, which could suggest more difficult control of the foot support in that technique. In the actual reaching movement phase, the TE was the most complex to coordinate, followed by the IE with the OE the least complex. The main difference existed in the joint reversals in the lower limbs, where the IE and TE showed greater use of the knees.

5.13. Conclusion

The primary goal of this study was to identify kinematic differences in the three rock climbing techniques. Significantly different centre of mass displacement and velocity patterns, both in terms re-orientating the right foot and reaching and grasping a new hold, were identified between the techniques. The different orientations of the foot significantly effected the organisation of the rest of the body. The re-orientation of the foot required different postural strategies, in the moving limb and in the rest of the body. However, despite the different body postures the reaching arm coordination was demonstrated to be stable. A stable final arm posture was identified, with the coordinative structure of the reaching arm adapting to the different body postures through the angle of elevation in the shoulder.

Proximal-distal sequencing in the lower limbs was shown to characterise the IE and TE techniques, but not the OE technique. The change in orientation of the right foot from the IE to the TE technique had the effect of removing the proximal-distal sequencing in the right leg and extending the proximal-distal sequencing from the hip to the ankle in the left leg. The continued rotation of the foot from the TE to the OE technique returned the proximal-distal sequencing in the right leg but removed the sequencing in the left leg and the coinciding knee extensions.

The orientation of the ipsilateral foot impacted upon the complexity of the coordination of the reaching task. The OE showed greater complexity in the re-orientation of the ipsilateral foot but subsequently showed the least complexity in phases 3, 4 and 5.

A detailed analysis of the three techniques has shown that they are identifiably different, both in terms of whole-body centre of mass trajectory and the joint angular kinematics. Two specific conclusions can be drawn. The first is that the orientation of the right foot did not affect the organisation of the reaching arm in any of the three techniques. The second conclusion is that the orientation of the right foot significantly affected the body geometry in the remaining limbs, the temporal sequencing and coordination complexity of the limbs before, during and after the reaching movement.

The effect of foot orientation on the performance of the reaching task now provides the focus for Comparative Study 2.

Chapter 6. Comparative Study 2 – Investigating Effect on Performance

6.1. Introduction

Detailed kinematic descriptions of the three techniques revealed significant differences in the whole-body centre of mass motion and body geometry for the performance of a hand reach. The orientation of the ipsilateral foot induced significant changes in the way the climbers organised their bodies; however, the actual organisation of the reach was remarkably invariant. Comparison Study 1 thus confirmed that differences existed in the techniques and provided the descriptive analysis of the climbing techniques in performing a hand reach. Technique analysis is not only descriptive, but has an analytical goal in how effective the techniques are (Lees, 2002). The purpose of this second study is, therefore, to compare the effectiveness of the three techniques in terms of stability maintenance, movement efficiency and bio-energetic efficiency.

The original intention was to use the kinematics of the reaching arm as an indicator of difficulty of postural stability, as Bourdin et al. (1999) and Nougier et al. (1993) had both demonstrated that the kinematics of the end effector (the reaching hand) were affected by postural difficulty. However, the findings of Comparison Study 1 demonstrated invariance in the final arm posture and the co-ordinative structure of the reaching arm. Therefore, no significant differences would be expected in the kinematics of the end effector. Accordingly, the work of Bourdin et al. (1999) and Nougier et al. (1999) would suggest that no postural differences existed between the three techniques. Bourdin et al. (1999) proposed that climbers did not adjust the reaching aspects of the prehension task, but delayed adjustments until contact with the hold was made. Thus the characteristics of the reaching hand were a shorter deceleration phase and a high impact velocity, where the target hold was used as a mechanical stop.

Comparison Study 1 identified that the whole body centre of mass remained outside the functional base of support in all three techniques. Therefore there is a body weight (BW) moment acting on the climber, about both the x and y axes. The BW moment must be counteracted by the reaction forces at the hand and footholds in order for the climber to maintain equilibrium, as shown in Noé et al. (2001) and Quaine & Martin (1999). As the variability of the body weights of the climbers was consistent for each technique, since all the climbers performed all the techniques from the same start position, the BW moments were proportional to the displacement of the centre of mass along the x and y axes. The displacement of the centre of mass along the x and y axes will be reinterpreted in this study as indicators of the magnitude of the BW moment that the hands and feet have to counteract and thus an indication of the postural demand.

Comparison Study 1 also demonstrated that the body geometries in each technique were significantly different. Changes in body configuration alter the whole body moment of inertia

(MOI) about selected axes (Zatsiorsky, 2002). MOI is the resistance of the body to change in angular motion. As rock climbing is quasi-static, it could be argued from Newton's Second Law (Equation 6-1) that as the change in angular acceleration is small then the moment of inertia will have little influence on the difficulty of maintaining posture on the climbing wall.

$$T = I\alpha \qquad \textbf{Equation 6-1}$$

where T is the amount of torque, I is moment of inertia and α is angular acceleration

Consider the situation in Figure 6-1.

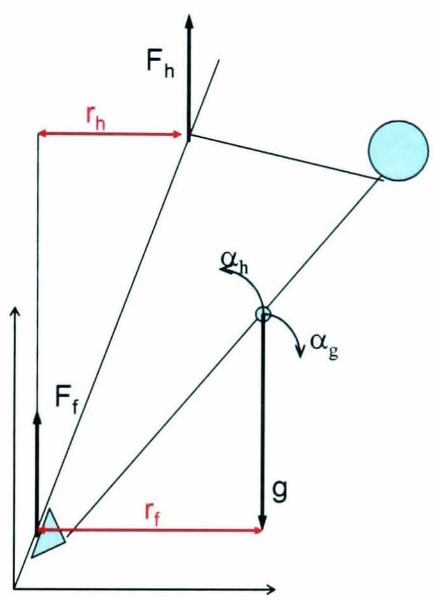


Figure 6-1 Free-body diagram of a rock climber on an overhanging wall

Gravity acts on the climber in a downwards direction at the whole-body centre of mass. The climber applies forces to the climbing surface, which in turn applies reaction forces to the climber in an upward direction (Newtons Third Law), preventing vertical collapse. Take moments about the feet. The climber is in static equilibrium, so the sum of the torques must equal zero

$$\sum T = 0 \qquad \textbf{Equation 6-2}$$

The torque due to the forces applied by the hands must be equal and opposite to the torque applied by gravity

$$T_h = -T_g \qquad \textbf{Equation 6-3}$$

where T_h is the torque on the body due to the reaction forces applied at the hands and T_g is the torque on the body due to gravity.

The torque is determined by the amount of force acting at a distance from the turning point, so the torque on the body due to the forces at the hand is

$$T_h = F_h . r_h \qquad \textbf{Equation 6-4}$$

where Fh is the reaction forces applied at the hands and rh is the perpendicular distance from the action line of the reaction force at the hands to the pivot point.

From Equation 6-1, the torque on the body due to gravity is

$$T_g = I\alpha_g$$ **Equation 6-5**

From Equation 6-3 therefore,

$$F_h . r_h = -I\alpha_g$$ **Equation 6-6**

If r_h and α_g remain constant then F_h is proportional to *I*. Therefore MOI can be used as a relative measure of the postural demand. Thus postural demands will be analysed through the interaction of the BW moments and whole body moments of inertia.

Analysis of the climbing competition indicated that successful performances were characterised by climbers making a large number of limb movements, up to a hundred in this particular competition, which utilised a relatively short route. Thus movement efficiency in each limb movement is an important factor in performance on a route. The competition performances suggested a trend that the higher ranked climbers tended to use the OE more and the IE technique less.

Trajectory efficiency has been studied using the concept of geometric entropy by a number of authors (e.g. Cordier et al., 1993; Pijpers et al., 2003, Boshker & Bakker, 2001). Geometric entropy is limited to two-dimensional analyses because of the requirement to calculate the convex hull of the trajectory. In essence, the geometric entropy is simply a ratio of how the trajectory varied relative to the most direct straight line path. Therefore, in order to study the efficiency of the trajectory in three dimensions, it is proposed to use a ratio of the distance travelled by the whole body centre of mass to the displacement vector of the centre of mass from the start to the end of movement.

Energetic efficiency is difficult to measure (Winter, 2005) and involves knowledge of the metabolic cost of movement. Estimates of efficiency have used a ratio of the mechanical work done by the muscles to the metabolic cost of the work done by the muscles (Winter, 2005; Caldwell et al., 2000). However, an indication of how efficient the techniques are at performing the hand-reach movement, can be measured through mechanical analysis of the whole body centre of mass motion. Note, this does not give an indication of the amount of energy expended by the musculature within each technique. The reaching task is constrained with a set start position and a set hold to reach to. In order to perform the task successfully, the climbers must move the whole body centre of mass. Thus the technique which allows the task to be performed with least mechanical energy changes to the centre of mass will be energetically superior.

The aims of the study are to compare the effectiveness of the three techniques in terms of a) the postural demands of maintaining stability during the arm reach, b) minimising the perturbations of the movement trajectory and c) minimising the mechanical energetics of the whole body centre of mass in performing successful arm movements.

6.2. Methodology

The experimental set-up, protocol, validation exercises and participants were identical to Comparison Study 1.

6.3. Global Reference Frames

Two global reference frames were defined. The first reference frame, GRS, was defined as in Chapter 5.6. Mechanical analysis measures and trajectory efficiency were calculated in the GRS.

The second reference frame, the Inertial Reference Frame (IRS), was orientated parallel to the climbing wall (Figure 6-2). The origin of the IRS was placed at the left end of the left foothold. The Z axis was parallel to the climbing wall in an upwards positive direction. The X axis pointed in a positive manner outwards, perpendicular to the climbing wall and the Y axis was perpendicular to the Z and the X axes, parallel to the climbing wall pointing positively to the right. Whole-body Moment of Inertia was calculated with respect to the axes of the IRS.

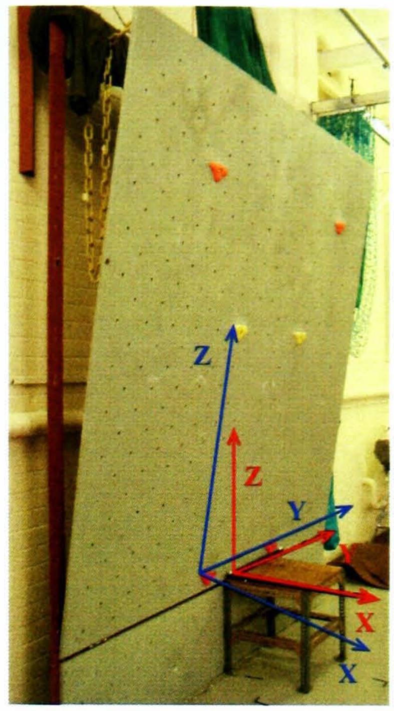


Figure 6-2 ProReflex global coordinate system (red) and the inertial reference system (blue)

6.4. Data Analysis

6.4.1. Work

The work done in each movement phase by the whole body centre of mass was calculated using Equation 4-10 (Chapter 4.2.6). The accumulated work was calculated as the movement progressed by summing the values of work done in each phase sequentially.

6.4.2. Power

The power of the centre of mass in each phase was calculated using Equation 6-7.

$$Power = \frac{dW}{dt}$$ **Equation 6-7**

where dW is the amount of work done by the centre of mass during the phase of movement and dt is the duration of the phase.

6.4.3. Efficiency

Efficiency of the centre of mass was calculated using Equation 4-14 (Chapter 4.5.4.3). Efficiency measures were taken for the whole movement and within each phase.

6.4.4. Whole Body Moment of Inertia

Anatomical coordinate systems are attached to the body segments as defined in Chapter 4.3.2. The anatomical coordinate systems were assumed to coincide with the principal axes of inertia (Zatsiorsky, 2002). The moment of inertia about a segmental principal axis was calculated using the body segment inertia parameters of de Leva (1996) in Equation 6-8.

$$I = mk^2$$ **Equation 6-8**

As the moments of inertia are taken about the principle axes, the tensor of inertia for the segment is presented in a diagonalised form.

$$^{d}[I] = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix}$$ **Equation 6-9**

The orientation and position of the segment i is defined with respect to the IRS by rotation matrix $[R]_i$, and the coordinates of the origin of the anatomical coordinate system (segmental centre of mass) x_i, y_i and z_i. The inertia tensor for segment i relative to the IRS is given by Equation 6-10.

$$^{G}[I]_i = [R]_i [I]_i [R]_i^T + m_i \begin{bmatrix} y_i^2 + z_i^2 & -x_i y_i & -x_i z_i \\ -y_i x_i & x_i^2 + z_i^2 & -y_i z_i \\ -z_i x_i & -z_i y_i & x_i^2 + y_i^2 \end{bmatrix}$$

Equation 6-10

(Zatsiorsky, 2002)

The tensor of inertia for the whole body about the axes of the IRS is found through summing the individual segments' inertia tensors, $^{G}[I]_i$ (Equation 6-11)

$$[I]_{body} = \sum_i {}^{G}[I]_i = \sum_i [R]_i [I]_i [R]_i^T + \begin{bmatrix} \sum_i m_i(y_i^2 + z_i^2) & -\sum_i m_i x_i y_i & -\sum_i m_i x_i z_i \\ -\sum_i m_i y_i x_i & \sum_i m_i(x_i^2 + z_i^2) & -\sum_i m_i y_i z_i \\ -\sum_i m_i z_i x_i & -\sum_i m_i z_i y_i & \sum_i m_i(x_i^2 + y_i^2) \end{bmatrix}$$

Equation 6-11

(Zatsiorsky, 2002)

The analysis of the rock climbing movement is three dimensional in nature, thus both the moments of inertia and the products of inertia in the inertia tensor must be taken into account (Zatsiorsky, 2002). In order to study the tendency of the body to rotate about the axes of the IRS, the principal moments of inertia about the IRS axes need to be calculated. The principal moments of inertia are the eigenvalues of the inertia tensor (Zatsiorsky, 2002). The eigenvalues of a matrix are found through solving the characteristic equation of the matrix (Jeffrey, 1979). Therefore,

$$\begin{vmatrix} I_{XX}-\lambda & -I_{XY} & -I_{XZ} \\ -I_{YX} & I_{YY}-\lambda & -I_{YZ} \\ -I_{ZX} & -I_{ZY} & I_{ZZ}-\lambda \end{vmatrix} = 0$$

Equation 6-12

where λ is the eigenvalue. Solving equation 6-12 results in three values of λ, representing the three principal moments of inertia.

6.4.5. Reaching Hand Kinematics

The displacement of the right hand centre of mass was differentiated twice, using double finite difference technique, to obtain velocity and acceleration time profiles. Resultant velocity and accelerations were found by calculating the magnitude of the velocity and acceleration vector at each time point. The following dependent measures were derived from the kinematic data: maximum velocity (ms^{-1}), time to maximum velocity (s), impact velocity (ms^{-1}), maximum and minimum accelerations (ms^{-2}), time to maximum and minimum accelerations (s), duration of acceleration and deceleration phases (s) and the ratio of duration of acceleration phase to deceleration phase.

6.5. Data Reduction

Data reduction on the principal moment of inertia data was performed as in Chapter 5.10. No time normalisation was required for efficiency, work, power and hand velocity and accelerations.

The work done, power and efficiency variables were calculated in each movement phase for every trial by the participants. Each technique was performed three times. The average of the three trials was taken, to produce a single representative data set of each technique per participant. These representative trials were averaged to produce representative sets of data for each technique across the group.

A similar data reduction method was performed on the right hand centre of mass measures, but only during phase 4 (the reaching phase).

6.6. Statistical Analysis

Repeated Measures ANOVA and Within Subjects T-Tests were used to compare the techniques upon the performance measures, in the same way as in Chapter 5.11.
The efficiency data were not found to be normally distributed. Therefore, in phases 3 to 5 the three techniques were compared using the Friedman Test. In phases 1 and 2 the IE and OE techniques were compared using the Wilcoxon Test.

6.7. Results

6.7.1. Reaching Hand Kinematics

The three techniques showed the centre of mass of the reaching hand in the OE technique to have significantly lower magnitudes of maximum velocity and acceleration. The Bonferroni post-hoc test could not demonstrate significant differences between the OE and TE with respect to maximum velocity and maximum acceleration, despite the differences between the techniques being the greatest. The OE technique also showed the lowest minimum acceleration, within which measure the techniques were shown to be significantly different, but it did not show where the differences lay. Bourdin et al. (1999) reported greater maximum and minimum acceleration values in more complex posture conditions and that the time to maximum acceleration was greater in the complex condition. The data in this study showed greater values for peak velocity, acceleration and deceleration compared with Bourdin et al. (1999). While differences in the techniques were demonstrated in the magnitude of the peak values, no differences were shown in time to peak velocity, acceleration, or deceleration.

Table 6-1 Mean, standard deviations, P values and Effect sizes for dependent measures of the right hand as a function of technique

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P value	Effect Size
Velocity	Max (ms^{-1})	2.47[a]	0.50	2.21[a,*]	0.51	2.57[*]	0.46	0.046	0.49
	Time to Max vel. (s)	0.18	0.02	0.19	0.02	0.17	0.02		
	Impact Vel. (ms^{-2})	0.08	0.06	0.08	0.09	0.07	0.07	0.758	0.02
Acceleration	Max (ms^{-2})	18.00[a]	5.00	16.00[a,*]	5.00	19.00[*]	5.00	0.049	0.49
	Time to Max accel. (s)	0.09	0.02	0.09	0.02	0.08	0.01		
	Min (ms^{-2})	-15.00[*]	7.00	-12.00[*]	5.00	-16.00[*]	5.00	0.026	0.46
	Time to Min accel.	0.28	0.03	0.29	0.04	0.26	0.03		
	Duration +ve accel (s)	0.18	0.02	0.19	0.02	0.17	0.02	0.130	0.29
	Duration -ve accel (s)	0.28	0.12	0.30	0.09	0.27	0.11	0.188	0.28
	Ratio	0.64		0.63		0.63			

[a] denotes where significant differences lie between techniques $P<0.05$
* denotes possible type II error

No significant differences were shown to exist between the techniques in terms of impact velocity. The impact velocity data demonstrated a minimal hand velocity at the point of contact (region of 0.08ms^{-1}). Bourdin et al. (1999), in contrast, reported impact velocities in the region of 0.12-0.13ms^{-1} for hand reaches in an easy posture and 0.16-0.20ms^{-1} for a complex posture.

The techniques could not be differentiated through temporal aspects of the reaching movement. Bourdin et al. (1999) reported consistent times to maximum velocity and therefore a constant acceleration phase. This study showed similar positive acceleration phase durations for all techniques. The deceleration phase was consistently greater in duration than the acceleration phase for all three techniques. However, the standard deviations show that the duration of this phase was more variable compared to the acceleration phase duration in the group of climbers, with the OE technique showing the least variability. The acceleration:deceleration ratios ranged from 0.63 to 0.64 across the techniques. These values are larger than those reported by Bourdin et al. (1999) for the complex posture condition, but lower than the values for the easy posture. However, the ratios reported by Bourdin et al. (1999) appear to be erroneous. Bourdin et al.'s (1999) data do, however, demonstrate shorter deceleration phase durations compared with the acceleration phase duration, which contrasts with the findings of this study.

The low-impact velocities and longer deceleration phase durations imply that a precision effect was demonstrated by the climbers, in line with prehension tasks studied in conditions without supra-postural constraints (Marteniuk et al., 1987; Zaal & Bootsma, 1993).

6.7.2. Body Weight Moments

The positions of the whole-body centre of mass at the end of each phase are presented in Appendix B. Displacement in the x axis indicates the magnitude of the BW moment about the y axis. Similarly, the displacement in the y direction indicates the BW moment about the x axis. The OE technique had significantly greater BW moment about the y axis at the end of phase 1 and just misses significance at the end of phase 2. At the end of phase 2, the BW moment in the OE technique was greater than in the IE technique. The BW moment about the y axis was significantly greater for the TE technique at the end of phase 3 compared with both the IE and OE techniques. Although the OE BW moment was less than that for the IE technique, the difference was non-significant. About the x axis, the OE technique had a significantly greater BW moment, compared with the other two techniques.

No significant differences between the techniques were found at the end of phase 4 in terms of BW moments about the x axis. About the y axis, the BW moment for the OE technique was significantly lower than that for either the IE or TE techniques. The same pattern in BW moments was seen at the end of phase 5.

6.7.3. Whole Body Moment Of Inertia

The changes in MOI about the axes of IRS are shown in Figures 6-2 to 6-4. Tables 6-2 to 6-4 report the end of phase values and the comparison statistics between techniques.
The starting position showed no significant differences between the techniques in MOI about the x and y axes (Tables 6-2 and 6-3). Significant differences were found for MOI about the z axis (Table 6-4), though the difference in maximum and minimum values in real terms was small, at $0.09 kg.m^2$.

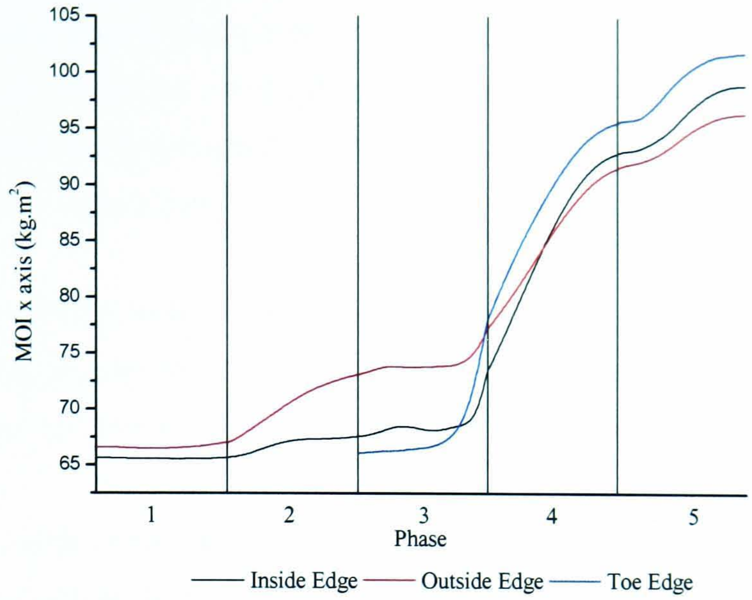


Figure 6-3 Moment of inertia values about the x axes for all three techniques for the whole movement

Table 6-2 Mean, standard deviations, P values and effect sizes for MOI values around the x axis at the start of movement and at the end of each movement phase as a function of technique

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P value	Effect Size
Start		65.66	10.52	66.58	9.91	66.11	9.98	0.214	0.23
End of phase	1	65.67	10.21	67.01	8.80			0.112	0.37
	2	67.58	10.88	73.05	9.40			0.004	0.78
	3	73.21	9.16	77.06	8.20	77.69	9.93	0.060	0.38
	4	92.92	9.65	91.58[a]	10.03	95.67[a]	11.66	0.022	0.47
	5	99.16	15.18	96.58[a]	13.83	102.04[a]	16.01	0.007	0.56

[a] denotes where significant differences lie between techniques P<0.05

Similar trends and magnitudes for MOI were demonstrated in each technique about the x and y axes (Figure 6-3 and 6-4). All three techniques increased the MOI from the start position through to the end of movement. In phases 1 and 2, the OE technique had greater MOI about the x and y axis compared with the IE technique. The difference in MOI about the y axis just missed significance, with a moderate effect size, at the end of phase1. By the end of phase 2, the OE had significantly greater MOI about both axes.

In phase 3, all three techniques maintained a constant MOI until the latter part of the phase, when there was a rapid increase. The TE technique started the phase with the lowest MOI about the x and y axes, but finished it with the greatest values. At the end of phase 3, the TE and OE techniques had similar values for MOI about both x and y axes. The IE technique had lower values about both axes, but the differences just miss being significant, with a small/moderate effect size.

During phase 4, all three techniques increased MOI about the x and y axes. The TE technique maintained the highest values throughout the phase, ending phase 4 with values significantly greater than the OE technique, but not significantly higher with respect to the IE technique. The IE technique ends phase 4, however, with a greater value for MOI about both axes than the OE technique, although not significantly so.

In phase 5, all three techniques showed the same pattern of increase, with the TE technique remaining significantly greater than the OE technique by the end of the phase. The OE technique maintained the lowest values of MOI about the x and y axes throughout the phase.

The MOI about the z axis, in contrast to the values about the x and y axes, had much smaller values in all three techniques. In the first two phases, the OE technique showed little change, +0.02kg.m^2. The IE technique, however, showed a decrease (-0.44kg.m^2) over the two phases, the most rapid being in phase 2 (-0.39kg.m^2). At the end of phase 2, the IE technique had significantly lower values of MOI about the z axis. In phase 3, the MOI values associated with the OE and TE techniques fell and the values in the IE rose, so that there were no significant differences at the end of the phase. All three techniques showed an increase over phase 4. The TE MOI had the largest increase, whereas the OE demonstrated the least, finishing the phase with the lowest values for MOI about the z axis. No significant differences were demonstrated, however, between the techniques at the end of phase 4.

Phase 5 showed the IE increasing in value, the TE remaining essentially constant and the OE decreasing in value. However the three techniques were not significantly different at the end of the movement.

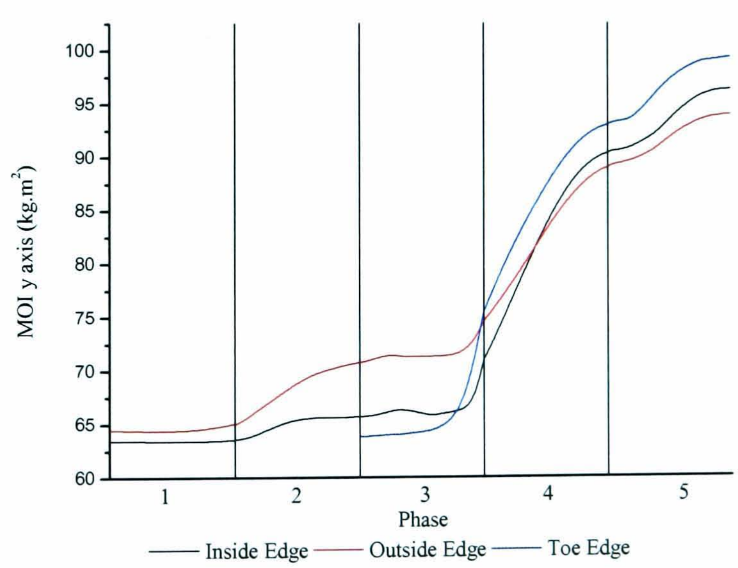


Figure 6-4 Moment of inertia values about the y axis for all three techniques over the whole movement

Table 6-3 Mean, standard deviations, P values and effect sizes for MOI values around the y axis at the start of movement and at the end of each movement phase as a function of technique

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P value	Effect Size
Start		63.48	10.29	64.46	9.72	63.82	9.77	0.159	0.26
End of phase	1	63.54	10.00	65.02	8.55			0.086	0.41
	2	65.70	10.74	70.72	9.10			0.005	0.75
	3	70.71	8.85	74.41	7.91	75.15	9.86	0.063	0.37
	4	90.29	9.48	88.92[a]	9.76	92.96[a]	11.35	0.022	0.47
	5	96.29	14.59	93.87[a]	13.48	99.30[a]	15.60	0.006	0.58

[a] denotes where significant differences lie between techniques P<0.05

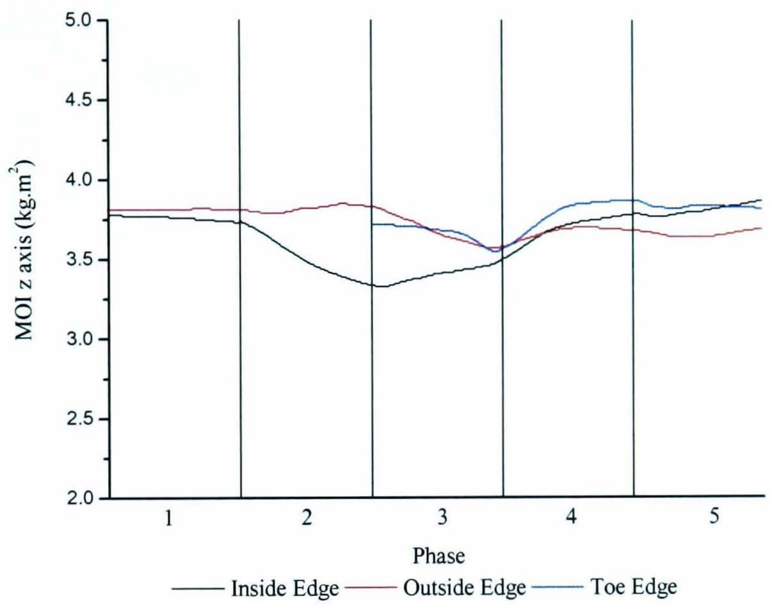


Figure 6-5 Moment of inertia values about the z axis for all three techniques for the whole movement

Table 6-4 Mean, standard deviations, P values and effect sizes for MOI values around the z axis at the start of movement and at the end of each movement phase as a function of technique

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P value	Effect Size
Start		3.78*	0.41	3.81*	0.40	3.72*	0.36	0.035	0.43
End of phase	1	3.73	0.41	3.81	0.33			0.117	0.36
	2	3.34	0.31	3.83	0.45			0.004	0.78
	3	3.50	0.55	3.58	0.42	3.56	0.50	0.757	0.07
	4	3.78	0.64	3.68	0.41	3.87	0.61	0.373	0.15
	5	3.87	0.67	3.69	0.40	3.82	0.55	0.35	0.16

* denotes possible type II error

6.7.4. Work

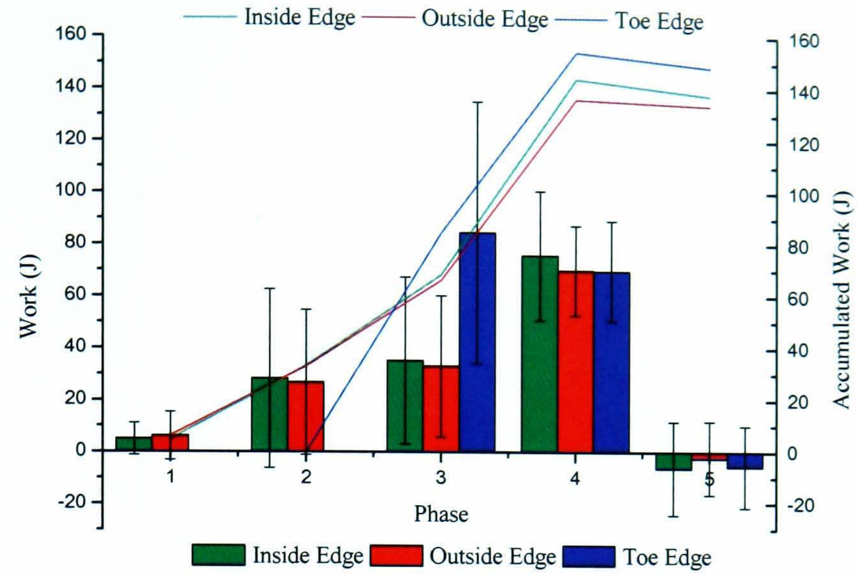


Figure 6-6 Work done on the whole body centre of mass in each movement phase and accumulated work done across the movement

External work values differed significantly in phase 3 only, where the TE technique involved significantly more work than the IE or OE technique. The IE and OE did not significantly differ in this phase.

The greatest amount of work done in the OE and IE techniques was in the reaching phase (69.9±17.2J and 75.6±24.9J, respectively). A similar amount of work was done on the centre of mass in the TE technique in phase 4 (69.7±19.4J), but an even greater amount of work was done in phase 3 (84.4±50.5J).

Over the first two phases, the IE and OE showed little difference in accumulated work. From phase 3 onwards, the IE technique demonstrated higher values of accumulated work done and OE showed the lowest values of the three techniques. The work done in TE in phase 3 was greater than the accumulated work done by either IE or OE. The accumulated work associated with the TE technique remained elevated compared with the other techniques for the entire movement.

6.7.5. Power

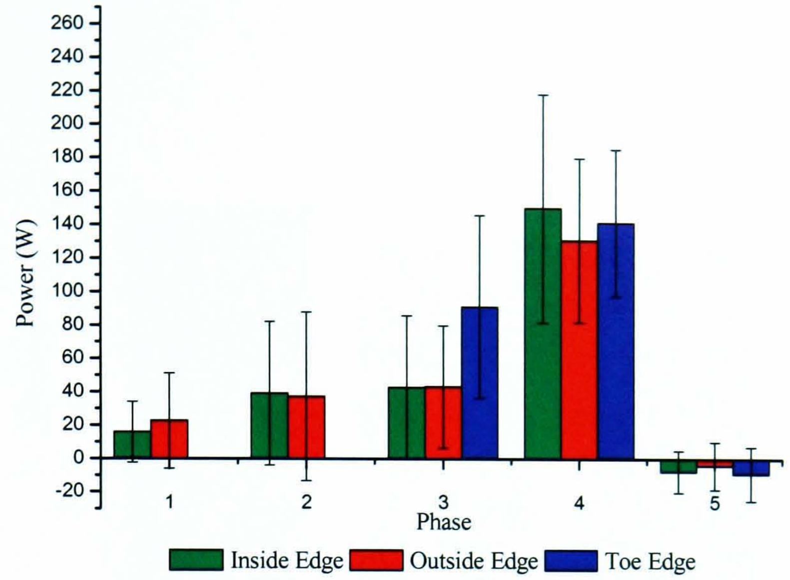


Figure 6-7 Power associated with the whole-body centre of mass movement for the IE, OE and TE techniques in each phase of the reaching task

The techniques only differed significantly in phase 3; specifically, the difference lay between the TE technique and the two other techniques. The IE and OE techniques were not shown to be significantly different.

Over the whole movement, the greatest amount of power associated with the movement of the centre of mass was found in phase 4 for all three techniques. The largest value of power was in the IE technique, the least measured power was in the OE technique, however the differences were not significant.

Negative power was associated with the movement of the centre of mass in phase 5 for all the techniques. The OE demonstrated the least negative power, the TE technique demonstrated the most.

6.7.6. Efficiency of Centre of Mass trajectory

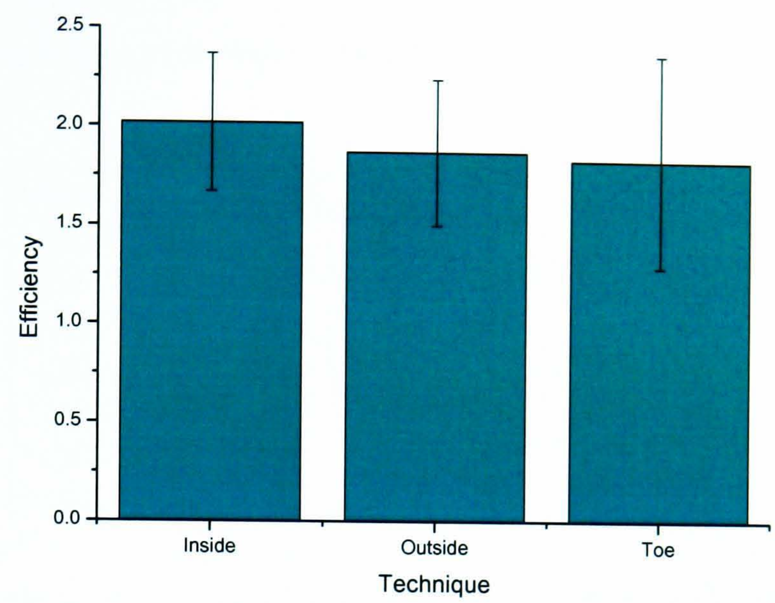


Figure 6-8 Trajectory efficiency over the whole reaching movement task

The trajectory efficiency for the whole movement found the IE to be the least efficient and the TE technique to be the most. However the difference between the IE and TE was small (mean difference 0.19) and non significant.

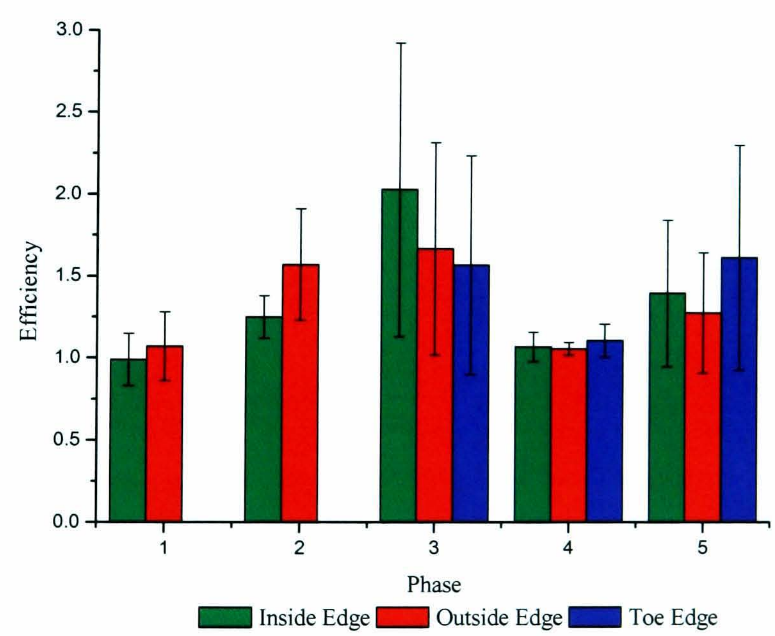


Figure 6-9 Trajectory efficiency within each movement phase for each technique

The only significant differences in efficiency of the centre of mass trajectories occurred in phase 2, where the IE technique was shown to be significantly more efficient. For the IE and OE techniques, phase 3 was shown to be the least efficient phase, whereas phases 3 and 5 were both as inefficient for the TE technique. Although not significant, the IE technique was the most inefficient in phase 3. The most efficient (apart from phase 1) and least variable centre of mass trajectory efficiencies were demonstrated during the hand reaching phase, phase 4.

6.7.7. Technique Perception

Table 6-5 Subjective ranking of the techniques in terms of stability, work, and usefulness on a route

	Stability			Work			Usefulness		
Participant	most		least	most		least	most		least
1	OE	TE	IE	T	I	O	O	T	I
2	OE	IE	TE	T	I	O	O	I	T
3	TE	OE	IE	I	T	O	O	T	I
4	OE	IE	TE	T	I	O	O	I	T
5	OE	TE	IE	I	T	O	O	T	I
6	OE	IE	TE	I	T	O	O	I	T
7	OE	TE	IE	T	I	O	O	I	T

Table 5 shows that the group of expert climbers felt the OE technique to be the most useful technique of the three, in a route setting. The OE technique was rated as requiring the least amount of work in performing the reaching task and the majority of the group rated the OE technique as the most stable. The OE was consistently rated as more stable than the IE technique, but there was less agreement on the relative merits of the IE and TE techniques in terms of work, stability and usefulness.

6.8. Discussion

Analysis of BW moments and MOI were used to make inferences about the difficulty of maintaining balance on the climbing wall. No single technique demonstrated consistent performance benefits, in terms of postural stability, across the whole movement. The reorganisation of the right foot orientation was less posturally demanding using the IE technique. The BW moment was significantly less about the y axis in the IE technique, compared with the OE technique at the end of phase 1, and just missed significance at the end of phase 2. About the x axis, the OE had significantly greater BW moment at the end of phase 2. Thus in the OE, the magnitude of the forces at the hand and foot holds was greater during the reorientation of the foot. The MOI was significantly greater in the OE technique about both the x and y axes. So not only were the magnitudes of the force greater in the OE technique, but the forces had to overcome a greater resistance to the angular motion. Therefore the OE technique was more posturally demanding in terms of orientating the foot. As the foot was being re-orientated, the postural demand to prevent rotation about the x axis had to be met primarily by the right hand. The left hand could contribute to counteracting the BW moment about the x axis, but as the left hand was directly above the axis, the forces would have to have been very large. Thus in the OE technique, the postural demand on the right hand was significantly greater than in the IE technique.

The situation was more complex in the actual reaching movement. At the start of hand movement, the OE had a significantly larger BW moment than both the TE and IE techniques about the x axis. About the y axis, the IE and OE techniques had significantly lower BW moments than the TE technique, with the OE showing the lowest BW moment. Greater forces were therefore needed on the right hand and foot supports in the OE technique; however, at the same time less collective force was required in the hands. In the TE technique greater forces were required at the hand supports. In terms of MOI, the IE had lower values than both the TE and OE about the x and y axes, only just missing significance. Therefore the IE, overall, was the least posturally demanding at the start of the hand reach. The TE and OE techniques had similar MOI values about the x and y axes. Therefore the OE technique was more posturally demanding on the right hand side supports, whereas the TE was more demanding on the hands.

In phase 4, all three techniques increased in MOI about the x and y axes. As the right hand was not in contact with the wall, the BW moment about the x axis had to be counteracted mainly by the right foot; about the y axis, the left hand was solely responsible for the maintenance of postural stability. At the end of the reach, there were no significant differences in the BW moment about the x axis between the three techniques. In terms of MOI about the x axis, the TE was significantly greater than both the IE and OE techniques, with the OE having the lower MOI of the two techniques but not significantly so. The TE was therefore the most posturally demanding technique for maintaining balance about the x axis. About the y axis, the OE technique was the least posturally demanding in terms of balance maintenance. The BW moment was significantly less for the OE technique, compared with the other two techniques, as was the MOI about the y axis. Therefore the OE placed less demand on the left hand, compared with the other two techniques. The TE had the greatest BW moment and MOI about the y axis, but the difference was not significant when compared with the IE technique.

Once the new hold had been reached, the postural demands in all three techniques increased. The BW moments and MOI continued to increase about the x axis, though the only significant differences were between the TE and OE. The OE technique was the least demanding at the end of the movement for maintaining balance about the x axis. The OE also had significantly lower BW moment about the y axis compared with both the IE and TE techniques and had the lowest MOI, which was significantly lower than the TE technique. Both the MOI and BW moments increased during phase 5, thus the postural demand increased for all three techniques; the OE remained the least demanding of the techniques.

Overall, the data suggests that the TE technique was the most demanding technique for postural stability during the reaching movement. The IE technique was posturally less demanding for re-orientating the foot and continued to be until the hand reach started. However, the OE technique offered greater stability for performing a hand reach, by reducing the postural demand on both the left and the right foot, compared with the other two techniques. These results agree with the majority of the subjective ratings by the participants with respect to the stability afforded by each technique. The data also indicate that the right foot played a more important role in the OE technique, as evidenced at the beginning of the reach, whereas the left hand was more important in the TE technique. As the musculature in the legs is greater than in the arms, a greater postural demand on the legs, as opposed to the arms, would be more beneficial to performance. The physiological requirements of overhanging climbing are greater (Watts & Drobish, 1998), primarily due to the greater involvement of the arms in maintaining equilibrium (Noé et al., 2001). Therefore, less demand on the arms would be physiologically advantageous.

The mechanical analysis demonstrated that the OE technique was the least energetically demanding of the three techniques in performing a reaching movement. Less mean work was done on the whole-body centre of mass in the OE technique over the movement as a whole, and in the actual reaching phase the OE technique had the least mean power associated with the whole-body centre of mass motion. All the participants also ranked the OE technique as the least energy demanding. There was less consistency, however, in which technique the participants found to be the most energetically demanding. The TE technique was shown to have the greatest power and work done of the three techniques in phase 3. In phase 4 the mean work done was the lowest in the TE technique but this did not equate to the lowest amount of power.

The most energetically demanding technique was the IE technique, evidenced by the magnitude of mean power in phase 4.

In the first two phases, the IE and OE technique demonstrated near identical levels of work done on the whole-body centre of mass. There was a consistent trend for the OE technique to be slightly more energetically demanding over the first two phases.

The differences in the techniques within each phase tended to be small and non-significant. The lack of significant differences between the three techniques may be due to the large standard deviations within the group. This variability is attributed to the attenuation of differences in centre of mass displacement between the climbers through the energetic calculation process. The exception to the non-significant differences lies in phase 3, where the TE technique was significantly greater in terms of work done and power than both the OE and IE techniques. These differences can be explained through the variation in the position of the climber at the start of phase 3, particularly in terms of the vertical position. In the TE technique, the climber moved directly from the set start position to a position where the hand left the handhold. In the IE and OE techniques, the climber had to adjust the orientation of the right foot first. This orientation had the effect of moving the centre of mass closer to the wall and, importantly, vertically upwards (Comparative Study 1). At the end of phase 3, the TE had a significantly greater vertical centre of mass displacement (Comparative Study 1). As the work done measure was calculated through the change in potential and kinetic energy, differences in the vertical displacement of the centre of mass will have large effects on the potential energy changes.

The energetic analysis in this study focussed on the mechanical energy changes associated with the movement of the whole body centre of mass in performing the reaching task. In essence, the work and power measures can be thought of as indicators of the energetic demand of the task. Thus it was the energetic demands of the task that the techniques were compared on – the implicit assumption being that the technique involving the least mechanical energy changes to the whole body centre of mass was superior for completing the task.

The work done measure does not represent the total work, or mechanical energy expenditure (Aleshinsky, 1986a; Zatsiorsky, 2002), in each technique, unless the mechanical energy change is monotonic (Zatsiosky, 2002). The results of the mechanical analysis clearly show negative work and power in phase 5 of the movement, indicating that the mechanical energy increased and decreased in the movement.

A number of authors (e.g. Willems et al., 1995; Thys et al., 1996) advocate the calculation of MEE through the summation of the work done on the whole body centre of mass (external work) and the work associated with the mechanical energy changes of the body segments relative to the whole-body centre of mass (internal work). Certainly this model could be applied to the data collected in this study. Theoretically, however, this approach has been proven to be unsound (Aleshinsky, 1986b). A second model, the fractions model (Aleshinsky, 1986a), calculates the change in the mechanical energy of the whole body from the mechanical energy changes in the body segments, using different assumptions about energy transfer conditions between segments (Pierrynowski et al., 1980; Winter, 2005; Zatsiorsky & Gregor, 2000). The model is problematic for anti-symmetrical movements occurring at the same time, because there is an assumption of energy transfer (Purkiss & Robertson, 2003; Zatsiorsky, 2002). Comparative study 1 demonstrated that the three climbing techniques involved complex coordination of joint angular changes with anti-symmetrical movements. For example, in phase 3, the OE technique shows the left elbow extending , while the left knee flexes. Thus the fractions model would not provide a valid estimate of MEE. Experimentally, the validity of the fractions approach has not been supported (Purkiss & Robertson, 2003; Kautz et al., 1994; Arampatzis et al., 2000).

The only model that could be applied to calculate MEE in a non-controversial manner is the model of Aleshinsky (1986a, b), based on classical mechanics theory (Zatsiorsky & Gregor, 2000; Zatsiorsky, 1998). However, this model requires knowledge of kinetic data.

The most efficient technique over the whole movement in terms of centre of mass trajectory was the TE technique. The least efficient was the IE technique, but the differences were small and non-significant. However, the IE was actually significantly more efficient in the reorganisation of the foot than the OE technique. In phase 3, the trajectory efficiency of the IE technique was lost, compared with the OE technique. Phase 3 contained the most deviation from the straight path trajectory for both the IE and OE technique and also constitutes the most variable phase within the group of climbers for both techniques. The trajectory inefficiencies are attributed to the post foot movement adjustments and preparatory movements for the hand movement. The adjustments and preparatory movements would seem to have been relatively greater in the IE, as this technique was the most inefficient. The TE had a better ratio of distance to displacement, due to the absence of post foot re-orientation adjustments in this technique.

The centre of mass hardly deviated from the most direct route during the actual phase of reaching, as demonstrated by all three techniques having values close to one. The efficiencies of the climbers was far less variable during phase 4. These trends are unsurprising as the tripedal stance was the most unstable phase, thus the less perturbing the trajectory, the less postural stability was unduly affected.

Post hand reach, the OE offered the most efficient trajectory for stabilising the posture. The TE technique had the greatest deviation from the straight trajectory of the entire movement in phase 5.

The kinematics of the reaching hand produced some interesting results. The temporal characteristics of events were not significantly different between techniques, but the magnitudes of the velocity and acceleration were significantly less in the OE technique, except for impact velocity. As the distance between holds was constant, the significant differences are probably due to inaccuracy in the determination of when the hand left the starting hold and finished on the target hold.

The main conclusion from the hand kinematics is that an appreciable precision effect was measured, through a longer deceleration phase and low impact velocity. This contrasts with the work of Bourdin et al. (1999), which suggested that postural constraints in rock climbing removed the precision characteristics of reaching, so that the hand used the target hold as a mechanical stop. The results from this study are more comparable with the patterns found in prehension tasks in non-posturally demanding situations (e.g. Marteniuk et al., 1987; Jeannerod, 1981). The climbers in this study were able to overcome the postural constraints and precisely place the reaching hand on the target hold with minimal velocity. The postural demand analysis demonstrated significant differences between the techniques in terms of BW moments and MOI. However, these differences in postural demand did not manifest themselves in the hand kinematics. The results of this study suggest that a reassessment of the role of posture in prehension activities is required. The theoretical contribution of this study and Comparative study 1 to the theory of prehension and, specifically, the role of postural constraints, is developed in the General Discussion chapter (Chapter 7).

6.9. Conclusion

Comparison of the effectiveness of the three techniques in terms of postural stability, trajectory efficiency and energetic efficiency suggests that no single technique was consistently superior. The OE technique was the optimal technique of the three for performing the hand reaching movement, as indicated by the decreased postural demand on the left hand and right foot, combined with being energetically less demanding, resulting in significantly lower velocities and acceleration in the reaching hand. However, to re-orientate the foot into the OE position was more demanding posturally and energetically.

The results of the study suggest that a re-examination of the role of posture in organising reaching movements is required. The role of posture in relation to reaching tasks will be discussed in the General Discussion chapter (Chapter 7).

Chapter 7. General Discussion

7.1. Summary of the Research Area

The analysis of rock climbing in this thesis has focussed upon the role of technique in the performance of a reaching task on an overhanging climbing wall. Three techniques were identified for the movement of the hand from an initial support to a target hold; two came from rock climbing manuals and the third was identified from the experimental work in Chapter 3. The techniques differed essentially through the orientation of the ipsilateral foot on the support during the reaching motion. The foot could be orientated so that the medial phalanges and metatarsals of the foot were in contact with the foothold, this was termed the Inside Edge technique (IE). Placement of the lateral phalanges and metatarsals of the foot on the foothold was defined as the Outside Edge technique (OE). The third technique, the Toe Edge technique (TE), utilised the phalanges of the foot on the support in such a way that the foot was perpendicular to the wall.

Rock climbing training advice, through manuals and magazine articles, recommends the use of the OE technique on overhanging terrain (Goddard & Neumann, 1993; Richardson, 2001). The OE technique is claimed to have biomechanical reach advantages (Goddard & Neumann, 1993), be more stable (Richardson, 2001) and energetically superior (Gresham, 2002a). The role of technique has been identified as an important factor in overall climbing performance (Goddard & Neumann, 1993; Kösstermeyer, 2002; Watts, 2004), yet scientific endeavour in this field is rare. The majority of studies into rock climbing have analysed the anthropometric aspects (Watts 2004; Grant et al., 2001; Watts et al., 1993; Mermier et al., 1997; Watts et al., 2003), the physiological requirements of the activity (Watts, 2004; Mermier et al., 1997; Watts & Drobish, 1998) and injury (Shea et al., 1992), particularly to the fingers (Bollen, 1988; Schweizer, 2001; Quaine et al., 2003). The interaction of the climbers with the environment has been investigated through concepts of affordances (Boschker et al., 1999, 2002), learning (Boschker & Bakker 2001, Cordier et al. 1993, 1994) and the role of anxiety (Pijper et al., 2003). In biomechanics, important contributions have been made by Quaine and Martin and co-workers into the knowledge and understanding of balance maintenance in rock climbing through mechanical analyses of the reaction supporting forces (Quaine et al., 1997a, 1997b) and moment reactions (Quaine & Martin, 1999; Noé et al., 2001), in both vertical (Quaine & Martin, 1999) and overhanging environments (Noé et al., 2001). Balance maintenance as a supra-postural goal in limb movements has been demonstrated through changes in the organisation of reaching movements with postural constraints (Nougier et al., 1993; Bourdin et al. 1998, 1999).

To date, however, no studies have investigated the relative merits of different techniques in performing a rock climbing movement. The aim of this thesis, therefore, was to investigate the role of technique in a rock climbing movement. Non-scientific literature proposed the superiority of the OE technique over the IE technique in making an arm movement on steep, overhanging terrain. As the research base was limited, an initial qualitative study was performed to contextualise the research aim (Lees, 2002). This study confirmed the use of both techniques by competition climbers and identified a third, the TE technique. Although there was a tendency for the higher placed climbers to use the OE technique more often, all the competitors utilised all three techniques during their performance. Therefore the research question was to evaluate the impact of ipsilateral foot orientation on reaching tasks in overhanging environments.

Technique is the sequence of movements involved in sporting movement tasks (*Dictionary of Sports Science*, 1992). The first stage of answering the research question was, therefore, to determine the sequence of movements induced by the differing orientations of the right foot before, during and after an arm reaching movement task. Characterisation and differentiation of each technique was achieved through analysis of the centre of mass pathways and three-dimensional joint rotations (Chapter 5). These measures demonstrated significant differences between the techniques.

The techniques having been characterised as different from one another, the second stage of the research was to establish how effective each technique was on the performance of a reaching task. In essence, the performance of a reaching task in rock climbing is successful if the climber manages to grasp the new hold without falling off. Thus postural stability is an important determinant of success (Bourdin et al., 1998, 1999). The organisation of the reaching and grasping movement has been shown to be affected by postural constraint (Bourdin et al. 1998, 1999; Nougier et al., 1993). Specifically, the reaching movement was performed at higher speed, and the hold contacted with a greater velocity, when the postural constraints were higher (Bourdin et al., 1999), which, as the authors state, could create problems for the successful grasp of the target hold. Thus a technique which reduces the postural demands of maintaining stability, would have performance benefits to the climber making the reach and grasp movement.

Maintenance of balance in an overhanging environment is mechanically easier than in the vertical, due to the existence of a base of support and the increased role of the vertical forces in the arms in keeping equilibrium in the former environment (Noé et al., 2001). Physiologically, however, overhanging climbing is more demanding (Watts & Drobish, 1998; Billat et al., 1995; Booth et al., 1999). The smaller musculature and greater loading on the arms has been suggested as accounting for the greater physiological activity (Noé et al., 2001; Booth et al., 1999). Analysis of the rock climbing competition (Chapter 3) demonstrated that a large number of limb movements are performed by a climber on a route. Therefore a technique that allows the reaching movement to be made with less energetic cost would allow more moves to be performed for a certain level of energy and thus allow the climber to progress further along a route.

The most efficient trajectory for the centre of mass would be to move directly along the straight-line path from the start of the movement to the end of the movement. Smoothness of trajectory has been shown to be an index of performance (Cordier et al., 1994), using the tool of geometric entropy. Unfortunately, geometric entropy cannot be applied to a three-dimensional movement. An alternative tool of the ratio of distance travelled over displacement is proposed as a measure of trajectory efficiency.

The performance measures for judging the effectiveness of the different techniques on the performance of an arm reach were therefore: postural demand for stability, mechanical energy changes associated with the reaching task and the efficiency of the trajectory. In order to evaluate the effect of technique on the performance variables, the movement task was constrained. The participants performed all three techniques in a random sequence. Each time, the climbers started from the same set start position and reached for the same hold at a set distance. In this way the study was controlled so that technique would be the independent variable on performance.

7.2. Optimal Technique for Performing an Arm Reach in an Overhanging Environment

Technique did not affect the actual reaching movement in the rock climbing task performed in this research. The kinematics of reaching were shown to be invariant to the orientation of the right foot in terms of coordinative structure (Comparative study 1) and in the velocity-time profiles of the end effector (Comparative study 2). Significant differences in the magnitudes of the end-effector velocity and accelerations were identified. However, considering the error in acceleration, the differences are small in real terms (there is further discussion about the acceleration error in the limitations section, section 7.8)

Technique did affect the performance of the whole body in successful attainment of the reaching task. The effect of placing the right foot in different orientations significantly affected the way the climbers organised their bodies as a whole to perform a successful reaching manoeuvre. This was evidenced in significant differences in joint rotations between techniques at the end of each phase and through the different joint sequencing.

The least energetically demanding technique during the reaching phase was the OE technique. This was achieved through the centre of mass only moving upwards and towards the wall. Movement of the centre of mass to the right was small compared with the other techniques and was delayed for the first fifth of the movement phase. The OE technique was able to achieve a lower displacement to the right in the reaching phase, through a greater displacement to the right during the re-orientation of the foot phase. The OE technique was therefore more posturally demanding about the x axis, so the demand on the right hand and foot for balance maintenance was greater at the start of the movement using the OE technique. The importance of the right leg was noted in the description of the joint angular changes. It was felt that the right leg extensions opposed the actions of the left leg by the start of the reaching phase. In the preparation phase the right arm opposed the left leg, but when the right hand started to move there was no effect on the centre of mass velocity in the y direction. So the right hand is not thought to have affected balance maintenance about the x axis. Therefore the right foot support was extremely important in maintaining balance just prior to hand release.

None of the techniques manoeuvred the centre of mass of the climber into the base of support. Therefore, body weight moments were constantly applied to the climbers. The IE technique started the reaching phase as the least posturally demanding of the three techniques overall. The centre of mass was positioned further to the left than in both the OE and TE techniques. At the end of the reach there were no significant differences in the positions of the centre of mass in the y direction. The IE technique therefore required a greater velocity in the y direction during the reaching phase. The greater lateral movement required in the IE technique meant that in the reaching phase the IE was most energetically demanding technique.

The TE technique was the most energetically demanding in the preparation phase prior to the start of the reaching movement. This was due to the starting position. As the TE technique did not require the foot to be re-orientated, the climbers prepared for the reaching movement from a centre of mass position further away from the wall and lower. Greater whole-body centre of mass velocities were therefore generated by the climber during the reach preparation phase.

The greater velocity requirements in the IE and TE are thought to have occurred through the proximal-distal sequencing in the legs. Proximal-distal sequencing has been demonstrated in activities such as vertical jumping (Bobbert & van Ingen Schenau, 1988), with the aim of producing high take-off velocities. It therefore seems reasonable to draw conclusions about the proximal-distal sequencing evidenced in this work being associated with the velocity requirements of the IE and TE technique. Production of greater velocities must be achieved through greater force applications at the supports, which also have to control the greater momentum (Testa et al., 1999).

As has been stated the OE technique had the lowest whole-body centre of mass velocities during the arm reach in the y and z directions. In the x direction, the OE had a velocity, along with the

TE, significantly greater than that of the IE technique. Greater movement towards the wall reduced the BW moment, which decreased postural demand on the hands. As the hand was released, the velocities towards the wall and vertically peaked and decreased through the whole movement phase. This was reasonable, as the right hand could no longer apply forces to move the whole body centre of mass. The removal of the right hand meant that postural demands for maintaining balance increased on the left hand and right foot. The importance of the right foot was evidenced in all three techniques, through the effective fixation of the angular changes in the ankle.

Although the MOI about both the x and y axes increased during the hand reach for all three techniques, the OE finished the hand reach with lowest values. The OE technique also had significantly lower BW moment about the y axis. Thus the postural demand on the left hand and right foot were relatively less at the end of the reach.

The TE technique was the most demanding posturally at the end of the reach on both the left hand and the right foot. The importance of the left hand in the TE technique and the right foot in the OE technique was evidenced through the number of joint reversals. The pattern of joint reversals demonstrated that in the OE and IE the whole of the left arm linkage was varied to control the changing postural demands, compared with the TE technique, which primarily used adjustments in the wrist and shoulder only. In the legs, the OE primarily adjusted the actions at the ankles, whereas the TE technique showed greater knee adjustments and the IE used the knee and ankles.

After the hand reach was made, significant differences were shown in the duration of time for the centre of mass to stop. The OE technique stabilised the centre of mass in the shortest time. The number of joint reversals were fewer for the OE technique in this phase and although the postural demands continued to increase, the increase was least in the OE. Less negative work and power were associated with the OE technique in the last phase.

7.3. Preparation for the Reaching Movement

The IE and OE techniques both had an initial foot re-orientation from the starting position prior to making the hand reach. The OE technique was shown to be the most posturally demanding, in terms of body-weight moment and whole body moment of inertia. The increased postural demand is due to the hips in the OE technique having to be pushed away from the wall in order to adduct at the right hip and bring the knee through. This is achieved by the left leg extending, thus the left arm would appear to be important in the control of balance during the foot re-orientation. Interestingly, the right arm geometry remains essentially fixed with relatively few adjustments, in the plane of elevation and the hyper-extension of the wrist. This may represent the behavioural response to the contra-lateral transfer of forces accompanying the loss of support on the right foot (Noé et al., 2001). The right arm in the OE technique becomes more active after the leg has moved into adduction. It is at this point that the climber starts to move to the right, while still re-orientating the foot. The re-orientation of the right foot also takes longer in the OE technique compared to the IE technique. So for the OE technique not only are the postural demands greater but the time in which to be in the more posturally demanding position is greater.

Energetically the two techniques hardly differ. In terms of trajectory efficiency, during the actual movement of the foot the OE technique is less efficient. However, once the foot has been re-orientated, the IE efficiency decreases markedly. There is also more joint reversals evidenced in the IE technique during this phase, both in the arms and the legs. As the IE technique is in a posturally less demanding position, it is unclear as to why there is greater complexity of co-ordination. A possible explanation may be that the joint reversals represent a fine control by the climbers in the preparation of the reaching movement; the OE technique may not afford such luxury.

The requirement of displacing the hips in order to re-orientate the foot means that the OE technique is the more difficult and demanding of the two techniques

7.4. Optimal Technique for the Whole Task

The optimal technique for performing the reaching task was the OE technique. Although more posturally demanding during the preparation period, the postural and energetic demands in the actual reaching movement were reduced using the OE technique. This conclusion supports the perceptions of the majority of the participants, who felt that the OE technique offered greater stability for less work.

7.5. Contribution to Scientific Knowledge of Rock Climbing

The work presented in this thesis makes a number of contributions to our knowledge and understanding of rock climbing.

The first contribution is that it provides a detailed three-dimensional kinematic analysis of a rock climbing movement. Previous research into single limb movements in rock climbing has tended to involve kinetic analyses (Noé et al., 2001; Quaine & Martin, 1999) with minimal kinematics (e.g. Bourdin et al., 1999). There have been a few kinematic-based studies, but these focussed either on whole-body centre of mass pathways over a climbing route (e.g. Cordier et al., 1994), or in one case (Werner et al., 2000) on overcoming environmental features, specifically a roof. Comparative Study 1 is the first study to describe in detail the way in which the body moves to perform a climbing movement. The descriptions of the joint angular changes demonstrated that alterations in right-foot orientation significantly affected the body geometry and temporal sequencing of the limbs accompanying the reaching movement. The kinematic analyses were therefore shown to be powerful enough to determine differences in technique. As a result, there now exists, within the field of rock climbing, a tool allowing analysis of whole-body co-ordination during movement.

Comparative Study 2 further demonstrated that a kinematic analysis of a climbing movement was able to determine the effect of technique upon the performance of the reaching movement, in terms of postural demands, energetic demands and trajectory efficiency. The kinematic methodology pioneered in this research allows rock climbing manoeuvres to be analysed in wider settings than previously, such as on a natural piece of rock, where kinetic analyses would be impossible or, as in the case of a series of climbing movements, unfeasible.

The postural changes in the whole body accompanying the re-orientation of the right foot would appear to provide support for a contra-lateral shift of forces during unweighting of a limb (Noé et al., 2001). Both the IE and OE techniques showed a shift in the centre of mass to the left, as the right foot became unweighted. In the IE, this was achieved through limb movements, suggesting reinforcement of the foot and hand supports. In contrast, the limb movements in the OE technique imply that the lateral movement to the left was primarily the responsability of the left arm. No contra-lateral centre of mass movement was evidenced prior to the release of the right hand support. Collectively, these results show that the goal of the limb movement significantly affected the behavioural strategy accompanying the unweighting of a limb, from which it may be inferred that the pattern of contra-lateral force organisation is not unique (Quaine & Martin, 1999).

The centre of mass movement during right foot re-orientation in the OE technique was especially interesting because, once the right foot had started to move, the centre of mass changed direction and displaced to the right. The centre of mass displacement prior to limb movement is, therefore, not always towards the position it needs to be in at the end of the movement, contradicting the assertion by Testa et al. (1999). In fact, the centre of mass does not have to displace in a particular direction prior to limb movement, as evidenced by the delayed shift in whole-body centre of mass to the right in the reaching movement in the OE technique.

The major contribution of this study has been to determine the role of technique in the performance of a rock climbing movement. To our knowledge, no other such study has been performed in the field of rock climbing. The analysis identified three types of technique, based on the orientation of the ipsilateral foot on the support, for performing a rock climbing reaching task and found the techniques to be fundamentally different in terms of body geometry, temporal limb sequencing and centre of mass trajectory. Moreover, the role of technique was demonstrated *not* to be involved in the actual organisation of the reaching arm, but rather in how the body is organised around that reaching arm strategy. The wider implications of a fixed arm strategy are discussed in relation to general prehension theory in section 7.7. The adoption of different techniques was shown to affect whole-body performance of the reaching movement. On the basis of the data in this study at least, the Outside Edge (OE) technique can be said to be the optimal one for reaching towards a hold on a rock climbing wall. However, given the limitations of the study (see section 7.8 below), one needs to be cautious about generalising this conclusion to wider rock climbing situations.

7.6. Practical Implications for Coaches and Practitioners

The effect of foot orientation upon overhanging reaching tasks has several implications for practitioners and coaches. Ipsilateral foot orientation has been shown to have no effect upon the co-ordination or performance of the reaching arm movement component of the overall task. There is an effect upon the body geometry around the reaching arm movement. Climbers should therefore think about placement of the foot as a means for obtaining the optimal body posture within the environment. The reaching movement of the arm will be made in the same way regardless body geometry, thus it is through changes in body posture that the climber can improve their performance at reaching tasks.

Climbers, in overhanging situations, should try to position the body as close to the climbing surface as possible. This will reduce the body weight moments. They should also try to reduce the whole-body moment of inertia, as this will reduce the postural demand on the hands and feet. However, whole-body moment of inertia is not an easy concept to visualise. In the absence of a detailed kinematic analysis, climbers should experiment with their body postures on specific reaching task problems to determine body postures which give a feeling of being more stable. Climbers should focus on trying to minimise the velocity of the hand on contact with the target hold, as it is possible to have a precision effect in a reaching hand trajectory in posturally demanding situations. A possible exercise would be to place the reaching hand just above the target hold, rather than try to grasp the hold. This may increase the ability of the climber to perform arm reaching movements with a precise end grasp.

Initial difficulty in obtaining a foot orientation may provide the climber with a more beneficial performance in the reaching task as a whole. The use of the OE technique in this study demonstrated for the particular reaching task, re-orientating the foot was posturally more demanding yet overall the technique was the most beneficial for performance, particularly at the end of the reaching task.

The OE technique cannot be unequivocally recommended due to the specific environment in which this study was performed. Further work into the effect of foot orientation on reaching tasks in different environments will allow greater generalisation of the particular merits of one technique. The OE technique did position the centre of mass closer to the base of support compared with the other techniques. Therefore there may be a benefit in using the OE technique on steeper routes, which will provide larger base of supports that the centre of mass will be able to project vertical forces upon.

The IE and TE techniques may be more useful when the target hold is outside the natural reach of the climber. Both techniques use a proximal-distal sequencing in the legs prior to the reaching movement, thus these techniques are similar in co-ordination to vertical jumping. Therefore the IE and TE techniques would be more suitable when the climber has to jump for the next hold.

7.7. Theoretical Aspects of Prehension Activities

Rock climbing provides a unique environment in which to study reaching and grasping movements. There are two essential differences from the traditional prehension experiments. Firstly there are two goals, the prehensile movement task and the requirement to maintain postural stability (Bourdin et al., 1998, 1999). Secondly, in rock climbing the hold is grasped and the body moved around the hold, as opposed to manipulation of the object about the person (Bourdin et al., 1998). It has been proposed that the existence of postural constraints fundamentally alters the organisation of the reaching arm (Bourdin et al., 1998, 1999).

The kinematic characteristics of the reaching arm by the climbers in Comparative Study 2 demonstrated a 'precision effect', through a longer deceleration phase and minimal impact velocity. This contrasts with Bourdin et al. (1999), but is in agreement with results from traditional prehension studies, such as Marteniuk et al. (1987). Further, the technique used by the climbers did not affect these trends. The three techniques have been demonstrated as placing different postural demands on the climber to maintain balance before, during and after the reaching movement. These results therefore imply that different postural constraints do *not* necessarily alter the kinematic characteristics of the hand performing a set reaching movement.

Bourdin et al. (1999) altered postural constraints by changing the size of the starting hold for the reaching hand. The validity of this method for altering postural demand is, however, questionable. Marteniuk et al. (1987) defined *task* as the interaction of the performer and the environment within set movement goals. The set movement goals were constant in Bourdin et al.'s (1999) study, but the environment was altered, by changing initial hold size. Therefore, comparison of reaching performance from different-sized holds is, in actual fact, a comparison of two separate tasks. In Comparative Study 2, the environment remained constant, but the interaction of the climbers was manipulated (they were instructed to use different techniques) to confer different postural constraints in the performance of the task.

In the only study to analyse joint angular changes in a reaching movements in posturally demanding environments, Comparative Study 1 demonstrated a fixed strategy in solving the joint redundancy problem across the techniques. The existence of significantly different body geometries in the different techniques was incorporated into the fixed strategy, or coordinative structure (Turvey, 1990), solely through the elevation angle of the shoulder joint. The behavioural strategy of the climbers was economical in terms of the number of degrees of freedom involved to maintain an optimal arm posture at the end of the reach, following the suggestion by Jeannerod et al. (1998). Invariant final arm posture for object orientation (Desmurget et al., 1995) and position (Gréa et al., 2000) for a given movement start position (Desmurget et al., 1998) has been previously reported. The final arm posture has been suggested as a control variable (Paulignan et al., 1997; Gréa et al., 2000; Desmurget & Prablanc, 1997; Jeannerod et al., 1998) within a global planning of prehension theory. The invariant final arm postures and coordinative structures demonstrated by the climbers in the work presented here supports the notion of global planning theory in prehension.

In conclusion, the results of Comparative Study 1 and 2 indicate that postural constraint was not an important variable in the planning and control of a reaching movement.

7.7.1. Future Directions

Future work should analyse the robustness of this conclusion. Reaching movements should be studied with variations in the spatial domain (i.e. having object holds in different locations, altering the start position of the hand), in the intrinsic properties of the object (shape, size, texture) and in the environment (different supports for the legs and contra-lateral hand, different angles of the climbing wall), as there may be evidence of stereotyped responses for particular environmental and task configurations. In particular, it would be interesting to use a hold that afforded the climber a number of different ways of providing support. In this way, the joint redundancy would not be limited by the mechanical properties of the target hold. Analysis of different populations performing reaching tasks in posturally demanding situations would further illuminate the role of posture in prehension. The work in Comparative Study 1 and 2 is limited by the fact that a very specific population was studied. These participants may have adapted to the activity sufficiently that, for that population, the postural constraints did not represent a greater constraint than those of the reaching task.

7.8. Limitations

There are a number of limitations to the research. The limitations in the general methodology employed to answer the research question will be discussed first, then the limitations of the kinematic model and measures.

A major limitation of the thesis lies in the generality of the results of the studies. The real-life environment in which competitive rock climbing activity takes place is almost infinitely varied (Goddard & Neumann, 1993). In Comparative Study 1 and 2 the movement of the climbers was controlled and the environment kept constant: an approximately 10° overhanging wall with wedge shaped supports 10cm in width and 2.5cm in depth, though the inter-hold distances were normalised to the individual climber's anthropometry. Environmental characteristics were based on previous experimental work by other authors (e.g. Noé et al., 2001) and on the climbing competition study (Chapter 3). Consistency of environment was maintained to allow fair comparison of the techniques. However, the results of the study must be interpreted with the proviso that they apply to a very specific movement performed in a specific environment.

Secondly, variations in the joint angles between techniques were observed in the set starting position. The participants had prior knowledge of the subsequent technique to perform when they stepped onto the wall, which may have influenced the starting position. With hindsight, participants should have attained the start position before being instructed as to which technique to use to perform the reach. The use of kinetic data would have enabled a set start position with equalised forces on all the supports, as in Quaine & Martin (1999), which would have helped to decrease variability.

The start of the reaching phase was determined through identifying the instant that the hand started to move upwards from the initial hold. The end of the phase was defined by the upward movement of the hand, terminating on the new hold. If the hand rotated about the starting hold before starting the motion to the new hold, then the criteria used in this study to define initiation of the reach phase would be erroneous. In Comparative study 2, the kinematics of the reaching hand demonstrated that the temporal characteristics were consistent between techniques, but the magnitude of maximum velocity, acceleration and deceleration differed significantly. Acceleration measures of a projectile demonstrated a maximum mean error of $0.85ms^{-2}$. Thus the differences in acceleration values between techniques may be due to measurement error and errors in the definition of the start and end of the reaching phase.

The mean group values of the measures were used in the analyses to compare the techniques. The research question involved defining and comparing the actual techniques, thus variability within the group was reduced as much as possible, through methodological and data conditioning processes. However, there was still variability in the measures. Quantification of the homogeneity of the participant group was performed through analysis of the coefficient of variation in centre of mass trajectories. The population was felt to be homogenous as the intra and inter-participant CV were less than 10%.

The kinematic model of the climber employed in the study has specific accuracy limitations. The model comprised 14 segments, which were assumed to have rigid body properties. Segmentation has limited accuracy because humans are not multi-link chains, but continuous entities containing rigid and non-rigid tissue. Skin movement artefacts undermine the rigid body assumptions, creating sizable errors in anatomical landmark identification (Cappozzo et al., 1996b). The effect of skin movement in the present study was minimised through methodology (based on astute work and recommendations of Cappozzo et al., 1997; Cappello et al., 1997; Cappozzo et al., 1995a,b) and the optimisation routine of Söderqvist and Wedin (1993), which exploits the redundancy in the degrees of freedom of the skin markers to produce technical co-ordinate systems. The application of Body Segment Inertia Parameters (BSIP) represented a compromise between accuracy and complexity of the scaling procedure. As the research involved repeated measures on the same population group, it was felt that ease of application was relatively more important than fine tuning the BSIP to each individual. The BSIP data from Zatsiorsky & Seluyanov (1983, 1985) best represented the population tested in this research. To apply these BSIP more easily, De Leva's (1996) published adjustments relative to joint centres were used. The major simplification in the kinematic model was to represent the trunk as a single segment. Again, the trunk clearly does not consist of a rigid structure with uniform density (Zatsiorsky, 2002), so the mass-inertia characteristics of the trunk have a limited accuracy.

The analysis of co-ordination was limited through the lack of a quantitative measure. Although three-dimensional analyses of co-ordination have been performed (e.g. Lees & Nolan, 2002), the quantitative tools are essentially applied to planar movements. The movements in rock climbing have been shown to be complex three-dimensional movements. Comparisons of every joint rotation in each direction would have been impractical given the research question.

The mechanical analysis of the techniques in Comparative Study 2 was limited in scope. If kinetic data had been available, a more detailed study of the energy generation and absorption in the joints could have been undertaken, using the model of Aleshinsky (1986a, b). In the absence of force data, only the mechanical changes of the whole-body centre of mass were analysed, as discussed in Chapter 6.

The lack of force data in Comparative Study 2 meant that the postural demands at the hands and right foot were inferred from analyses of the body weight (BW) moments and the whole-body moment of inertia's acting on the climber. The use of kinetic data from the supports would have allowed a more complete analysis of the actual organisation of the forces in maintaining stability and producing the movements required to perform the reaching task.

7.9. Future Directions

The future directions of research extending from the work presented will now be considered. Future prehension focussed research has been previously discussed in section 7.7.1.

7.9.1. Generality of Technique in Reaching Movements

A direct extension of the work presented would be investigate the generality of the results. A similar study to ours could be performed but with the environment systematically varied. This may lead to a greater generalisation of the attributes of each type of foot orientation. Alternatively specific environments may produce specific responses with each foot orientation. Use of steeper angled walls would allow investigation of the whole-body centre of mass interaction with the base of support. The movement patterns may become fundamentally different when the mechanics of the situation fundamentally change.

Analysis of each technique over longer routes may amplify the differences in performance measures. Thus climber could utilise each technique to perform the same route and the performances compared.

7.9.2. Advances in the Coordination in the Techniques

Further investigation into the coordinative aspects of each technique is warranted. Unfortunately, three-dimensional movement currently lacks a tool for quantifying co-ordination in a similar way to relative phase measures in two-dimensional movement, so the development of such a tool is needed.

Quantification of co-ordination may be achieved through electromyographic (EMG) analyses of the muscle activations. This technique has previously been used in analyses of cycling (e.g. Neptune et al., 1997) and vertical jumping (Bobbert & van Ingen Schenau, 1988). Analyses of the whole body using EMG analysis would provide a greater understanding of coordination complexity within each technique.

The type of technique used to make a reaching movement has been shown by the research presented here to affect the performance of the task. An interesting future direction would be to investigate the dynamics of acquiring expertise in each of the techniques. The traditional view of a proximal-distal release of degrees of freedom with expertise (Bernstein, 1967) has been challenged in balance maintenance tasks (e.g. Ko et al., 2001). Therefore, investigation into how each technique is acquired would not only provide insight into the relative difficulty of attaining proficiency in each technique, which would be of interest to climbers and coaches, but also into more general motor control theories of learning.

Analysis of the variability of the joint rotations within subjects would allow investigation of the adaptability of each technique to different environmental challenges. Rock climbers have to be able to constantly adapt to the infinitely variable terrain. Therefore, knowledge of how the coordinative patterns associated with each technique vary with differing environmental constraints would be beneficial.

7.9.3. Mechanical Analyses

It was noted above that there were limitations in the mechanical and postural analyses. Future work should seek to enhance the analyses in this thesis, through study of the application of forces on the supports. Previous research, as discussed in detail in the Literature Review, has established the use of kinetic analyses (e.g. Noé et al., 2001; Quaine & Martin, 1999), but not in the investigation of different techniques and not in combination with three-dimensional kinematics. The use of both types of analysis would allow MEE to be calculated in a non-controversial manner, using Aleshinsky's (1986a,b) model and the pattern of force organisational change accompanying a reaching movement. Measurement of the forces applied by the hands and feet to the supports would allow the mechanisms for maintaining postural stability to be measured directly. A more detailed mechanical analysis would allow the generation and absorption of energy at different joints to be investigated, greatly increasing the understanding of the energetics associated with each technique. For example, reduction in the produced power of the arm musculature in a particular technique would be beneficial to performance, as it might delay the onset of fatigue.

The use of electromyographic (EMG) analysis of the forearm flexors has had previous research interest in terms of different types of hand grip (Watts et al., 2003) and fatigue (Quaine & Vigouroux, 2004). This methodology could be extended to determine the impact of different techniques on fatigue in the finger flexors. Digital, wireless EMG measurement units are now available; if they were employed, participants could use each of the three techniques identified in our work to climb a whole route, and have their the flexor activity monitored. This would provide further understanding of the effect of technique on the performance of reaching movements.

Isometric muscle contractions have been recognised to be a component of rock climbing activity (Booth et al., 1999); indeed isometric contractions can constitute up to a third of the total time to complete a route (Billat et al., 1995). Application of any contemporary mechanical work models is therefore limited. However, metabolic energy expenditure of each technique could be investigated. The use of portable metabolic analysis systems has already been employed in analyses of climbers' performances over whole routes (Watts, 2004). Similar to the EMG study suggested above, whole climbing routes may then be attempted with the climbers just using one particular technique to perform the arm reaches. The effectiveness of the techniques on performance could then be compared in terms of metabolic energy expenditure.

7.10. Conclusions

The research question for this study was to evaluate the impact of different ipsilateral foot orientations on reaching tasks in overhanging rock climbing situations. To help answer the question three specific research objectives were formulated.

1) To establish that the ways in which climbers in an overhanging rock environment solve a reaching-movement task, using different orientations of the ipsilateral foot, constitute separate techniques.

Objective 1 was achieved through a detailed analysis of the sequence of movements made by climbers solving a particular reaching task with different ipsilateral foot orientations, in a specific overhanging situation. It was demonstrated that different specific sequences of movements occurred in the successful completion of the task with different orientations of the foot. The different orientations of the foot can be said to constitute separate, identifiable techniques for solving a reaching task on an overhanging wall. The different orientations of the foot did not constitute separate techniques for making the actual hand reach movement. A single coordinative structure was identified for the arm making the reach, which adapted to the different body geometry through the elevation angle at the shoulder.

2) To establish a robust methodology for detailed quantitative analysis of the position and orientation of the climber using any of these techniques on an overhanging wall

A robust methodology was established via a series of validation studies. These studies served to validate the successful application of theoretical principles to a kinematic model of a climber on an overhanging climbing wall. The studies also validated the mostly custom written programs.

3) To establish the effect of ipsilateral foot orientation on the performance of the reaching task on an overhanging wall.

Ipsilateral foot orientation was shown to affect the performance of a reaching task in terms of postural demand and energetic demand but not in terms of trajectory efficiency.

Evaluating the impact of foot orientation on reaching tasks in overhanging situations has lead to the overall conclusion that although the reaching arm movement are not affected by foot orientation, the overall technique and performance of a reaching task is.

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Appendix A Anatomical Terminology

The following definitions will be used in this thesis. Positional terms are referenced to the standard 'neutral' anatomical position (the person is standing, looking forward, facing the reader, with palms facing forward).

Positional terms

Anterior	towards the font, or in front
Distal	away from the trunk or root of the limb
Inferior	below
Lateral	away from the midline
Medial	towards the midline
Posterior	towards the rear, or behind
Proximal	close to the trunk or root of the limb
Superior	above

Planes

Plane of elevation 0° is abduction, 90°is forward flexion.

Anatomical landmarks

Head

VER	most cranial point of the head (vertex)
INI	The external occipital protuberance (inion)

Thorax

C7	processus spinosus (spinous process) of the 7th cervical vertebra
T8	processus spinosus (spinal process) of the 8th thoracic vertebra
IJ	deepest point of incisura jugularis (suprasternal notch, SCN)
PX	processus xiphoideus (xiphoid process), most caudal point on the sternum

Humerus

GH	glenohumeral rotation centre, estimated by regression or motion recordings
EL	most caudal point on lateral epicondyle
EM	most caudal point on medial epicondyle

Forearm

RS	most caudal-lateral point on the radial styloid
US	most caudal-medial point on the ulnar styloid

Hand

H1	3rd metacarple – a point on the dorsal sulcus between the tip of the third metacarpal and the base of the third finger

Pelvis

ASIS	anterior superior iliac spine
PSIS	posterior superior iliac spine

Femur

FH	centre of the femoral head
ME	medial epicondyle
LE	lateral epicondyle

Shank

TT	prominence of the tibial tuberosity
HF	apex of head of the fibula
MM	distal apex of the medial malleolus
LM	distal apex of the lateral malleolus

Foot

SM	second metacarpal head
CM	dorsal aspect of the cuboidmetatarsal joint
CP	calcaneous posterior surface

Anatomical coordinate systems

Head

Y_h	the line connecting the midpoint between IJ and C7 and the VER, pointing upwards
Z_h	the line perpendicular to the plane formed by VER, INI and the midpoint between IJ and C7, pointing to the right
X_h	the common line perpendicular to the Z_h- and Y_h-axis, pointing forwards

Trunk

Y_{tr}	the line connecting the midpoint between LHJ and RHJ and the midpoint between IJ and C7, pointing upwards.
Z_{tr}	the line perpendicular to the plane formed by IJ, midpoint between LHJ and RHJ and the midpoint between IJ and C7, pointing to the right.
X_{tr}	the common line perpendicular to the Z_{tr}- and Y_{tr}-axis, pointing forwards

Thorax

Y_t	the line connecting the midpoint between PX and T8 and the midpoint between IJ and C7, pointing upward.
Z_t	the line perpendicular to the plane formed by IJ, C7, and the midpoint between PX and T8, pointing to the right.
X_t	the common line perpendicular to the Z_t- and Y_t-axis, pointing forwards.

Humerus

Y_{h2}	the line connecting GH and the midpoint of EL and EM, pointing to GH.
Z_{h2}	the line perpendicular to the plane formed by Y_{h2} and Y_f, pointing to the right.
X_{h2}	the common line perpendicular to the Z_{h2}- and Y_{h2}-axis, pointing forward.

Forearm

Y_f	the line connecting US and the midpoint of EL and EM, pointing proximally.
X_f	the line perpendicular to the plane through US, RS, and the midpoint between EL and EM, pointing forward.
Z_f	the common line perpendicular to the X_f- and Y_f-axis, pointing to the right

Hand

Y_{ha}	the line connecting H1 and the midpoint of US and RS, pointing proximally.
X_{ha}	the line perpendicular to the plane through US, RS and H1, pointing forward
Z_{ha}	the common line perpendicular to the X_{ha}- and Y_{ha}-axis, pointing to the right

Pelvis

Z_p	the z axis is oriented as the line passing through the ASISs with its positive direction from left to right.
X_p	the x axis lies in the quasi-transverse plane defined by the ASISs and the midpoint between the PSISs and with its positive direction forwards.
Y_p	the y axis is orthogonal to the xz plane and its positive direction is proximal.

Femur

Y_t	the y axis joins the origin with the centre of the femoral head (FH) and its positive direction is proximal.
Z_t	the z axis lies in the quasi-frontal plane defined by the y axis and by the epicondyles with its positive direction from left to right.
X_t	the x axis is orthogonal to the yz plane with its positive direction forwards.

Shank

Y_s the malleoli and the head of the fibula landmarks (HF) define a plane which is quasi-frontal. A quasi-sagittal plane, orthogonal to the quasi-frontal plane, is defined by the midpoint between the malleoli and the tibial tuberosity (TT). The y axis is defined by the intersection between the above-mentioned planes, with its positive direction proximal.

Z_s the z axis lies in the quasi-frontal plane with its positive direction from left to right.

X_s the x axis is orthogonal to the yz plane with its positive direction forwards.

Foot

X_{fo} the line connecting CP and SM, pointing distally.

Y_{fo} the line perpendicular to the plane through CP, CM, SM, pointing cranially.

Z_{fo} the common line perpendicular to X_{fo}- and Y_{fo}-axis, pointing to the right.

Direction of motion

The following are referenced to the three cardinal anatomical planes: transverse (horizontal), coronal (frontal) and sagittal (median)

- *Abduction* The movement of a body segment in a coronal plane that moves away from the midline of the body.
- *Adduction* The movement of a body segment in a coronal plane such that it moves towards the midline of the body.
- *Flexion* The bending of adjacent body segments in the sagittal plane, so that their two anterior / posterior surfaces are brought together.
- *Extension* The moving apart or straightening of two opposing surfaces in a sagittal plane. It also refers to movement beyond the neutral position in the direction opposite of flexion.
- *External rotation* Rotation of a limb segment about its longitudinal axis away from the midline of the body.
- *Internal rotation* Rotation of a limb segment about its longitudinal axis towards the midline of the body.

Foot

- *Eversion* Rotation of a limb segment about its longitudinal axis away from the midline of the body.
- *External rotation* The movement of a body segment in a coronal plane that moves away from the midline of the body.
- *Extension* The moving apart or straightening of two opposing surfaces in a sagittal plane. It also refers to movement beyond the neutral position in the direction opposite of flexion.
- *Flexion* The bending of adjacent body segments in the sagittal plane, so that their two anterior / posterior surfaces are brought together.
- *Internal rotation* The movement of a body segment in a coronal plane such that it moves towards the midline of the body.
- *Inversion* Rotation of a limb segment about its longitudinal axis towards the midline of the body.

References

Wu et al., 2002, 2005; de Leva, 2002; Cappozzo et al., 1997.

Appendix B. Mean Centre of Mass Displacement and Velocity Values in x, y and z directions, P values and Effect size in each Movement Phase

Table B-1 Centre of Mass displacement values in the x direction, P values and Effect Size values for comparisons between techniques at the start of the movement and at the end of each phase.

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P Value	Effect Size
Start Movement		0.402	0.043	0.414	0.037	0.412	0.054	0.457	0.09
End of Phase	1	0.400	0.040	0.420	0.034			0.002	0.82
	2	0.382	0.031	0.400	0.037			0.077	0.43
	3	0.352^{a}	0.029	0.343^{b}	0.029	$0.376^{a,b}$	0.034	0.001	0.70
	4	0.308^{a}	0.026	$0.277^{a,b}$	0.017	0.320^{b}	0.018	0.001	0.71
	5	0.334^{a}	0.025	$0.298^{a,b}$	0.018	0.356^{b}	0.051	0.001	0.71

^{a,b} denote where significant differences lie between techniques P<0.05
* denotes possible type II error

Table B-2 Centre of Mass displacement values in the y direction, P values and Effect Size values for comparisons between techniques at the start of the movement and at the end of each phase.

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P Value	Effect Size
Start Movement		0.422	0.031	0.425	0.027	0.417	0.021	0.265	0.20
End of Phase	1	0.414	0.026	0.417	0.023			0.506	0.08
	2	0.385	0.031	0.457	0.029			0.001	0.88
	3	0.410^{a}	0.035	$0.468^{a,b}$	0.027	0.431^{b}	0.026	0.005	0.75
	4	0.473	0.029	0.491	0.017	0.472	0.021	0.373	0.22
	5	0.547	0.046	0.546	0.043	0.541	0.044	0.728	0.03

^{a,b} denote where significant differences lie between techniques P<0.05
* denotes possible type II error

Table B-3 Centre of Mass displacement values in the z direction, P values and Effect Size values for comparisons between techniques at the start of the movement and at the end of each phase.

		IE Mean	IE SD	OE Mean	OE SD	TE Mean	TE SD	P Value	Effect Size
Start Movement		0.717	0.055	0.718	0.058	0.726	0.052	0.114	0.30
End of Phase	1	0.724	0.054	0.727	0.051			0.554	0.06
	2	0.761	0.069	0.763	0.061			0.859	0.06
	3	0.803[a]	0.049	0.804*	0.028	0.833[a,*]	0.041	0.049	0.39
	4	0.928[a]	0.035	0.916[b]	0.028	0.956[a,b]	0.033	0.000	0.88
	5	0.918[a]	0.049	0.913*	0.045	0.947[a,*]	0.049	0.013	0.62

[a,b] denote where significant differences lie between techniques P<0.05
* denotes possible type II error

Table B-4 Centre of Mass velocity values in the x direction, P values and Effect Size values for comparisons between techniques at the end of each phase

		IE Mean	IE SD	OE Mean	OE SD	TE Mean	TE SD	P Value	Effect Size
End of Phase	1	-0.00	0.02	0.04	0.04			0.030	0.57
	2	-0.04	0.04	-0.07	0.05			0.585	0.06
	3	-0.19[a,b]	0.10	-0.21[a]	0.05	-0.22[b]	0.06	0.004	0.67
	4	0.02[a]	0.04	-0.02[a,*]	0.03	0.03*	0.05	0.011	0.53
	5	-0.01	0.01	0.00	0.01	-0.01	0.01		

[a,b] denote where significant differences lie between techniques P<0.05
* denotes possible type II error

Table B-5 Centre of Mass velocity values in the y direction, P values and Effect Size values for comparisons between techniques at the end of each phase

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P Value	Effect Size
	1	-0.06	0.04	-0.05	0.05			0.266	0.20
End	2	0.01	0.05	0.07	0.04			0.044	0.52
of	3	0.12[a]	0.09	0.00[a,*]	0.03	0.06[*]	0.07	0.003	0.63
Phase	4	0.11[*]	0.06	0.07[*]	0.03	0.11[*]	0.05	0.015	0.50
	5	0.01	0.01	0.02	0.02	0.01	0.01		

[a,b] denote where significant differences lie between techniques P<0.05
* denotes possible type II error

Table B-6 Centre of Mass velocity values in the z direction, P values and Effect Size values for comparisons between techniques at the end of each phase

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	P Value	Effect Size
	1	0.05	0.05	0.08	0.09			0.411	0.12
End	2	0.01	0.04	-0.02	0.04			0.206	0.25
of	3	0.39	0.25	0.31[a]	0.16	0.50[a]	0.19	0.006	0.57
Phase	4	0.01	0.02	0.04	0.04	0.00	0.05	0.127	0.29
	5	0.00	0.00	0.00	0.01	0.01	0.01		

[a,b] denote where significant differences lie between techniques P<0.05
* denotes possible type II error

Appendix C Joint Rotation Angles, P values and Effect size between Techniques at the end of each Movement Phase

Table C-1 Mean Joint Rotation angular values, p values between the Inside Edge and Outside Edge techniques and the effect size for the twelve joints at the end of phase 1

		IE		OE			
		Mean	SD	Mean	SD	Main Effect	Effect Size
Left ankle	Z	27	8	24	9	0.027	0.59
	x	17	9	16	10	0.271	0.20
	y	6	5	6	4	0.724	0.02
Left knee	Z	-84	11	-75	11	0.016	0.65
	x	11	3	10	5	0.656	0.04
	y	-26	13	-28	11	0.227	0.23
Left hip	Z	50	17	55	15	0.139	0.33
	x	-42	10	-40	11	0.108	0.37
	y	-20	23	-17	21	0.179	0.28
Left shoulder	Y	20	27	27	24	0.003	0.79
	x	-59	7	-60	8	0.465	0.09
	y	-67	11	-73	9	0.005	0.76
Left elbow	Z	112	12	111	12	0.464	0.09
	y	97	16	99	16	0.014	0.66
Left wrist	Z	-23	17	-21	16	0.146	0.32
	x	-12	14	-13	13	0.463	0.09
Right ankle	Z	7	8	7	10	0.765	0.02
	x	39	9	42	9	0.029	0.58
	y	35	10	34	14	0.397	0.12
Right knee	Z	-81	10	-73	10	0.010	0.70
	x	12	10	5	9	0.007	0.72
	y	-18	14	-25	12	0.001	0.88
Right hip	Z	49	8	49	9	0.705	0.03
	x	-21	14	-9	9	0.003	0.79
	y	-1	15	3	13	0.007	0.73
Right shoulder	Y	23	13	26	11	0.341	0.15
	x	-63	12	-63	12	0.525	0.11
	y	-68	11	-70	8	0.945	0.00
Right elbow	Z	111	15	111	14	0.678	0.03
	y	107	9	105	11	0.260	0.21
Right wrist	Z	-26	12	-27	9	0.539	0.07
	x	-7	6	-8	6	0.267	0.20

Table C-2 Mean Joint Rotation angular values, p values between the Inside Edge and Outside Edge techniques and the effect size for the twelve joints at the end of phase 2

		IE		OE			
		Mean	SD	Mean	SD	Main Effect	Effect Size
Left ankle	Z	29	7	14	7	0.000	0.97
	x	19	8	15	10	0.135	0.33
	y	5	6	12	6	0.001	0.85
Left knee	Z	-84	12	-58	6	0.002	0.83
	x	16	6	3	6	0.009	0.77
	y	-23	14	-21	8	0.780	0.01
Left hip	Z	36	17	58	14	0.000	0.93
	x	-40	8	-35	13	0.121	0.35
	y	-29	23	-10	19	0.000	0.92
Left shoulder	Y	17	22	24	17	0.074	0.44
	x	-47	11	-65	11	0.000	0.97
	y	-61	11	-71	8	0.014	0.66
Left elbow	Z	119	13	111	14	0.022	0.68
	y	95	14	101	13	0.049	0.50
Left wrist	Z	-26	20	-23	19	0.042	0.53
	x	-17	13	-14	13	0.110	0.37
Right ankle	Z	9	10	8	9	0.850	0.01
	x	27	9	39	6	0.002	0.81
	y	17	12	39	13	0.000	0.94
Right knee	Z	-77	9	-76	12	0.697	0.03
	x	30	7	-10	7	0.000	0.99
	y	-42	13	-24	11	0.001	0.88
Right hip	Z	47	13	41	10	0.114	0.36
	x	-31	9	13	4	0.000	0.98
	y	-8	17	18	15	0.000	0.90
Right shoulder	Y	13	14	17	18	0.177	0.28
	x	-57	14	-46	15	0.014	0.659
	y	-62	12	-59	18	0.334	0.16
Right elbow	Z	116	14	119	13	0.208	0.25
	y	105	12	106	9	0.684	0.03
Right wrist	Z	-30	12	-33	13	0.022	0.61
	x	-10	6	-10	5	0.900	0.00

Table C-3 Mean Joint Rotation angular values, p values between the three techniques and the effect size for the twelve joints at the end of phase 3

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	Main Effect	Effect Size
Left ankle	Z	19	12	11	5	17	9	0.028	0.45
	x	32	9	26	8	27	8	0.051	0.48
	y	17	12	19	6	15	7	0.382	0.13
Left knee	Z	$-78^{a,b}$	18	-55^{a}	9	-64^{b}	14	0.002	0.65
	x	13^{*}	6	$2^{*,a}$	6	9^{a}	5	0.007	0.56
	y	-21	13	-23	7	-28	10	0.090	0.33
Left hip	Z	$31^{a,b}$	13	$52^{a,c}$	12	$41^{b,c}$	14	0.000	0.87
	x	-43	6	-34	12	-44	8	0.055	0.44
	y	$-29^{a,b}$	22	$-7^{b,c}$	14	$-19^{a,c}$	20	0.000	0.83
Left shoulder	Y	-5	14	-3	12	-7	12	0.493	0.11
	x	-45^{a}	4	$-66^{a,b}$	5	-45^{b}	7	0.000	0.93
	y	-41^{a}	12	$-53^{a,b}$	5	-41^{b}	12	0.002	0.66
Left elbow	Z	121	8	118	7	120	11	0.202	0.23
	y	94	12	95	14	95	11	0.835	0.03
Left wrist	Z	-29^{*}	17	-23^{*}	15	-32^{*}	19	0.006	0.58
	x	-19^{*}	15	$-14^{*,a}$	14	-22^{a}	15	0.001	0.68
Right ankle	Z	14	11	7	14	9	10	0.303	0.18
	x	$26^{a,b}$	10	43^{a}	9	41^{b}	8	0.000	0.79
	y	$14^{a,b}$	12	$39^{a,*?}$	17	$28^{b,*?}$	14	0.000	0.76
Right knee	Z	-78^{a}	13	-85^{b}	13	$-63^{a,b}$	16	0.000	0.77
	x	$32^{a,b}$	6	$-10^{b,c}$	10	$5^{a,c}$	11	0.000	0.94
	y	-33	7	-40	13	-32	20	0.308	0.18
Right hip	Z	35	15	31	12	32	13	0.493	0.09
	x	$-33^{a,b}$	8	$23^{b,c}$	4	$-1^{a,c}$	18	0.000	0.87
	y	$-18^{a,b}$	18	$16^{b,c}$	16	$0^{a,c}$	17	0.000	0.84
Right shoulder	Y	-5	16	-14	19	-2	17	0.074	0.35
	x	$-42^{a,b}$	11	$-29^{a,*}$	9	$-36^{b,*}$	11	0.000	0.72
	y	-36^{*}	24	$-14^{*,a}$	20	-32^{a}	17	0.004	0.60
Right elbow	Z	123^{*}	5	125^{*}	6	121^{*}	5	0.03	0.441
	y	100	11	100	13	102	12	0.77	0.042
Right wrist	Z	-32	13	-37	14	-33	14	0.228	0.22
	x	-16	7	-19	8	-19	10	0.302	0.181

^{a,b} denote where significant differences lie between techniques

* denotes possible type II error

Table C-4 Mean Joint Rotation angular values, p values between the three techniques and the effect size for the twelve joints at the end of phase 4

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	Main Effect	Effect Size
Left ankle	Z	-2	6	-7	6	-6	10	0.252	0.21
	x	36[a]	9	28[a]	9	32	7	0.028	0.76
	y	26	12	26	4	24	9	0.765	0.044
Left knee	Z	-39[*]	19	-31[*]	12	-31[*]	15	0.039	0.42
	x	12	7	4	4	7	5	0.074	0.42
	y	-39[*]	11	-30[*,a]	9	-36[a]	9	0.020	0.48
Left hip	Z	23[a]	12	37[a,b]	12	28[b]	12	0.000	0.83
	x	-31	7	-25	7	-32	5	0.087	0.34
	y	-18[a]	15	-7[a,b]	14	-16[b]	16	0.001	0.71
Left shoulder	Y	-17[a]	10	-10[a,*]	10	-16[*]	12	0.002	0.64
	x	-46[a]	10	-60[a,b]	7	-48[b]	9	0.000	0.84
	y	-30[a]	13	-41[a,b]	9	-29[b]	13	0.001	0.70
Left elbow	Z	116	13	116	6	117	14	0.94	0.01
	y	100[*]	17	96[*]	15	102[*]	15	0.032	0.44
Left wrist	Z	-37[a]	12	-28[a,b]	12	-41[b]	16	0.001	0.71
	x	-28	16	-24	14	-28	15	0.061	0.37
Right ankle	Z	11	12	7	13	9	9	0.632	0.07
	x	27[a,b]	8	40[a]	10	38[b]	7	0.005	0.58
	y	16[a]	11	35[a]	16	24	13	0.006	0.57
Right knee	Z	-58[*,a]	19	-69[*,b]	19	-41[a,b]	16	0.000	0.79
	x	31[a,b]	8	-17[a,c]	10	4[b,c]	13	0.000	0.93
	y	-40	13	-42	11	-34	12	0.273	0.20
Right hip	Z	25	15	22	11	19	13	0.286	0.19
	x	-22[a,b]	7	18[a,*]	3	0[b,*]	15	0.000	0.82
	y	-26[a,b]	13	13[a,c]	13	-7[b,c]	13	0.000	0.89
Right shoulder	Y	-12	12	-12	8	-12	11	0.988	0.002
	x	-105[a]	9	-93[a]	10	-99	15	0.001	0.71
	y	-116	15	-113	18	-113	25	0.878	0.32
Right elbow	Z	23	2	24	3	25	3	0.601	0.08
	y	148	22	149	25	148	29	0.965	0.01
Right wrist	Z	-13	5	-13	5	-13	8	0.985	0.003
	x	2	8	1	8	0	7	0.282	0.19

[a,b] denote where significant differences lie between techniques
* denotes possible type II error

Table C-5 Mean Joint Rotation angular values, p values between the three techniques and the effect size for the twelve joints at end of phase 5

		IE		OE		TE			
		Mean	SD	Mean	SD	Mean	SD	Main Effect	Effect Size
Left ankle	Z	-7[a]	11	-13[a]	11	-11	12	0.012	0.52
	x	26*	8	19*	12	21*	9	0.027	0.45
	y	18	9	21	4	17	10	0.407	0.17
Left knee	Z	-34*	23	-22*	16	-25	18	0.011	0.53
	x	12	8	5	5	6	3	0.154	0.31
	y	-40*	11	-31*	9	-36	10	0.078	0.48
Left hip	Z	16[a]	11	31[a,b]	10	20[b]	13	0.000	0.81
	x	-34	7	-26	7	-34	5	0.059	0.38
	y	-24[a]	15	-11[a,b]	16	-23[b]	16	0.000	0.75
Left shoulder	Y	-5*	10	2*	9	0*	11	0.026	0.46
	x	-51[a]	6	-63[a,b]	5	-50[b]	6	0.000	0.82
	y	-46	9	-50	7	-44	12	0.059	0.38
Left elbow	Z	98	13	101	12	96	15	0.325	0.17
	y	104	14	101*	13	107*	15	0.006	0.57
Left wrist	Z	-35[a]	12	-26[a,b]	12	-39[b]	16	0.001	0.67
	x	-24	13	-25	13	-26	11	0.326	0.17
Right ankle	Z	14	12	7	13	10	14	0.291	0.19
	x	28[a,*]	9	38*	10	35[a]	8	0.023	0.47
	y	14[a]	11	37[a]	14	24	9	0.001	0.66
Right knee	Z	-61[a]	17	-70[b]	17	-44[a,b]	16	0.000	0.83
	x	30[a,b]	6	-16[a,c]	8	4[a,b]	12	0.000	0.94
	y	-35	11	-42	12	-30	11	0.095	0.33
Right hip	Z	24	12	22	11	19	14	0.315	0.18
	x	-19[a,c]	7	19[b]	4	1[c]	16	0.000	0.81
	y	-25[a,*]	14	15[a,b]	15	-5[b,*]	10	0.000	0.86
Right shoulder	Y	-13	14	-14	10	-10	15	0.270	0.20
	x	-107[a]	15	-96[a]	14	-103	17	0.003	0.62
	y	-88	21	-93	20	-84	22	0.172	0.36
Right elbow	Z	35	17	32	18	35	17	0.351	0.20
	y	130	27	135	30	127	25	0.200	0.24
Right wrist	Z	-18	8	-17	9	-19	10	0.379	0.15
	x	5	6	4	5	4	7	0.763	0.04

[a,b] denote where significant differences lie between techniques

* denotes possible type II error

Appendix D. Medical Questionnaire

UNIVERSITY OF LEEDS
SCHOOL OF SPORT AND EXERCISE SCIENCES
MEDICAL QUESTIONNAIRE

If you feel unwell on the day of a proposed test, or have been feeling poorly within the last two weeks, you are excluded from taking part in an exercise test. The considerations that follow apply to people who have been feeling well for the preceding two weeks.

NAME: ....

SEX: M/F AGE: .... (yr) HEIGHT: .... (m) WEIGHT: .... (kg)
Handed: Left/Right/Ambi Arm span: ....cm

Details of last medical examination (where appropriate):

Date: .... Location: ....
(day/mo/yr)

Exercise lifestyle:
What kind(s) of exercise do you regularly do (20 minutes or more per session), and how often? (*Please circle the number of times per average week*):

Bouldering	1	2	3	4	5+
Sport Climbing	1	2	3	4	5+
Trad Climbing	1	2	3	4	5+
Walking	1	2	3	4	5+
Running	1	2	3	4	5+
Cycling	1	2	3	4	5+
Swimming	1	2	3	4	5+
Skiing	1	2	3	4	5+
Rowing	1	2	3	4	5+
Gymnastics	1	2	3	4	5+
Martial Arts	1	2	3	4	5+
Weight Training	1	2	3	4	5+
Field Athletics	1	2	3	4	5+
Racket Sports	1	2	3	4	5+
Rugby/soccer/hockey	1	2	3	4	5+
Others*	1	2	3	4	5+

*(*Please specify*) ....

How long have you been exercising at least twice/week for at least 20 minutes/session?
.... years

How long have you been rock climbing: ....years...........months

What type of rock do you regularly climb: ....

Which type of rock did you first learn to climb on: ....

What is your preferred aspect of climbing: ....

What grade do you regularly expect to on-sight
Bouldering: ....
Traditional Climbing: ....
Sport Climbing: ....

What is the hardest grade you have climbed on-sight
Bouldering: ....
Traditional Climbing: ....
Sport Climbing: ....

What is the hardest grade you have ever climbed
Bouldering: ....
Traditional Climbing: ....
Sport Climbing: ....

Illnesses: Have you ever had any of the following? (*Please circle NO or YES*)

Anaemia	NO/YES	Asthma	NO/YES
Diabetes	NO/YES	Epilepsy	NO/YES
Heart Disease	NO/YES	High Blood Pressure	NO/YES
Other*	NO/YES		

*(*Please specify*) ....

Symptoms:

Have you ever had any of the following symptoms to a significant degree at rest or during exercise? That is, have you had to consult a physician relating to any of the following?

	Rest	*Exercise*
Breathlessness	NO/YES	NO/YES
Chest Pain	NO/YES	NO/YES
Dizzy Fits/Fainting	NO/YES	NO/YES
Heart Murmurs	NO/YES	NO/YES
Palpitations	NO/YES	NO/YES
Tightness in chest, jaw or arm	NO/YES	NO/YES
Other*	NO/YES	

*(*Please specify*) ....

Muscle or joint injury:
Do you have/or have had any muscle or joint injury which could affect your safety in performing exercise (*e.g.* cycling or running)? NO/YES*

*(*Please specify*) ....

Medication:
Are you currently taking any medication? NO/YES*

*(*Please specify*) ....

Family History of Sudden Death:
Is there a history of sudden death in people under 40 years in your family?
NO/YES*

*(*Please specify*) ....

The following exclusion and inclusion criteria will apply to this study:
Exclusion criteria: If you have any of the following, you will be excluded from the study::

(a) Asthma, diabetes, epilepsy, heart disease, a family history of sudden death at a young age, fainting bouts, high blood pressure, anaemia, and muscle or joint injury.
(b) A recent illness or viral infection within two weeks of the experiment.
(c) Taking any medication that may adversely health or exercise performance.
(d) Taking recreational or performance-enhancing drugs.

Inclusion criteria:

(a) Male or female subject aged at least 18 years
(b) Participating for at least two hours per week in rock climbing activity
(c) Be able to climb at or above a level of F7a
(d) In good health at the time of testing.

If you are involved in more than one visit to the laboratory, you will be asked to complete the medical and physical activity questionnaire on each subsequent visit, to establish whether or not your health status has changed. If the investigator has any concern in this regard (see Exclusion criteria above), you will be excluded.

Signature .... Date ....

Appendix E. Post-task Questionnaire

UNIVERSITY OF LEEDS
SCHOOL OF SPORT AND EXERCISE SCIENCES
TECHNIQUE PERCEPTION QUESTIONNAIRE

NAME: ....

Now that you have completed the experiment, please rank the three techniques you have performed, using the criteria below. Please try to be honest about how it felt to perform each technique and not allow any prior opinions of the techniques influence your answer.

STABILITY

MOST STABLE

1) ....
2) ....
3) ....

LEAST STABLE

WORK

MOST EFFORT

1) ....
2) ....
3) ....

LEAST EFFORT

MOST USEFUL TECHNIQUE ON AN OVERHANGING ROUTE

1) ....
2) ....
3) ....

LEAST USEFUL TECHNIQUE ON AN OVERHANGING ROUTE

REASONS:...
....
....
....
....

Appendix F Segment Coordinate Program

```
function
[headlcs,thoraciclcs,pelvislcs,trunklcs,lhandlcs,lforelcs,l
humlcs,rhandlcs,rforelcs,rhumlcs,lfootlcs,lshanklcs,lfe
murlcs,rfootlcs,rshanklcs,rfemurlcs,thoraciclcsb,pelvisl
csb,lhandlcsb,lforelcsb,lhumlcsb,lfootlcsb,lshanklcsb,lf
emurlcsb] =
lcscom(movement,localvectors,CSinvtransmatrix)
% Matlab function to calculate the a)local coordinate
system for each segment
% with the origin at the segmental CoM for a 14
segment human body in each
% frame

% Written by Chris Low 15/6/04 Adapted 5/1/05
%
% Local coord systems based on ISB recommendations
for legs and arms
% LCS for head and trunk not based on an ISB
recommendation

% requires the use of localvectors2 program to give the
localvectors of the
% anatomical landmarks in the correct form

% Ouput:   a) Right hand CS for each of 14 body
segments plus the thorax and
%          pelvis
%          b) Mirrored Right hand CS for the left side of
the body plus
%          thorax and pelvis (denoted by a b postfix). The
mirrored CS
%          should be used for parameterising the
transformation matrices
%          when studying joint orientations. Mirroring
achieved through
%          negating the saggittal data (y=-y)


% Identify technical clusters
% Create transformation matrices for each technical
cluster
% which will convert a local vector into a global vector
[trunk] = transform(movement(:,10:18));
LIC = movement(:,61:63);
RIC = movement(:,64:66);
LPSIS = movement(:,67:69);
RPSIS = movement(:,70:72);
MPSIS = (LPSIS+RPSIS)/2;
pelvistechmarkers = [LIC,MPSIS,RIC];
[hip] = transform(pelvistechmarkers);
[LUA] = transform(movement(:,19:27));
[LF] = transform(movement(:,28:36));
% Only 3 markers on thigh
Lthightechmarkers = [movement(:,73:81)];
[Lthigh] = transform(Lthightechmarkers);
% Only 3 markers on shank
Lshanktechmarkers = [movement(:,82:90)];
[Lshank] = transform(Lshanktechmarkers);

[RUA] = transform(movement(:,40:48));
[RF] = transform(movement(:,49:57));
% Only 3 markers on thigh
Rthightechmarkers = [movement(:,100:108)];
[Rthigh] = transform(Rthightechmarkers);
% Only 3 markers on shank
Rshanktechmarkers = [movement(:,109:117)];
[Rshank] = transform(Rshanktechmarkers);

% Identify the movement markers required
[VER] = movement(:,1:3);
[INI] = movement(:,4:6);
[C7] = movement(:,10:12);
[T8] = movement(:,16:18);
[LH1] = movement(:,37:39);
[RH1] = movement(:,58:60);
[LTO] = movement(:,91:93);
[LP1] = movement(:,94:96);
[LHL] = movement(:,97:99);
[RTO] = movement(:,118:120);
[RP1] = movement(:,121:123);
[RHL] = movement(:,124:126);

% Input anatomical markers local vectors and convert
into
% global co-ords
% local vectors in form 1,x,y,z; 1 vector per row
[SCN] = globalanat(trunk,localvectors(1,:)');
[XIP] = globalanat(trunk,localvectors(2,:)');
[OMP] = globalanat(trunk,localvectors(3,:)');
[LASIS] = globalanat(hip,localvectors(4,:)');
[RASIS] = globalanat(hip,localvectors(5,:)');
[LSH] = globalanat(LUA,localvectors(6,:)');
[LE1] = globalanat(LUA,localvectors(7,:)');
[LE2] = globalanat(LUA,localvectors(8,:)');
[LW1] = globalanat(LF,localvectors(9,:)');
[LW2] = globalanat(LF,localvectors(10,:)');
[LK1] = globalanat(Lthigh,localvectors(12,:)');
[LK2] = globalanat(Lthigh,localvectors(13,:)');
[LTT] = globalanat(Lshank,localvectors(14,:)');
[LHF] = globalanat(Lshank,localvectors(15,:)');
[LA1] = globalanat(Lshank,localvectors(16,:)');
[LA2] = globalanat(Lshank,localvectors(17,:)');
[RSH] = globalanat(RUA,localvectors(18,:)');
[RE1] = globalanat(RUA,localvectors(19,:)');
[RE2] = globalanat(RUA,localvectors(20,:)');
[RW1] = globalanat(RF,localvectors(21,:)');
[RW2] = globalanat(RF,localvectors(22,:)');
[RK1] = globalanat(Rthigh,localvectors(24,:)');
[RK2] = globalanat(Rthigh,localvectors(25,:)');
[RTT] = globalanat(Rshank,localvectors(26,:)');
[RHF] = globalanat(Rshank,localvectors(27,:)');
[RA1] = globalanat(Rshank,localvectors(28,:)');
[RA2] = globalanat(Rshank,localvectors(29,:)');


% Local coordinate system pelvis [PelvisCS]
[pelvislcs] = pelvisref(LASIS,RASIS,LPSIS,RPSIS);
% now calculate hip joint centres
[LHJ] = globalanat(pelvislcs,localvectors(11,:)');
[RHJ] = globalanat(pelvislcs,localvectors(23,:)');

% Convert global co-ords from ProReflex Global CS to
Climbing Wall Global
% CS
[VER] = climbCS(VER,CSinvtransmatrix);
[INI] = climbCS(INI,CSinvtransmatrix);
```

```
[C7] = climbCS(C7,CSinvtransmatrix);
[T8] = climbCS(T8,CSinvtransmatrix);
[SCN] = climbCS(SCN,CSinvtransmatrix);
[XIP] = climbCS(XIP,CSinvtransmatrix);
[OMP] = climbCS(OMP,CSinvtransmatrix);
[LASIS] = climbCS(LASIS,CSinvtransmatrix);
[RASIS] = climbCS(RASIS,CSinvtransmatrix);
[LPSIS] = climbCS(LPSIS,CSinvtransmatrix);
[RPSIS] = climbCS(RPSIS,CSinvtransmatrix);
[LSH] = climbCS(LSH,CSinvtransmatrix);
[LE1] = climbCS(LE1,CSinvtransmatrix);
[LE2] = climbCS(LE2,CSinvtransmatrix);
[LW1] = climbCS(LW1,CSinvtransmatrix);
[LW2] = climbCS(LW2,CSinvtransmatrix);
[LH1] = climbCS(LH1,CSinvtransmatrix);
[LHJ] = climbCS(LHJ,CSinvtransmatrix);
[LK1] = climbCS(LK1,CSinvtransmatrix);
[LK2] = climbCS(LK2,CSinvtransmatrix);
[LTT] = climbCS(LTT,CSinvtransmatrix);
[LHF] = climbCS(LHF,CSinvtransmatrix);
[LA1] = climbCS(LA1,CSinvtransmatrix);
[LA2] = climbCS(LA2,CSinvtransmatrix);
[LTO] = climbCS(LTO,CSinvtransmatrix);
[LP1] = climbCS(LP1,CSinvtransmatrix);
[LHL] = climbCS(LHL,CSinvtransmatrix);
[RSH] = climbCS(RSH,CSinvtransmatrix);
[RE1] = climbCS(RE1,CSinvtransmatrix);
[RE2] = climbCS(RE2,CSinvtransmatrix);
[RW1] = climbCS(RW1,CSinvtransmatrix);
[RW2] = climbCS(RW2,CSinvtransmatrix);
[RH1] = climbCS(RH1,CSinvtransmatrix);
[RHJ] = climbCS(RHJ,CSinvtransmatrix);
[RK1] = climbCS(RK1,CSinvtransmatrix);
[RK2] = climbCS(RK2,CSinvtransmatrix);
[RTT] = climbCS(RTT,CSinvtransmatrix);
[RHF] = climbCS(RHF,CSinvtransmatrix);
[RA1] = climbCS(RA1,CSinvtransmatrix);
[RA2] = climbCS(RA2,CSinvtransmatrix);
[RTO] = climbCS(RTO,CSinvtransmatrix);
[RP1] = climbCS(RP1,CSinvtransmatrix);
[RHL] = climbCS(RHL,CSinvtransmatrix);

% Mirrored anatomical landmarks
[LH1b] = [LH1(:,1),LH1(:,2)*-1,LH1(:,3)];
[LW1b] = [LW1(:,1),LW1(:,2)*-1,LW1(:,3)];
[LW2b] = [LW2(:,1),LW2(:,2)*-1,LW2(:,3)];
[LE1b] = [LE1(:,1),LE1(:,2)*-1,LE1(:,3)];
[LE2b] = [LE2(:,1),LE2(:,2)*-1,LE2(:,3)];
[LSHb] = [LSH(:,1),LSH(:,2)*-1,LSH(:,3)];
[LTOb] = [LTO(:,1),LTO(:,2)*-1,LTO(:,3)];
[LP1b] = [LP1(:,1),LP1(:,2)*-1,LP1(:,3)];
[LHLb] = [LHL(:,1),LHL(:,2)*-1,LHL(:,3)];
[LA1b] = [LA1(:,1),LA1(:,2)*-1,LA1(:,3)];
[LA2b] = [LA2(:,1),LA2(:,2)*-1,LA2(:,3)];
[LHFb] = [LHF(:,1),LHF(:,2)*-1,LHF(:,3)];
[LTTb] = [LTT(:,1),LTT(:,2)*-1,LTT(:,3)];
[LK1b] = [LK1(:,1),LK1(:,2)*-1,LK1(:,3)];
[LK2b] = [LK2(:,1),LK2(:,2)*-1,LK2(:,3)];
[LHJb] = [LHJ(:,1),LHJ(:,2)*-1,LHJ(:,3)];
[SCNb] = [SCN(:,1),SCN(:,2)*-1,SCN(:,3)];
[XIPb] = [XIP(:,1),XIP(:,2)*-1,XIP(:,3)];
[C7b] = [C7(:,1),C7(:,2)*-1,C7(:,3)];
[T8b] = [T8(:,1),T8(:,2)*-1,T8(:,3)];
[LASISb] = [LASIS(:,1),LASIS(:,2)*-1,LASIS(:,3)];
[LPSISb] = [LPSIS(:,1),LPSIS(:,2)*-1,LPSIS(:,3)];
[RASISb] = [RASIS(:,1),RASIS(:,2)*-1,RASIS(:,3)];
[RPSISb] = [RPSIS(:,1),RPSIS(:,2)*-1,RPSIS(:,3)];

% Calculate the centre of mass of each segment
% head centre of mass
[hcom] = headcom(SCN,C7,VER);
% trunk centre of mass
[tcom] = trunkcom(SCN,C7,RHJ,LHJ);
% left and right hand centre of mass
[lhacom,rhacom] =
handcom(LW1,LW2,LH1,RW1,RW2,RH1);
% left and right forearm centre of mass
[lfcom,rfcom] =
forecom(LW1,LW2,LE1,LE2,RW1,RW2,RE1,RE2);
% left and right humerus centre of mass
[lhucom,rhucom] =
humeruscom(LE1,LE2,LSH,RE1,RE2,RSH);
% left and right foot centre of mass
[lfocom,rfocom] =
footcom(LTO,LP1,LHL,RTO,RP1,RHL);
% left and right shank centre of mass
[lshcom,rshcom] =
shankcom2(LA1,LA2,LK1,LK2,RA1,RA2,RK1,RK2);
% left and right femur centre of mass
[lfecom,rfecom] =
femurcom(LK1,LK2,LHJ,RK1,RK2,RHJ);

% calculate the relative mass of each segment at the
segmental centre of mass
[headinert] = hcom*6.94;
[trunkinert] = tcom*43.46;
[lhuinert] = lhucom*2.71;
[lfinert] = lfcom*1.62;
[lhainert] = lhacom*0.61;
[lfeinert] = lfecom*14.16;
[lshinert] = lshcom*4.33;
[lfoinert] = lfocom*1.37;
[rhuinert] = rhucom*2.71;
[rfinert] = rfcom*1.62;
[rhainert] = rhacom*0.61;
[rfeinert] = rfecom*14.16;
[rshinert] = rshcom*4.33;
[rfoinert] = rfocom*1.37;

% W should equal 100
[W] =
6.94+43.46+2*(2.71+1.62+0.61+14.16+4.33+1.37);
% com equals sum of inertia values for each segment
[com] =
(headinert+trunkinert+lhuinert+lfinert+lhainert+lfeinert
+lshinert+lfoinert+rhuinert+rfinert+rhainert+rfeinert+rs
hinert+rfoinert)/W;

% Mirrored CS
% Local coordinate system pelvis
[pelvislcsb] =
pelvisrefb(LASISb,RASISb,LPSISb,RPSISb);
% Local coordinate system thoracic
[thoraciclcsb] = thoracicref(SCNb,XIPb,C7b,T8b);
% Local coordinate system left and right hand
[lhandlcsb] = handrefb(LW1b,LW2b,LH1b);
% Local coordinate system left and right forearm
[lforelcsb] = forerefb(LW1b,LW2b,LE1b,LE2b);
% Local coordinate system left and right humerus isb
convention
```

```
[lhumlcsb] = humerusrefb(LE1b,LE2b,LSHb,LW2b);
% Local coordinate system left and right foot
[lfootlcsb] = footrefb(LTOb,LP1b,LHLb);
% Local coordinate system left and right shank
[lshanklcsb] = shankrefb(LA1b,LA2b,LHFb,LTTb);
% Local coordinate system left and right femur
[lfemurlcsb] = femurrefb(LK1b,LK2b,LHJb);

% Right handed CS
% Local coordinate system head
[headlcs] = headref(SCN,C7,INI,VER,hcom);
% Local coordinate system trunk
[trunklcs] = trunkref(SCN,C7,RHJ,LHJ,tcom);
% Local coordinate system thoracic
[thoraciclcs] = thoracicref(SCN,XIP,C7,T8);
% Local coordinate system pelvis [PelvisCS]
[pelvislcs] = pelvisref(LASIS,RASIS,LPSIS,RPSIS);
% Local coordinate system left and right hand
[lhandlcs,rhandlcs] =
handref(LW1,LW2,LH1,RW1,RW2,RH1,lhacom,rhaco
m);
% Local coordinate system left and right forearm
[lforelcs,rforelcs] =
foreref(LW1,LW2,LE1,LE2,RW1,RW2,RE1,RE2,lfco
m,rfcom);
% Local coordinate system left and right humerus isb
convention
[lhumlcs,rhumlcs] =
humerusrefisb(LE1,LE2,LSH,LW2,RE1,RE2,RSH,RW
2,lhucom,rhucom);
% Local coordinate system left and right foot
[lfootlcs,rfootlcs] =
footref(LTO,LP1,LHL,RTO,RP1,RHL,lfocom,rfocom);
% Local coordinate system left and right shank
[lshanklcs,rshanklcs] =
shankref(LA1,LA2,LHF,LTT,RA1,RA2,RHF,RTT,lshc
om,rshcom);
% Local coordinate system left and right femur
[lfemurlcs,rfemurlcs] =
femurref(LK1,LK2,LHJ,RK1,RK2,RHJ,lfecom,rfecom)
;

%%%%%%SUB-FUNCTIONS%%%%%%%%%%

% transform: Matlab function to determine the
transformation
% matrix of the local co-ord system of a rigid body with
respect to global
% taking account of skin errors over the total movement
duration
%
% Written by Chris Low
% Requires the localglobal. m program written by Chris
Low which utilises
% the soder.m program written by:
% Ron Jacobs (R.S. Dow Neurological Institute,
Porland OR),
% adapted by Ton van den Bogert (University of
Calgary).
% Using algorithm described in:
% I. Soederqvist and P.A. Wedin (1993) Determining
the movement of the skeleton
%   using well-configured markers. J. Biomech.
26:1473-1477.
% Same algorithm is described in:
% J.H. Challis (1995) A prodecure for determining
rigid body transformation
%   parameters, J. Biomech. 28, 733-737.
% The latter also includes possibilities for scaling,
reflection, and
% weighting of marker data.
%
% Input:
% data: Matrix of 3-D marker coordinates of rigid body
over time (9 columns, 3 for each marker,
%    one row for each frame of data)
%
% Output:
% T: Matrix comprising of each frames Transformation
matrix to convert co-ordinates from local to global
reference
%    systems OR gives the rotation and translation of
the local frame with
%    regard to the global
%
% the rigid body model is: y = R*x + d

function [T] = transform(data)

%calculate the number of frames of data
nframe = size(data,1);

%start the T matrix with a 4x4 identity matrix
T = eye(4);

%Iterative loop which takes each frame of data,
reshapes to a 3x3 position
%matrix, calculates the transformation matrix using the
localglobal.m
%program. The transformation matrix is successively
placed in matrix t
for a = 1:nframe
   Aa = [reshape(data(a,:)',3,size(data,2)/3)]';
   [Ta] = localglobal(Aa);
   T = [T;Ta];
end

%Remove the first four lines (the identity matrix) from
T matrix
T(1:4,:) = [];

% localglobal: Matlab function to determine the
transformation
% matrix of a rigid body taking account of skin errors
% Written by Chris Low
% Using algorithm described in:
% I. Soederqvist and P.A. Wedin (1993) Determining
the movement of the skeleton
%   using well-configured markers. J. Biomech.
26:1473-1477.
% Same algorithm is described in:
% J.H. Challis (1995) A prodecure for determining
rigid body transformation
%   parameters, J. Biomech. 28, 733-737.
% The latter also includes possibilities for scaling,
reflection, and
% weighting of marker data.
%
% Requires the soder.m program written by:
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% Ron Jacobs (R.S. Dow Neurological Institute, Porland OR),
% adapted by Ton van den Bogert (University of Calgary).
%
% Input:
% x: 3-D marker coordinates of rigid body in position 1 (3 columns, one row for each marker)
%
%
% Output:
% T: Transformation matrix to convert co-ordinates from local to global reference
% systems OR gives the rotation and translation of the local frame with
% regard to the global
%
%
% the rigid body model is: y = R*x + d

function [T] = localglobal(x)

% construct an identity matrix to represent the global reference system
a = eye(3);

% Use the soder2k.m program to calculate the rigid body transformation
% parameters based around the singular value decomposition technique
[R,d,rms] = soder2k(a,x);

% Construct the transformation matrix
T = [1 0 0 0;d,R];

% soder.m: Matlab function to determine rigid body rotation & translation
% From:
% I. Soederqvist and P.A. Wedin (1993) Determining the movement of the skeleton
%   using well-configured markers. J. Biomech. 26:1473-1477.
% Same algorithm is described in:
% J.H. Challis (1995) A prodecure for determining rigid body transformation
%   parameters, J. Biomech. 28, 733-737.
% The latter also includes possibilities for scaling, reflection, and
% weighting of marker data.
%
% Written by Ron Jacobs (R.S. Dow Neurological Institute, Porland OR),
% adapted by Ton van den Bogert (University of Calgary).
%
% Input:
% x: 3-D marker coordinates in position 1 (3 columns, one row for each marker)
% y: 3-D marker coordinates in position 2 (same format)
%
% Output:
% R: rotation matrix
% d: translation vector
% rms: the root mean square fit error of the rigid body model
%
% the rigid body model is: y = R*x + d
%
function[R,d,rms]=soder2k(x,y)

[nmarkers,ndimensions]=size(x);
% we could give an error message if ndimensions is not 3

mx=mean(x);
my=mean(y);

% construct matrices A and B, subtract the mean so there is only rotation
for i=1:nmarkers,
  A(i,:)=x(i,:)-mx;
  B(i,:)=y(i,:)-my;
end
A = A';
B = B';

% The singular value decomposition to calculate R with det(R)=1
C=B*A';
[P,T,Q]=svd(C);
R=P*diag([1 1 det(P*Q')])*Q';

% Calculate the translation vector from the centroid of all markers
d=my'-R*mx';

% calculate RMS value of residuals
sumsq = 0;
for i=1:nmarkers
  ypred = R*x(i,:)' + d;
  sumsq = sumsq + norm(ypred-y(i,:)')^2;
end
rms = sqrt(sumsq/3/nmarkers);

% globalanat: Matlab function to determine the global co-ords of an anatomical marker
% defined in a technical cluster over the total movement duration
%
% Written by Chris Low
%
% Input:
% data:Matrix of technical clusters' transformation matrices for each frame of data
% x: 3-D anatomical marker local coordinates (1 column, 4 rows of form
% [1;x;y;z])
%
% Output:
% d: Matrix of anatomical marker global co-ords in each frame of data
% (nframe rows, 3 columns x,y,z in global reference system)
%
% the rigid body model is: y = R*x + d

function [d] = globalanat(data,x)
% calculate the number of rows
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nrows = size(data,1);

%calculate the number of frames
nframe = nrows/4;

%start b matrix
b = [1;0;0;0];

%Iterative loop which takes each transformation matrix
and multiplies it by
%the local co-ordinate vector of the anatomical marker
to give the global
%co-ordinates of the anatomical marker. The global co-
ords are succesively
%placed in matrix b
for a = 1:4:(nrows-3)
  A = (data(a:(a+3),:)*x);
    b = [b;A];
end

%remove the first four elements of matrix b
b(1:4) = [];

%reshape matrix b into a nframex4 matrix (1 row is one
frame of data, 1st
%column = 1, 2nd, 3rd and 4th columns represent x,y
and z respectively)
d = reshape(b,4,nframe)';

%Remove the 1st column to leave x,y,z co-ordinates of
anatomical marker
%in each frame
d(:,1) = [];

function [NEW] = climbCS(OLD,matrix)
% Matlab function to convert global co-ords from one
reference system to a
% second reference system when there is translation
and rotation
nrows = size(OLD,1);
% Need to add a column of ones to start of OLD data so
that the data can be
% multplied by the 4x4 inverse transformation matrix
OLD = [ones(size(OLD,1),1),OLD];
NEW = [1,1,1];
for a = 1:nrows
  m = matrix*OLD(a,:)';
% remove the 1st row from the vector to leave the 3
coords
  n = m(2:4);
  NEW = [NEW;n'];
end
NEW(1,:) = [];

% Segmental Centre of Mass Programs
% Input:
% data: Matrix of 3-D marker coordinates of rigid body
over time (9 columns, 3 for each marker,
%   one row for each frame of data)
% Output:
% T: Matrix comprising of centre of mass position of
segment in each frame
% References
% De Leva (1996) Adjustments to Zatsiorsky-
Seluyanov's Segment Inertia
% Parameters

function [Cm] = headcom(SCN,C7,VER)
data = [SCN,C7,VER];
nframe = size(data,1);
Cm = [1,1,1];
for a = 1:nframe
%   find midpoint SCN and C7
  SCNC7MID = (data(a,1:3)'+data(a,7:9)')/2; %column
%   find y axis
  y = SCNC7MID - data(a,7:9)'; %column
%   find vector b from vertex to C7
  b = data(a,4:6)'-data(a,7:9)';   %column
%   make unit vector of y
  ymag = norm(y);
  u = y/ymag; %column
%   find c, the magnitude of component of vector b
along the longitudinal
%   segment of the segment, vector y
  c = dot(b,u);
%   find magnitude of vector from head to centre of
mass
  d = (c/100)*50.02;
%   find vector D
  D = d*u;
%   find centre of mass position on longitudinal axis of
head segment
  cm = data(a,7:9)'+D;
  Cm = [Cm;cm'];
end
Cm(1,:) = [];

function [Cm] = trunkcom(SCN,C7,RHJ,LHJ)
data = [SCN,C7,RHJ,LHJ];
nframe = size(data,1);
Cm = [1,1,1];
for a = 1:nframe
%   find midpoint HJC
  HJCMID = (data(a,7:9)'+data(a,10:12)')/2; %column
%   find midpoint SCN and C7
  SCNC7MID = (data(a,1:3)'+data(a,7:9)')/2; %column
%   find y axis
  y = SCNC7MID - HJCMID; %column
%   find vector b from mid hip to SCN
  b = data(a,1:3)'-HJCMID;   %column
%   make unit vector of y
  ymag = norm(y);
  u = y/ymag; %column
%   find c, the magnitude of component of vector b
along the longitudinal
%   segment of the segment, vector y
  c = dot(b,u);
%   find magnitude of vector from mid hip to centre of
mass
  d = (c/100)*(100-44.86);
%   find vector D
  D = d*u;
%   find centre of mass position on longitudinal axis of
trunk segment
  cm = HJCMID+D;
  Cm = [Cm;cm'];
end
Cm(1,:) = [];
```

```
function [LCm,RCm] =
handcom(LW1,LW2,LH3,RW1,RW2,RH3)
data = [LW1,LW2,LH3,RW1,RW2,RH3];
nframe = size(data,1);
LCm = [1,1,1];
RCm = [1,1,1];
for a = 1:nframe
%    find the origin at Mid wrist joint
   lorigin = (data(a,1:3)'+data(a,4:6)')/2;
   rorigin = (data(a,10:12)'+data(a,13:15)')/2;
%    find y axis
   ly = data(a,7:9)'-lorigin; %LH3
   ry = data(a,16:18)'-rorigin; %RH3
 %    make unit vectors
   lymag = norm(ly);
   lu = ly/lymag;
   rymag = norm(ry);
   ru = ry/rymag;
%    find magnitude of vector from mid wrist to centre
of mass
   lb = (lymag/100)*79.0; % was 0.61 this is an error,
0.61 is actually % of total mass
   rb = (rymag/100)*79.0; % attributed to the hand
segment. Correction made 29th Sept 04
%    find vector B, from mid wrist to centre of mass
   lB = lb*lu;
   rB = rb*ru;
%    find centre of mass position on longitudinal axis of
wrist segment
   lcm = lorigin+lB;
   rcm = rorigin+rB;
   LCm = [LCm;lcm'];
   RCm = [RCm;rcm'];
end
LCm(1,:) = [];
RCm(1,:) = [];

function [LCm,RCm] =
forecom(LW1,LW2,LE1,LE2,RW1,RW2,RE1,RE2)
data = [LW1,LW2,LE1,LE2,RW1,RW2,RE1,RE2];
nframe = size(data,1);
LCm = [1,1,1];
RCm = [1,1,1];
for a = 1:nframe
%    find the origin at Mid elbow joint
   lorigin = (data(a,7:9)'+data(a,10:12)')/2;
   rorigin = (data(a,19:21)'+data(a,22:24)')/2;
%    find midpoint of wrist
  LWMID = (data(a,1:3)'+data(a,4:6)')/2;
  RWMID = (data(a,13:15)'+data(a,16:18)')/2;
%    find y axis
   ly = LWMID-lorigin;
   ry = RWMID-rorigin;
%    make unit vectors
   lymag = norm(ly);
   lu = ly/lymag;
   rymag = norm(ry);
   ru = ry/rymag;
%    find magnitude of vector from mid elbow to centre
of mass
   lb = (lymag/100)*45.74;
   rb = (rymag/100)*45.74;
%    find vector B, from mid elbow to centre of mass
   lB = lb*lu;
   rB = rb*ru;
%    find centre of mass position on longitudinal axis of
forearm segment
   lcm = lorigin+lB;
   rcm = rorigin+rB;
   LCm = [LCm;lcm'];
   RCm = [RCm;rcm'];
end
LCm(1,:) = [];
RCm(1,:) = [];

function [LCm,RCm] =
humeruscom(LE1,LE2,LSH,RE1,RE2,RSH)
data = [LE1,LE2,LSH,RE1,RE2,RSH];
nframe = size(data,1);
LCm = [1,1,1];
RCm = [1,1,1];
for a = 1:nframe
%    find the origin at shoulder joint centre joint
   lorigin = data(a,7:9)'; %LSH
   rorigin = data(a,16:18)'; %RSH
%    find midpoint of elbow
  LEMID = (data(a,1:3)'+data(a,4:6)')/2;
  REMID = (data(a,10:12)'+data(a,13:15)')/2;
%    find y axis
   ly = LEMID-lorigin;
   ry = REMID-rorigin;
%    make unit vectors
   lymag = norm(ly);
   lu = ly/lymag;
   rymag = norm(ry);
   ru = ry/rymag;
%    find magnitude of vector from shoulder joint
centre to centre of mass
   lb = (lymag/100)*57.72;
   rb = (rymag/100)*57.72;
%    find vector B, from shoulder joint centre to centre
of mass
   lB = lb*lu;
   rB = rb*ru;
%    find centre of mass position on longitudinal axis of
humerus segment
   lcm = lorigin+lB;
   rcm = rorigin+rB;
   LCm = [LCm;lcm'];
   RCm = [RCm;rcm'];
end
LCm(1,:) = [];
RCm(1,:) = [];

function [LCm,RCm] =
footcom(LTO,LP1,LHL,RTO,RP1,RHL)
data = [LTO,LP1,LHL,RTO,RP1,RHL];
nframe = size(data,1);
LCm = [1,1,1];
RCm = [1,1,1];
for a = 1:nframe
%    find the origin at heel
   lorigin = data(a,7:9)'; %LHL
   rorigin = (data(a,16:18))'; %RHL
%    find y axis (longitudinal axis - actually x, not
matter)
   ly = data(a,1:3)'-data(a,7:9)';
   ry = data(a,10:12)'-data(a,16:18)';
%    make unit vectors
   lymag = norm(ly);
```

```
  lu = ly/lymag;
  rymag = norm(ry);
  ru = ry/rymag;
%   find magnitude of vector from heel to centre of
mass
  lb = (lymag/100)*44.15;
  rb = (rymag/100)*44.15;
%   find vector B, from heel to centre of mass
  lB = lb*lu;
  rB = rb*ru;
%   find centre of mass position on longitudinal axis of
foot segment
  lcm = lorigin+lB;
  rcm = rorigin+rB;
  LCm = [LCm;lcm'];
  RCm = [RCm;rcm'];
end
LCm(1,:) = [];
RCm(1,:) = [];

function [LCm,RCm] =
shankcom2(LA1,LA2,LK1,LK2,RA1,RA2,RK1,RK2)
data = [LA1,LA2,LK1,LK2,RA1,RA2,RK1,RK2];
nframe = size(data,1);
LCm = [1,1,1];
RCm = [1,1,1];
for a = 1:nframe
%   find the origin at the knee joint centre
  lorigin = (data(a,7:9)'+data(a,10:12)')/2;
  rorigin = (data(a,19:21)'+data(a,22:24)')/2;
%   find the ankle joint centre joint
  lAJC = (data(a,1:3)'+data(a,4:6)')/2;
  rAJC = (data(a,13:15)'+data(a,16:18)')/2;
%   find y axis
  ly = lAJC-lorigin;
  ry = rAJC-rorigin;
%   make unit vectors
  lymag = norm(ly);
  lu = ly/lymag;
  rymag = norm(ry);
  ru = ry/rymag;
 %   find magnitude of vector from knee joint centre to
centre of mass
  lb = (lymag/100)*43.95;
  rb = (rymag/100)*43.95;
%   find vector B, from knee joint centre to centre of
mass
  lB = lb*lu;
  rB = rb*ru;
%   find centre of mass position on longitudinal axis of
shank segment
  lcm = lorigin+lB;
  rcm = rorigin+rB;
  LCm = [LCm;lcm'];
  RCm = [RCm;rcm'];
end
LCm(1,:) = [];
RCm(1,:) = [];


function [LCm,RCm] =
femurcom(LK1,LK2,LHJ,RK1,RK2,RHJ)
data = [LK1,LK2,LHJ,RK1,RK2,RHJ];
nframe = size(data,1);
LCm = [1,1,1];
RCm = [1,1,1];
for a = 1:nframe
%   find the origin at hip joint centre joint
  lorigin = data(a,7:9)'; %LHJ
  rorigin = data(a,16:18)'; %RHJ
%   find midpoint of knee
 LKMID = (data(a,1:3)'+data(a,4:6)')/2;
 RKMID = (data(a,10:12)'+data(a,13:15)')/2;
%   find y axis
  ly = LKMID-lorigin;
  ry = RKMID-rorigin;
%   make unit vectors
  lymag = norm(ly);
  lu = ly/lymag;
  rymag = norm(ry);
  ru = ry/rymag;
 %   find magnitude of vector from hip joint centre to
centre of mass
  lb = (lymag/100)*40.95;
  rb = (rymag/100)*40.95;
%   find vector B, from hip joint centre to centre of
mass
  lB = lb*lu;
  rB = rb*ru;
%   find centre of mass position on longitudinal axis of
femur segment
  lcm = lorigin+lB;
  rcm = rorigin+rB;
  LCm = [LCm;lcm'];
  RCm = [RCm;rcm'];
end
LCm(1,:) = [];
RCm(1,:) = [];

% Segment lcs programs
% Input:
% data: Matrix of 3-D marker coordinates of rigid body
over time (9 columns, 3 for each marker,
%   one row for each frame of data)
%
% Output:
% T: Matrix comprising of each frames Transformation
matrix to convert co-ordinates from local to global
reference
%   systems OR gives the rotation and translation of
the local frame with
%   regard to the global
%
% the rigid body model is: y = R*x + d
%

function [T] = headref(SCN,C7,INI,VER,hcom)
data = [SCN,C7,INI,VER];
nframe = size(data,1);
T = eye(4);
for a = 1:nframe
%   find the origin at head com
  origin = hcom(a,:)';
%   find midpoint of SCN and C7
  SCNC7MID = (data(a,1:3)'+data(a,7:9)')/2;
%   find y axis
  y = data(a,10:12)'-SCNC7MID;
%   find z axis perpendicular to plane fitted to points
SCNC7MID, VER and
%   INI pointing right (if looking at back of head)
```

```
  b = data(a,7:9)'-SCNC7MID;
  z = cross(y,b);
  %    find x axis perpendicular to z and y
  x = cross(y,z);
%    make unit vectors
  xmag = norm(x);
  x = x/xmag;
  ymag = norm(y);
  y = y/ymag;
  zmag = norm(z);
  z = z/zmag;

% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  R = [x,y,z];
  d = origin;
% Construct the transformation matrix and the inverse
transformation matrix
  Ta = [1 0 0 0;d,R];
  T = [T;Ta];
end
T(1:4,:) = [];


function [T] = pelvisref(LASIS,RASIS,LPSIS,RPSIS)
data = [LASIS,RASIS,LPSIS,RPSIS];
nframe = size(data,1);
T = eye(4);
for a = 1:nframe
%    x = [reshape(data(a,:)',3,size(data,2)/3)]';
%    find the origin
  origin = (data(a,1:3)'+data(a,4:6)')/2;
%    find midpoint PSIS's
  PSISMID = (data(a,7:9)'+data(a,10:12)')/2;
%    find z axis
  z = data(a,4:6)'-data(a,1:3)';
%    find x axis
  x = origin - PSISMID;
%    find y axis
  y = cross(z,x);
%    make unit vectors
  xmag = norm(x);
  x = x/xmag;
  ymag = norm(y);
  y = y/ymag;
  zmag = norm(z);
  z = z/zmag;

% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  R = [x,y,z];
  d = origin;
% Construct the transformation matrix and the inverse
transformation matrix
  Ta = [1 0 0 0;d,R];
  T = [T;Ta];
end
T(1:4,:) = [];

function [T] = thoracicref(SCN,XIP,C7,T8)
data = [SCN,XIP,C7,T8];
nframe = size(data,1);
T = eye(4);
for a = 1:nframe
%    find the origin
  origin = XIP(a,:)';
%    find midpoint XIP and T8
  XIPT8MID = (data(a,4:6)'+data(a,10:12)')/2;
%    find midpoint SCN and C7
  SCNC7MID = (data(a,1:3)'+data(a,7:9)')/2;
%    find y axis
  y = SCNC7MID-XIPT8MID;
%    find z axis perpendicular to plane fitted to points
SCN, C7 and
%    XIPT8MID pointing to right
%    b = data(a,7:9)'-data(a,1:3)';
  c = data(a,7:9)'-XIPT8MID;
  d = data(a,1:3)'-XIPT8MID;
  z = cross(d,c);
%    z = cross(y,b);
%    find x axis perpendicular to x and y, pointing
forward
  x = cross(y,z);
%    make unit vectors
  xmag = norm(x);
  x = x/xmag;
  ymag = norm(y);
  y = y/ymag;
  zmag = norm(z);
  z = z/zmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  R = [x,y,z];
  d = origin;
% Construct the transformation matrix and the inverse
transformation matrix
  Ta = [1 0 0 0;d,R];
  T = [T;Ta];
end
T(1:4,:) = [];


function [T] = trunkref(SCN,C7,RHJ,LHJ,tcom)
data = [SCN,C7,RHJ,LHJ];
nframe = size(data,1);
T = eye(4);
for a = 1:nframe
%    find the origin at Mid hip joint
  origin = tcom(a,:)';
%    find midpoint HJC
  HJCMID = (data(a,7:9)'+data(a,10:12)')/2;
%    find midpoint SCN and C7
  SCNC7MID = (data(a,1:3)'+data(a,7:9)')/2;
%    find y axis
  y = SCNC7MID - HJCMID;
%    find z axis perpendicular to plane fitted to points
SCNC7MID, SCN and
%    mid hip joints pointing left (if looked at front of
torso)
  b = data(a,1:3)'-HJCMID;
  z = cross(b,y);
```

```
  %    find x axis perpendicular to z and y
  x = cross(y,z);
%    make unit vectors
  xmag = norm(x);
  x = x/xmag;
  ymag = norm(y);
  y = y/ymag;
  zmag = norm(z);
  z = z/zmag;

% Calculate the rotation matrix R of the local system in the global and the
% position vector d of the origin of the local co-ordinate system (at marker
% 1)
  R = [x,y,z];
  d = origin;
% Construct the transformation matrix and the inverse transformation matrix
  Ta = [1 0 0 0;d,R];
  T = [T;Ta];
end
T(1:4,:) = [];

function [L,R] = handref(LW1,LW2,LH1,RW1,RW2,RH1,lhacom,rhacom)
data = [LW1,LW2,LH1,RW1,RW2,RH1];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%    find the origin at hand com
  lorigin = lhacom(a,:)';
  rorigin = rhacom(a,:)';
%    find mid wrist
  lmidw = (data(a,1:3)'+data(a,4:6)')/2;
  rmidw = (data(a,10:12)'+data(a,13:15)')/2;
%    find y axis
  ly = lmidw -data(a,7:9)'; %LH1
  ry = rmidw -data(a,16:18)'; %RH1
%    find x axis perpendicular to plane fitted to points W1, W2 and
%    H3 pointing anteriorally
  b = data(a,4:6)'-data(a,1:3)'; %LW2-LW1
  c = data(a,10:12)'-data(a,13:15)'; %RW1-RW2
  lx = cross(ly,b);
  rx = cross(ry,c);
%    find z axis perpendicular to x and y
  lz = cross(lx,ly);
  rz = cross(rx,ry);
%    make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
  rxmag = norm(rx);
  rx = rx/rxmag;
  rymag = norm(ry);
  ry = ry/rymag;
  rzmag = norm(rz);
  rz = rz/rzmag;
% Calculate the rotation matrix R of the local system in the global and the
% position vector d of the origin of the local co-ordinate system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
  rR = [rx,ry,rz];
  rd = rorigin;
% Construct the transformation matrix and the inverse transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
  rTa = [1 0 0 0;rd,rR];
  R = [R;rTa];
end
L(1:4,:) = [];
R(1:4,:) = [];

function [L,R] = foreref(LW1,LW2,LE1,LE2,RW1,RW2,RE1,RE2,lfcom,rfcom)
data = [LW1,LW2,LE1,LE2,RW1,RW2,RE1,RE2];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%    find the origin at forearm com
  lorigin = lfcom(a,:)';
  rorigin = rfcom(a,:)';
%    find mid elbow
  LEMID = (data(a,7:9)'+data(a,10:12)')/2;
  REMID = (data(a,19:21)'+data(a,22:24)')/2;
%    find midpoint of wrist
 LWMID = (data(a,1:3)'+data(a,4:6)')/2;
 RWMID = (data(a,13:15)'+data(a,16:18)')/2;
%    find y axis
  ly = LEMID - data(a,4:6)'; %LEMID-LW2
  ry = REMID - data(a,16:18)';% REMID-RW2
%    find x axis perpendicular to plane fitted to points W1, W2 and Midpoint
%  of epicondyles pointing anteriorally
  b = LEMID - data(a,1:3)'; %LEMID-LW1
  c = REMID - data(a,13:15)'; %REMID-RW1
  lx = cross(b,ly);
  rx = cross(c,ry);
%    find z axis perpendicular to x and y
  lz = cross(lx,ly);
  rz = cross(rx,ry);
%    make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
  rxmag = norm(rx);
  rx = rx/rxmag;
  rymag = norm(ry);
  ry = ry/rymag;
  rzmag = norm(rz);
  rz = rz/rzmag;
% Calculate the rotation matrix R of the local system in the global and the
```

```
% position vector d of the origin of the local co-ordinate system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
  rR = [rx,ry,rz];
  rd = rorigin;
% Construct the transformation matrix and the inverse transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
  rTa = [1 0 0 0;rd,rR];
  R = [R;rTa];
end
L(1:4,:) = [];
R(1:4,:) = [];


function [L,R] =
humerusrefisb(LE1,LE2,LSH,LW2,RE1,RE2,RSH,RW2,lhucom,rhucom)
data = [LE1,LE2,LSH,LW2,RE1,RE2,RSH,RW2];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%   find the origin at humerus com
  lorigin = lhucom(a,:)';
  rorigin = rhucom(a,:)';
%   find the shoulder joint centre
  LSH = data(a,7:9)'; %LSH
  RSH = data(a,19:21)'; %RSH
%   find midpoint of elbow
  LEMID = (data(a,1:3)'+data(a,4:6)')/2;
  REMID = (data(a,13:15)'+data(a,16:18)')/2;
%   find y axis
  ly = LSH - LEMID;
  ry = RSH - REMID;
%   find z axis perpendicular to plane formed by yhumerus and yforearm
%   pointing to the right
  lyf = LEMID-data(a,10:12)'; % Left mid epicondyle - ulnar styloid (LW2)
  ryf = REMID-data(a,22:24)'; % Right mid epicondyle - ulnar styloid (RW2)
  lz = cross(ly,lyf);
  rz = cross(ry,ryf);
%   find x axis perpendicular to x and y
  lx = cross(ly,lz);
  rx = cross(ry,rz);
%   make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
  rxmag = norm(rx);
  rx = rx/rxmag;
  rymag = norm(ry);
  ry = ry/rymag;
  rzmag = norm(rz);
  rz = rz/rzmag;
% Calculate the rotation matrix R of the local system in the global and the
% position vector d of the origin of the local co-ordinate system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
  rR = [rx,ry,rz];
  rd = rorigin;
% Construct the transformation matrix and the inverse transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
  rTa = [1 0 0 0;rd,rR];
  R = [R;rTa];
end
L(1:4,:) = [];
R(1:4,:) = [];

function [L,R] =
footref(LTO,LP1,LHL,RTO,RP1,RHL,lfocom,rfocom)
data = [LTO,LP1,LHL,RTO,RP1,RHL];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%   find the origin at centre of mass
  lorigin = lfocom(a,:)';
  rorigin = rfocom(a,:)';

%  find the longitudinal axis, for foot is x
  lx = data(a,1:3)'-data(a,7:9)';
  rx = data(a,10:12)'-data(a,16:18)';
%  find y axis, pointing cranially
  b = data(a,4:6)'-data(a,7:9)'; %LP1 -LHL
  c = data(a,13:15)'-data(a,16:18)'; %RP1-RHL
  ly = cross(lx,b);
  ry = cross(c,rx);
%  find z perpendicular to x and y pointing to the right
  lz = cross(lx,ly);
  rz = cross(rx,ry);
%   make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
  rxmag = norm(rx);
  rx = rx/rxmag;
  rymag = norm(ry);
  ry = ry/rymag;
  rzmag = norm(rz);
  rz = rz/rzmag;
% Calculate the rotation matrix R of the local system in the global and the
% position vector d of the origin of the local co-ordinate system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
  rR = [rx,ry,rz];
  rd = rorigin;
% Construct the transformation matrix and the inverse transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
```

```
  rTa = [1 0 0 0;rd,rR];
  R = [R;rTa];
end
L(1:4,:) = [];
R(1:4,:) = [];

function [L,R] =
shankref(LA1,LA2,LHF,LTT,RA1,RA2,RHF,RTT,lshc
om,rshcom)
data = [LA1,LA2,LHF,LTT,RA1,RA2,RHF,RTT];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%   find the origin at shank com
  lorigin = lshcom(a,:)';
  rorigin = rshcom(a,:)';
%   find the midpoint of ankle
  LAMID = (data(a,1:3)'+data(a,4:6)')/2;
  RAMID = (data(a,13:15)'+data(a,16:18)')/2;
%   find x axis perpendicular to plane fitted to points
A1, A2 and
%   HF pointing anteriorally
  b = data(a,4:6)'-data(a,1:3)'; %LA2 -LA1
  c = data(a,13:15)'-data(a,16:18)'; %RA1-RA2
  d = data(a,7:9)'-data(a,1:3)'; %LHF-LA1
  e = data(a,19:21)'-data(a,13:15)'; %RHF-RA1
  lx = cross(d,b);
  rx = cross(e,c);
%   find vector m, normal to the plane of the ankle
midpoint, TT and vector x
  f = data(a,10:12)'-LAMID;
  g = data(a,22:24)'-RAMID;
  lm = cross(lx,f);
  rm = cross(rx,g);
%   find y axis as the line of intersection of the 2
planes
  ly = cross(lm,lx);
  ry = cross(rm,rx);
%   find z axis perpendicular to x and y
  lz = cross(lx,ly);
  rz = cross(rx,ry);
%   make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
  rxmag = norm(rx);
  rx = rx/rxmag;
  rymag = norm(ry);
  ry = ry/rymag;
  rzmag = norm(rz);
  rz = rz/rzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
  rR = [rx,ry,rz];
  rd = rorigin;
% Construct the transformation matrix and the inverse
transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
  rTa = [1 0 0 0;rd,rR];
  R = [R;rTa];
end
L(1:4,:) = [];
R(1:4,:) = [];


function [L,R] =
femurref(LK1,LK2,LHJ,RK1,RK2,RHJ,lfecom,rfecom)
data = [LK1,LK2,LHJ,RK1,RK2,RHJ];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%   find the origin at femur com
  lorigin = lfecom(a,:)';
  rorigin = rfecom(a,:)';
  LHJ = data(a,7:9)'; %LHJ
  RHJ = data(a,16:18)'; %RHJ
%   find midpoint of knee
 LKMID = (data(a,1:3)'+data(a,4:6)')/2;
 RKMID = (data(a,10:12)'+data(a,13:15)')/2;
%   find y axis
  ly = LHJ - LKMID;
  ry = RHJ - RKMID;
%   find x axis perpendicular to plane fitted to points
K1, K2 and
%   HJC pointing anteriorally
  b = data(a,4:6)'-data(a,1:3)'; %LK2 -LK1
  c = data(a,10:12)'-data(a,13:15)'; %RK1-RK2
  lx = cross(ly,b);
  rx = cross(ry,c);
%   find z axis perpendicular to x and y
  lz = cross(lx,ly);
  rz = cross(rx,ry);
%   make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
  rxmag = norm(rx);
  rx = rx/rxmag;
  rymag = norm(ry);
  ry = ry/rymag;
  rzmag = norm(rz);
  rz = rz/rzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
  rR = [rx,ry,rz];
  rd = rorigin;
% Construct the transformation matrix and the inverse
transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
```

```
  rTa = [1 0 0 0;rd,rR];
  R = [R;rTa];
end
L(1:4,:) = [];
R(1:4,:) = [];

%%%Velocity and Accel Sub-functions%%%%%
function [v] = velocity(T)
% uses double finite difference technique to calculate
velocity
% Input: T - matrix of position data in m
% Output: v - matrix of velocity data
nframes = size(T,1);
tau = 1/150; % frame rate 150 Hz
v = [1];
for a = 1:nframes
  b = T(a,:);
  if a < nframes-1
    c = T(a+2,:);
  else c = (1);
  end
  m = ((c)'-(b)');
  n = m*(1/(2*tau));
  v = [v;n];
end
v(1,:) = [];
v(size(v,1),:) = [];
v(size(v,1),:) = [];

function [ac] = accel(v)
% uses double finite difference technique to calculate
accel
% Input: v - matrix of velocity data in m
% Output: v - matrix of accel data

nframesac = size(v,1);
tau = 1/150;
ac = [1];
for a = 1:nframesac
  b = v(a,:);
  if a < nframesac-1
    c = v(a+2,:);
  else c = (1);
  end
  n = c-b; % in m per second
  AC = n/(2*tau); %in m per second^2
  ac = [ac;AC];
end
ac(1,:) = [];
ac(size(ac,1),:) = [];
ac(size(ac,1),:) = [];

%%%%Mirrorred Coordinate systems%%%%%
function [T] = pelvisrefb(LASIS,RASIS,LPSIS,RPSIS)
data = [LASIS,RASIS,LPSIS,RPSIS];
nframe = size(data,1);
T = eye(4);
for a = 1:nframe
%    x = [reshape(data(a,:)',3,size(data,2)/3)]';
%    find the origin
  origin = (data(a,1:3)'+data(a,4:6)')/2;
%    find midpoint PSIS's
  PSISMID = (data(a,7:9)'+data(a,10:12)')/2;
%    find z axis
  z = data(a,1:3)'-data(a,4:6)'; %LASIS-RASIS
%    find x axis
  x = origin - PSISMID;
%    find y axis
  y = cross(z,x);
%    make unit vectors
  xmag = norm(x);
  x = x/xmag;
  ymag = norm(y);
  y = y/ymag;
  zmag = norm(z);
  z = z/zmag;

% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  R = [x,y,z];
  d = origin;
% Construct the transformation matrix and the inverse
transformation matrix
  Ta = [1 0 0 0;d,R];
  T = [T;Ta];
end
T(1:4,:) = [];


function [L] = handrefb(LW1,LW2,LH1)
data = [LW1,LW2,LH1];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%    find the origin at hand LH1
  lorigin = LH1(a,:)';
%    find mid wrist
  lmidw = (data(a,1:3)'+data(a,4:6)')/2;
%    find y axis
  ly = lmidw -data(a,7:9)'; %LH1
%    find x axis perpendicular to plane fitted to points
W1, W2 and
%    H3 pointing anteriorally
  b = data(a,1:3)'-data(a,4:6)'; %LW1-LW2
  lx = cross(ly,b);
%    find z axis perpendicular to x and y
  lz = cross(lx,ly);
%    make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
% Construct the transformation matrix and the inverse
transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
end
```

```
L(1:4,:) = [];

function [L] = forerefb(LW1,LW2,LE1,LE2)
data = [LW1,LW2,LE1,LE2];
nframe = size(data,1);
L = eye(4);
for a = 1:nframe
%   find the origin at mid epicondyles
  lorigin = (data(a,7:9)'+data(a,10:12)')/2;
%   find mid elbow
  LEMID = (data(a,7:9)'+data(a,10:12)')/2;
%   find midpoint of wrist
  LWMID = (data(a,1:3)'+data(a,4:6)')/2;
%   find y axis
  ly = LEMID - data(a,4:6)'; %LEMID-LW2
%   find x axis perpendicular to plane fitted to points
W1, W2 and Midpoint
%  of epicondyles pointing anteriorally
  b = LEMID - data(a,1:3)'; %LEMID-LW1
  lx = cross(b,ly);
%   find z axis perpendicular to x and y
  lz = cross(lx,ly);
%   make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
% Construct the transformation matrix and the inverse
transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
end
L(1:4,:) = [];

function [L] = humerusrefb(LE1,LE2,LSH,LW2)
data = [LE1,LE2,LSH,LW2];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%   find the origin at humerus com
  lorigin = data(a,7:9)';
%   find the shoulder joint centre
  LSH = data(a,7:9)'; %LSH
%   find midpoint of elbow
  LEMID = (data(a,1:3)'+data(a,4:6)')/2;
%   find y axis
  ly = LSH - LEMID;
%   find z axis perpendicular to plane formed by
yhumerus and yforearm
%   pointing to the right
  lyf = LEMID-data(a,10:12)'; % Left mid epicondyle -
ulnar styloid (LW2)
  lz = cross(ly,lyf);
%   find x axis perpendicular to x and y
  lx = cross(ly,lz);
%   make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
% Construct the transformation matrix and the inverse
transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
end
L(1:4,:) = [];

function [L] = footrefb(LTO,LP1,LHL)
data = [LTO,LP1,LHL];
nframe = size(data,1);
L = eye(4);
R = eye(4);
for a = 1:nframe
%   find the origin at heel
  lorigin = data(a,7:9)';
%   find x axis
%   ly = data(a,7:9)'-data(a,1:3)';
  lx = data(a,1:3)'-data(a,7:9)';
%   find x axis perpendicular to plane fitted to points
TO, HL and
%   P1 pointing anteriorally
  b = data(a,4:6)'-data(a,7:9)'; %LP1 -LHL
%   d = data(a,1:3)'-data(a,7:9)'; %LTO-LHL
  ly = cross(b,lx);
%   find z axis perpendicular to x and y
  lz = cross(lx,ly);

%   make unit vectors
  lxmag = norm(lx);
  lx = lx/lxmag;
  lymag = norm(ly);
  ly = ly/lymag;
  lzmag = norm(lz);
  lz = lz/lzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
  lR = [lx,ly,lz];
  ld = lorigin;
% Construct the transformation matrix and the inverse
transformation matrix
  lTa = [1 0 0 0;ld,lR];
  L = [L;lTa];
end
L(1:4,:) = [];

function [L] = shankrefb(LA1,LA2,LHF,LTT)
data = [LA1,LA2,LHF,LTT];
nframe = size(data,1);
```

```
L = eye(4);
for a = 1:nframe
%    find the origin at mid ankles
   lorigin = (data(a,1:3)'+data(a,4:6)')/2;
%    find the midpoint of ankle
   LAMID = (data(a,1:3)'+data(a,4:6)')/2;
%    find x axis perpendicular to plane fitted to points
A1, A2 and
%    HF pointing anteriorally
%    b = data(a,4:6)'-data(a,1:3)'; %LA2 -LA1
   b = data(a,1:3)'-data(a,4:6)'; %LA1-LA2
   d = data(a,7:9)'-data(a,1:3)'; %LHF-LA1
   lx = cross(d,b);
%    find vector m, normal to the plane of the ankle
midpoint, TT and vector x
   f = data(a,10:12)'-LAMID;
   lm = cross(lx,f);
%    find y axis as the line of intersection of the 2
planes
   ly = cross(lm,lx);
%    find z axis perpendicular to x and y
   lz = cross(lx,ly);
%    make unit vectors
   lxmag = norm(lx);
   lx = lx/lxmag;
   lymag = norm(ly);
   ly = ly/lymag;
   lzmag = norm(lz);
   lz = lz/lzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
   lR = [lx,ly,lz];
   ld = lorigin;
% Construct the transformation matrix and the inverse
transformation matrix
   lTa = [1 0 0 0;ld,lR];
   L = [L;lTa];
end
L(1:4,:) = [];
```

```
function [L] = femurrefb(LK1,LK2,LHJ)
data = [LK1,LK2,LHJ];
nframe = size(data,1);
L = eye(4);
for a = 1:nframe
%    find the origin at femur com
   lorigin = data(a,7:9)';
   LHJ = data(a,7:9)'; %LHJ
%    find midpoint of knee
  LKMID = (data(a,1:3)'+data(a,4:6)')/2;
%    find y axis
   ly = LHJ - LKMID;
%    find x axis perpendicular to plane fitted to points
K1, K2 and
%    HJC pointing anteriorally
   b = data(a,1:3)'-data(a,4:6)'; %LK1 -LK2
   lx = cross(ly,b);
%    find z axis perpendicular to x and y
   lz = cross(lx,ly);
%    make unit vectors
   lxmag = norm(lx);
   lx = lx/lxmag;
   lymag = norm(ly);
   ly = ly/lymag;
   lzmag = norm(lz);
   lz = lz/lzmag;
% Calculate the rotation matrix R of the local system in
the global and the
% position vector d of the origin of the local co-ordinate
system (at marker
% 1)
   lR = [lx,ly,lz];
   ld = lorigin;
% Construct the transformation matrix and the inverse
transformation matrix
   lTa = [1 0 0 0;ld,lR];
   L = [L;lTa];
end
L(1:4,:) = [];
```

ıdix G Spline Filter Program

```
_filter: Matlab function to smooth marker data


ɪt

en by Chris Low 17/01/04
l on:
·ing Filter by
 Reina                  Created: 4/1/1998
Neurosciences Institute, San Diego, CA
Update: 4/7/1998 by GAR


: [coefficients, work, error] =
ilter2(data,opt_mode,opt_val)

 point padding to start data (take first two
everse them
dd to start of data) 19/01/04
(1:3,:);
(1,:);
:3
(j,:)-a(1,:))*-1;
1,:)+c;
;;d];

= [];
ıd(g);
g;data];
 point padding to end of data (take first two
everse them and add to start of data)
(size(data,1)-2:size(data,1),:);
(size(data,1),:);
:3
(j,:)-b(3,:))*-1;
3,:)+c;
ı;d];

[];
,1),:) = [];
ıd(h);
data;h];

3.141592654;
. = 5;          % Fifth-order (quintic) spline
 150;           % 100 Hz = sampling frequency
ING_TIME_DATA = 0; % Time in s when
ıta was begun
f_Freq = 240;
ler = (ORDER + 1) / 2;        % Order of spline
_order - 1
                  % This is to ensure odd
for spline
node = 1;
: for function GCVSPL (see gcvspl.m for
ion)

ırkers = size(data,2);
tapoints = size(data,1);

max_num_timepoints_allowed = num_datapoints;
%Initially set to zero. This will be updated based on
how many
                      % datapoints are contained
within the file.

timepoints(1:num_datapoints) =
STARTING_TIME_DATA + 1/FREQ *
(0:(num_datapoints - 1));

weight_x(1:num_datapoints) = 1.0;
weight_y(1:num_markers) = 1.0;
% opt_val = (FREQ/1000.0)/(2.0*PI*Cutoff_Freq /
1000.0 / ...
%           ((sqrt(2.0) - 1)^(0.5 / half_order)))^
(2.0*half_order);
% opt_val = 1.0e-007;

[coefficients, work, error] = gcvspl(timepoints, ...
        data, ...
        max_num_timepoints_allowed, ...
        weight_x, ...
        weight_y, ...
        half_order, ...
        num_datapoints, ...
        num_markers, ...
        opt_mode, ...
        opt_val, ...
        max_num_timepoints_allowed);

 % remove first and last 2 frames (padding)
 coefficients(1:2,:) = [];
 s = size(coefficients,1);
 coefficients(s-1:s,:) = [];

% gcvspl.mexsg
%
% Woltring's B-spline Algorithm in MATLAB
%
=====================================
%
%Purpose:
%
%    Natural B-spline data smoothing subroutine, using
the Generali-
%    zed Cross-Validation and Mean-Squared
Prediction Error Criteria
%    of Craven & Wahba (1979). Alternatively, the
amount of smoothing
%    can be given explicitly, or it can be based on the
effective
%    number of degrees of freedom in the smoothing
process as defined
%    by Wahba (1980). The model assumes
uncorrelated, additive noise
%    and essentially smooth, underlying functions. The
noise may be
%    non-stationary, and the independent co-ordinates
may be spaced
%    non-equidistantly. Multiple datasets, with
common independent
%    variables and weight factors are accomodated.
%
```

/IATLAB Calling convention:

[C, W, IER] = gcvspl(X, Y, NY, WX, WY, M, N, MD, VAL, NC);

/leaning of parameters:

pe

X(N) (I) Independent variables: strictly
:reasing knot 1-D array of double
sequence, with X(I-1).lt.X(I), I=2,...,N.
Y(NY,K) (I) Input data to be smoothed (or
erpolated). 2-D array of double
NY (I) First dimension of array Y(NY,K),
th NY.ge.N. Integer
WX(N) (I) Weight factor array; WX(I)
rresponds with 1-D array of double
the relative inverse variance of point
I,*).
If no relative weighting information is
available, the WX(I) should be set to
NE.
All WX(I).gt.ZERO, I=1,...,N.
WY(K) (I) Weight factor array; WY(J)
rresponds with 1-D array of double
the relative inverse variance of point
*,J).
If no relative weighting information is
available, the WY(J) should be set to
NE.
All WY(J).gt.ZERO, J=1,...,K.
NB: The effective weight for point
I,J) is
equal to WX(I)*WY(J).
M (I) Half order of the required B-splines
)line Integer
degree 2*M-1), with M.gt.0. The values
=
1,2,3,4 correspond to linear, cubic,
intic,
and heptic splines, respectively.
N (I) Number of observations per dataset,
th N.ge.2*M. Integer
K (I) Number of datasets, with K.ge.1.
MD (I) Optimization mode switch:
teger
|MD| = 1: Prior given value for p in
AL
(VAL.ge.ZERO). This is the
stest
use of GCVSPL, since no
:ration
is performed in p.
|MD| = 2: Generalized cross validation.
|MD| = 3: True predicted mean-squared
:or,
with prior given variance in VAL.
|MD| = 4: Prior given number of
grees of
freedom in VAL
ERO.le.VAL.le.N-M).

% MD < 0: It is assumed that the
contents of
% X, W, M, N, and WK have not
been
% modified since the previous
invoca-
% tion of GCVSPL. If MD < -1,
WK(4)
% is used as an initial estimate for
% the smoothing parameter p. At
the
% first call to GCVSPL, MD must
be > 0.
% Other values for |MD|, and
inappropriate values
% for VAL will result in an error
condition, or
% cause a default value for VAL to be
selected.
% After return from MD.ne.1, the same
number of
% degrees of freedom can be obtained, for
identical
% weight factors and knot positions, by
selecting
% |MD|=1, and by copying the value of p
from WK(4)
% into VAL. In this way, no iterative
optimization
% is required when processing other data
in Y.
% VAL (I) Mode value, as described above
under MD. Double
% C(NC,K) (O) Spline coefficients, to be used in
conjunction 2-D array of double
% with function SPLDER. NB: the
dimensions of C
% in GCVSPL and in SPLDER are
different! In SPLDER,
% only a single column of C(N,K) is
needed, and the
% proper column C(1,J), with J=1...K
should be used
% when calling SPLDER.
% NC (I) First dimension of array C(NC,K),
NC.ge.N. Integer
% WK(IWK) (I/W/O) Work vector, with length
IWK.ge.6*(N*M+1)+N. 1-D array of double
% On normal exit, the first 6 values of WK
are
% assigned as follows:
%
% WK(1) = Generalized Cross Validation
value
% WK(2) = Mean Squared Residual.
% WK(3) = Estimate of the number of
degrees of
% freedom of the residual sum of
squares
% per dataset, with 0.lt.WK(3).lt.N-
M.

WK(4) = Smoothing parameter p,
ltiplicative
with the splines' derivative
ıstraint.
WK(5) = Estimate of the true mean
ıared error
(different formula for |MD| = 3).
WK(6) = Gauss-Markov error variance.

If WK(4) --> 0 , WK(3) --> 0 , and an
ɜr-
polating spline is fitted to the data (p -->

A very small value > 0 is used for p, in
ler
to avoid division by zero in the GCV
ıction.

If WK(4) --> inf, WK(3) --> N-M, and
ɜast-
squares polynomial of order M (degree
1) is
fitted to the data (p --> inf). For
nerical
reasons, a very high value is used for p.

Upon return, the contents of WK can be
ɜd for
covariance propagation in terms of the
ıtrices
B and WE: see the source listings. The
ˈiance
estimate for dataset J follows as
K(6)/WY(J).

IER (O) Error parameter:
eger

IER = 0: Normal exit
IER = 1: M.le.0 .or. N.lt.2*M
IER = 2: Knot sequence is not
ictly
increasing, or some weight
factor is not positive.
IER = 3: Wrong mode parameter
value.

Remarks:

(1) GCVSPL calculates a natural spline of order
M (degree
2*M-1) which smoothes or interpolates a given
of data
points, using statistical considerations to
termine the
amount of smoothing required (Craven & Wahba,
79). If the
error variance is a priori known, it should be
ɔplied to
the routine in VAL, for |MD|=3. The degree of
ıoothing is

% then determined to minimize an unbiased estimate
of the true
% mean squared error. On the other hand, if the error
variance
% is not known, one may select |MD|=2. The routine
then deter-
% mines the degree of smoothing to minimize the
generalized
% cross validation function. This is asymptotically
the same
% as minimizing the true predicted mean squared
error (Craven &
% Wahba, 1979). If the estimates from |MD|=2 or 3
do not appear
% suitable to the user (as apparent from the
smoothness of the
% M-th derivative or from the effective number of
degrees of
% freedom returned in WK(3)), the user may select
an other
% value for the noise variance if |MD|=3, or a
reasonably large
% number of degrees of freedom if |MD|=4. If
|MD|=1, the proce-
% dure is non-iterative, and returns a spline for the
given
% value of the smoothing parameter p as entered in
VAL.
%
% (2) The number of arithmetic operations and the
amount of
% storage required are both proportional to N, so
very large
% datasets may be accomodated. The data points do
not have
% to be equidistant in the independant variable X or
uniformly
% weighted in the dependant variable Y. However,
the data
% points in X must be strictly increasing. Multiple
dataset
% processing (K.gt.1) is numerically more efficient
dan
% separate processing of the individual datasets
(K.eq.1).
%
% (3) If |MD|=3 (a priori known noise variance), any
value of
% N.ge.2*M is acceptable. However, it is advisable
for N-2*M
% be rather large (at least 20) if |MD|=2 (GCV).
%
% (4) For |MD| > 1, GCVSPL tries to iteratively
minimize the
% selected criterion function. This minimum is
unique for |MD|
% = 4, but not necessarily for |MD| = 2 or 3.
Consequently,
% local optima rather that the global optimum might
be found,
% and some actual findings suggest that local optima
might

yield more meaningful results than the global
timum if N
is small. Therefore, the user has some control over
:
search procedure. If MD > 1, the iterative search
rts
from a value which yields a number of degrees of
edom
which is approximately equal to N/2, until the
st (local)
minimum is found via a golden section search
ocedure
(Utreras, 1980). If MD < -1, the value for p
ntained in
WK(4) is used instead. Thus, if MD = 2 or 3 yield
o noisy
an estimate, the user might try |MD| = 1 or 4, for
itably
selected values for p or for the number of degrees

freedom, and then run GCVSPL with MD = -2 or
. The con-
tents of N, M, K, X, WX, WY, and WK are
sumed unchanged
since the last call to GCVSPL if MD < 0.

(5) GCVSPL calculates the spline coefficient
ray C(N,K);
this array can be used to calculate the spline
nction
value and any of its derivatives up to the degree
M-1
at any argument T within the knot range, using
brou-
tines SPLDER and SEARCH, and the knot array
N). Since
the splines are constrained at their Mth derivative,
ly
the lower spline derivatives will tend to be
liable
estimates of the underlying, true signal
rivatives.

(6) GCVSPL combines elements of subroutine
RVO5 by Utre-
ras (1980), subroutine SMOOTH by Lyche et al.
983), and
subroutine CUBGCV by Hutchinson (1985). The
ice of the
influence matrix is assessed in a similar way as
scribed
by Hutchinson & de Hoog (1985). The major
fference is
that the present approach utilizes non-symmetrical
spline
design matrices as described by Lyche et al.
983); there-
fore, the original algorithm by Erisman & Tinney
975) has
been used, rather than the symmetrical version
opted by
Hutchinson & de Hoog.

%
% (7) Our lab uses the following equation to
calculate VAL:
% VAL = (EMG_sampling_frequency/1000.0)
/ pow(2*PI*EMG_CUTOFF_FREQUENCY/1000.0/
% pow((sqrt(2.0) - 1), 0.5/M), 2.0*M)
% where PI is 3.1415... and the
EMG_CUTOFF_FREQUENCY is generally 10 Hz for
the
% arm data that we use (probably 5-6 Hz for
normal gait).
% (equation courtesy of Dan Moran)
%
%References:
%
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Canberra, ACT 2601,
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% F. Utreras (1980), Un paquete de programas para
ajustar curvas
% mediante funciones spline. Informe Tecnico MA-
80-B-209, Depar-
% tamento de Matematicas, Faculdad de Ciencias
Fisicas y Matema-
% ticas, Universidad de Chile, Santiago.
%
% Wahba, G. (1980). Numerical and statistical
methods for mildly,
% moderately and severely ill-posed problems with
noisy data.
% Technical report nr. 595 (February 1980).
Department of Statis-
% tics, University of Madison (WI), U.S.A.
%
% FORTRAN program converted to C by Dwight
Meglan using f2c converter.

% MATLAB 4.x mex file conversion by ChunXiang
Tian (7/4/96 - was he really working on July 4?)
% MATLAB 4.x mex update by David Carta (3/7/97)
% MATLAB 5.1 mex file conversion by Tony Reina
%
% Tony Reina Created: 4/2/1998
% The Neurosciences Institute, San Diego, CA
% Motor Systems Research Lab

Appendix H Work performed by Whole Body Centre of Mass Program

```
% Matlab prog to calculate external work performed by
the whole body centre
% of mass

% Etot = Ep + Ek
% Work  = change in energy (Ef-Ei)
% Input:   data - centre of mass data in m in form of 3
columns (x,y & z)
%          and 1 row per frame
%          mass - participants mass in kg

% Written by Chris Low 24.09.04, adapted
22.12.04,23.12.04(added vertical
% and horizontal kinetic energy)

function [Ep,Ek,Ekv,Ekh,Etot,work,worktot] =
workdone2(data,mass)
g = 9.81;
% calculate potential energy
Ep = [1];
h = data(:,3);
nrows = size(h,1);
for a = 1:nrows
   p = mass*g*h(a);
   Ep = [Ep;p];
end
Ep(1) = [];
nrowsEp = size(Ep,1);
Ep(nrowsEp) = [];
Ep(1) = [];
% calulate kinetic energy
% 1st calculate the velocity vector in each frame
[v] = velocityvect(data);
Ek = [1];
nrowsv = size(v,1);
for a = 1:nrowsv
   k = 0.5*mass*v(a,:)*v(a,:)';
   Ek = [Ek;k];
end
Ek(1) = [];

Ekv = [1];
for a = 1:nrowsv
   kv = 0.5*mass*v(a,3)*v(a,3)';
   Ekv = [Ekv;kv];
end
Ekv(1) = [];

Ekh = [1];
for a = 1:nrowsv
   kh = 0.5*mass*v(a,1:2)*v(a,1:2)';
   Ekh = [Ekh;kh];
end
Ekh(1) = [];

% calculate total energy

Etot = Ep+Ek;

% calculate work done on CoM
% work = (mg(hf-hi))+(((mvf^2)/2)-(mvi^2)/2)

% calculate mg(hf-hi) starting at second height data
point so as to mesh
% with velocity
W1 = [1];
for a = 2:nrows-2
   w = mass*g*(h(a+1)-h(a));
   W1 = [W1;w];
end
W1(1) = [];

%calculate kinetic energy
W2 = [1];
for a = 1:nrowsv-1
   w2 = ((mass/2)*(v(a+1,:)*v(a+1,:)'))-
((mass/2)*(v(a,:)*v(a,:)'));
   W2 = [W2;w2];
end
W2(1) = [];
work = W1+W2;
worktot = sum(work);
%as a check W1 and Dp are the same, W2 and Dk give
same results as do work
%and work2 and worktot and worktot2

%%%%%%%%%SUB-
FUNCTION%%%%%%%%%%%
function [vvect] = velocityvect(T)
% uses double finite difference technique to calculate
translation velocity
% vector from a set of position vectors

nframes = size(T,1);
tau = 1/240;
vvect = [1,1,1];
for a = 1:nframes
   b = T(a,:);
   if a < nframes-1
      c = T(a+2,:);
   else c = [1,1,1];
   end
   m = c'-b';
   n = m*(1/(2*tau)); % in m
   vvect = [vvect;n'];
end
vvect(1,:) = [];
vvect(size(vvect,1),:) = [];
vvect(size(vvect,1),:) = [];
```

Appendix I Moment of Inertia Program

```
function   [WBI,Ixx,Iyy,Izz] =
wholeinertia(headlcs,thoraciclcs,pelvislcs,trunklcs,l
handlcs,lforelcs,lhumlcs,rhandlcs,rforelcs,rhumlcs,l
footlcs,...

lshanklcs,lfemurlcs,rfootlcs,rshanklcs,rfemurlcs,hti,
tti,lhuti,lfti,lhati,lfeti,lshti,lfoti,rhuti,rfti,rhati,rfeti,rs
hti,rfoti,M)
   %input each segement
% Matlab function to calculate the whole body
moment of inertia and principal axes of inertia in
each frame

% Calculate the local terms
% head tensor inertia
[hlocalI] = localterms(headlcs,hti);
% trunk tensor inertia
[tlocalI] = localterms(trunklcs,tti);
% left and right hand tensor inertia
[lhalocalI] = localterms(lhandlcs,lhati);
[rhalocalI] = localterms(rhandlcs,rhati);
% left and right forearm tensor inertia
[lforlocalI] = localterms(lforelcs,lfti);
[rforlocalI] = localterms(rforelcs,rfti);
% left and right humerus tensor inertia
[lhulocalI] = localterms(lhumlcs,lhuti);
[rhulocalI] = localterms(rhumlcs,rhuti);
% left and right foot tensor inertia
[lfolocalI] = localterms(lfootlcs,lfoti);
[rfolocalI] = localterms(rfootlcs,rfoti);
% left and right shank tensor inertia
[lshlocalI] = localterms(lshanklcs,lshti);
[rshlocalI] = localterms(rshanklcs,rshti);
% left and right femur tensor inertia
[lfelocalI] = localterms(lfemurlcs,lfeti);
[rfelocalI] = localterms(rfemurlcs,rfeti);

%Sum of local terms in each frame
[Local] =
local(hlocalI,tlocalI,lhalocalI,lforlocalI,lhulocalI,lf
olocalI,lshlocalI,lfelocalI,...

rhalocalI,rforlocalI,rhulocalI,rfolocalI,rshlocalI,rfel
ocalI);


%Calculate remote terms
% Calculate the segmental masses
[hm] = (M/100)*6.94;
[tm] = (M/100)*43.46;
[lhum] = (M/100)*2.71;
[lform] = (M/100)*1.62;
[lham] = (M/100)*0.61;
[lfem] = (M/100)*14.16;
[lshm] = (M/100)*4.33;
[lfom] = (M/100)*1.37;
[rhum] = (M/100)*2.71;
[rform] = (M/100)*1.62;
[rham] = (M/100)*0.61;
[rfem] = (M/100)*14.16;
[rshm] = (M/100)*4.33;
[rfom] = (M/100)*1.37;

% Calculate remote term index 1,1
[h] = remo11(headlcs,hm);
[t] = remo11(trunklcs,tm);
[lhu] = remo11(lhumlcs,lhum);
[lfor] = remo11(lforelcs,lform);
[lha] = remo11(lhandlcs,lham);
[lfe] = remo11(lfemurlcs,lfem);
[lsh] = remo11(lshanklcs,lshm);
[lfo] = remo11(lfootlcs,lfom);
[rhu] = remo11(rhumlcs,rhum);
[rfor] = remo11(rforelcs,rform);
[rha] = remo11(rhandlcs,rham);
[rfe] = remo11(rfemurlcs,rfem);
[rsh] = remo11(rshanklcs,rshm);
[rfo] = remo11(rfootlcs,rfom);
[remote11] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote11] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 1,2
[h] = remo12(headlcs,hm);
[t] = remo12(trunklcs,tm);
[lhu] = remo12(lhumlcs,lhum);
[lfor] = remo12(lforelcs,lform);
[lha] = remo12(lhandlcs,lham);
[lfe] = remo12(lfemurlcs,lfem);
[lsh] = remo12(lshanklcs,lshm);
[lfo] = remo12(lfootlcs,lfom);
[rhu] = remo12(rhumlcs,rhum);
[rfor] = remo12(rforelcs,rform);
[rha] = remo12(rhandlcs,rham);
[rfe] = remo12(rfemurlcs,rfem);
[rsh] = remo12(rshanklcs,rshm);
[rfo] = remo12(rfootlcs,rfom);
[remote12] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote12] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 1,3
[h] = remo13(headlcs,hm);
[t] = remo13(trunklcs,tm);
[lhu] = remo13(lhumlcs,lhum);
[lfor] = remo13(lforelcs,lform);
[lha] = remo13(lhandlcs,lham);
[lfe] = remo13(lfemurlcs,lfem);
[lsh] = remo13(lshanklcs,lshm);
[lfo] = remo13(lfootlcs,lfom);
[rhu] = remo13(rhumlcs,rhum);
[rfor] = remo13(rforelcs,rform);
[rha] = remo13(rhandlcs,rham);
[rfe] = remo13(rfemurlcs,rfem);
[rsh] = remo13(rshanklcs,rshm);
[rfo] = remo13(rfootlcs,rfom);
```

```
[remote13] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote13] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 2,1
[h] = remo21(headlcs,hm);
[t] = remo21(trunklcs,tm);
[lhu] = remo21(lhumlcs,lhum);
[lfor] = remo21(lforelcs,lform);
[lha] = remo21(lhandlcs,lham);
[lfe] = remo21(lfemurlcs,lfem);
[lsh] = remo21(lshanklcs,lshm);
[lfo] = remo21(lfootlcs,lfom);
[rhu] = remo21(rhumlcs,rhum);
[rfor] = remo21(rforelcs,rform);
[rha] = remo21(rhandlcs,rham);
[rfe] = remo21(rfemurlcs,rfem);
[rsh] = remo21(rshanklcs,rshm);
[rfo] = remo21(rfootlcs,rfom);
[remote21] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote21] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 2,2
[h] = remo22(headlcs,hm);
[t] = remo22(trunklcs,tm);
[lhu] = remo22(lhumlcs,lhum);
[lfor] = remo22(lforelcs,lform);
[lha] = remo22(lhandlcs,lham);
[lfe] = remo22(lfemurlcs,lfem);
[lsh] = remo22(lshanklcs,lshm);
[lfo] = remo22(lfootlcs,lfom);
[rhu] = remo22(rhumlcs,rhum);
[rfor] = remo22(rforelcs,rform);
[rha] = remo22(rhandlcs,rham);
[rfe] = remo22(rfemurlcs,rfem);
[rsh] = remo22(rshanklcs,rshm);
[rfo] = remo22(rfootlcs,rfom);
[remote22] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote22] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 2,3
[h] = remo23(headlcs,hm);
[t] = remo23(trunklcs,tm);
[lhu] = remo23(lhumlcs,lhum);
[lfor] = remo23(lforelcs,lform);
[lha] = remo23(lhandlcs,lham);
[lfe] = remo23(lfemurlcs,lfem);
[lsh] = remo23(lshanklcs,lshm);
[lfo] = remo23(lfootlcs,lfom);
[rhu] = remo23(rhumlcs,rhum);
[rfor] = remo23(rforelcs,rform);
[rha] = remo23(rhandlcs,rham);
[rfe] = remo23(rfemurlcs,rfem);
[rsh] = remo23(rshanklcs,rshm);
[rfo] = remo23(rfootlcs,rfom);
[remote23] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote23] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 3,1
[h] = remo31(headlcs,hm);
[t] = remo31(trunklcs,tm);
[lhu] = remo31(lhumlcs,lhum);
[lfor] = remo31(lforelcs,lform);
[lha] = remo31(lhandlcs,lham);
[lfe] = remo31(lfemurlcs,lfem);
[lsh] = remo31(lshanklcs,lshm);
[lfo] = remo31(lfootlcs,lfom);
[rhu] = remo31(rhumlcs,rhum);
[rfor] = remo31(rforelcs,rform);
[rha] = remo31(rhandlcs,rham);
[rfe] = remo31(rfemurlcs,rfem);
[rsh] = remo31(rshanklcs,rshm);
[rfo] = remo31(rfootlcs,rfom);
[remote31] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote31] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 3,2
[h] = remo32(headlcs,hm);
[t] = remo32(trunklcs,tm);
[lhu] = remo32(lhumlcs,lhum);
[lfor] = remo32(lforelcs,lform);
[lha] = remo32(lhandlcs,lham);
[lfe] = remo32(lfemurlcs,lfem);
[lsh] = remo32(lshanklcs,lshm);
[lfo] = remo32(lfootlcs,lfom);
[rhu] = remo32(rhumlcs,rhum);
[rfor] = remo32(rforelcs,rform);
[rha] = remo32(rhandlcs,rham);
[rfe] = remo32(rfemurlcs,rfem);
[rsh] = remo32(rshanklcs,rshm);
[rfo] = remo32(rfootlcs,rfom);
[remote32] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote32] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;

% Calculate remote term index 3,3
[h] = remo33(headlcs,hm);
[t] = remo33(trunklcs,tm);
[lhu] = remo33(lhumlcs,lhum);
[lfor] = remo33(lforelcs,lform);
[lha] = remo33(lhandlcs,lham);
[lfe] = remo33(lfemurlcs,lfem);
```

```
[lsh] = remo33(lshanklcs,lshm);
[lfo] = remo33(lfootlcs,lfom);
[rhu] = remo33(rhumlcs,rhum);
[rfor] = remo33(rforelcs,rform);
[rha] = remo33(rhandlcs,rham);
[rfe] = remo33(rfemurlcs,rfem);
[rsh] = remo33(rshanklcs,rshm);
[rfo] = remo33(rfootlcs,rfom);
[remote33] =
h+t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+r
sh+rfo;
% [remote33] =
t+lhu+lfor+lha+lfe+lsh+lfo+rhu+rfor+rha+rfe+rsh
+rfo;


% Calculate the remote terms matrix at each frame
[Remote] =
remote(remote11,remote12,remote13,remote21,re
mote22,remote23,remote31,remote32,remote33);

% Calculate the whole body tensor of inertia in
each frame
[WBI] = whole(Local,Remote);

% Calculate Ixx, Iyy and Izz
[Ixx,Iyy,Izz] = princaxes(WBI);
% figure
% plot(Ixx,'r')
% xlabel('frames')
% ylabel('Principal Moment of Inertia kg.m^2')
% hold on
% plot(Iyy,'m')
% plot(Izz,'b')
% legend('Ixx','Iyy','Izz',0)
% title('Whole body Moment of Inertia about the
Global Axes')

   %%%%%%SUB-
FUNCTIONS%%%%%%%%%
% Local terms sub-functions
function   [local] = localterms(lcs,TI)

nrows = size(lcs,1);
[R] = diag(ones(3,1));
for a = 1:4:(nrows-3)
   x = (lcs(a:(a+3),:));

   r=x(2:4,2:4);
   d = x(2:4,1);
   [R] = [R;r];
end
R(1:3,:) = [];
nrowsR = size(R,1);
nrowsTI = size(TI,1);
if nrowsR~=nrowsTI disp('error');
else
end
local = diag(ones(3,1));
for a = 1:3:(nrowsR-2)
   f = R(a:(a+2),:);
   g = TI(a:(a+2),:);
   h = f';
   l = f*g*h;
   [local] = [local;l];
end
local(1:3,:) = [];

% function [Local] =
local(tlocalI,lhalocalI,lforlocalI,lhulocalI,lfolocalI,l
shlocalI,lfelocalI,...
%
rhalocalI,rforlocalI,rhulocalI,rfolocalI,rshlocalI,rfel
ocalI)
 function [Local] =
local(hlocalI,tlocalI,lhalocalI,lforlocalI,lhulocalI,lf
olocalI,lshlocalI,lfelocalI,...

rhalocalI,rforlocalI,rhulocalI,rfolocalI,rshlocalI,rfel
ocalI)
nrows = size(tlocalI,1);
[Local] = diag(ones(3,1));
for a = 1:3:(nrows-2)
   h = hlocalI(a:(a+2),:);
   t = tlocalI(a:(a+2),:);
   lha = lhalocalI(a:(a+2),:);
   lfor = lforlocalI(a:(a+2),:);
   lhu = lhulocalI(a:(a+2),:);
   lfo = lfolocalI(a:(a+2),:);
   lsh = lshlocalI(a:(a+2),:);
   lfe = lfelocalI(a:(a+2),:);
   rha = rhalocalI(a:(a+2),:);
   rfor = rforlocalI(a:(a+2),:);
   rhu = rhulocalI(a:(a+2),:);
   rfo = rfolocalI(a:(a+2),:);
   rsh = rshlocalI(a:(a+2),:);
   rfe = rfelocalI(a:(a+2),:);
   l =
h+t+lha+lfor+lhu+lfo+lsh+lhu+rha+rfor+rhu+rfo+r
sh+rhu;
%    l =
t+lha+lfor+lhu+lfo+lsh+lhu+rha+rfor+rhu+rfo+rsh
+rhu;
   Local = [Local;l];
end
Local(1:3,:) = [];

% Remote term sub-functions
function [R] = remo11(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
   t = (lcs(a:(a+3),:));
   y = t(3,1);
   z = t(4,1);
   r = m*((y^2)+(z^2));
   R = [R;r];
end
R(1) = [];

function [R] = remo12(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
```

```
  t = (lcs(a:(a+3),:));
  x = t(2,1);
  y = t(3,1);
  r = m*x*y;
  R = [R;r];
end
R(1) = [];

function [R] = remo13(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
  t = (lcs(a:(a+3),:));
  x = t(2,1);
  z = t(4,1);
  r = m*x*z;
  R = [R;r];
end
R(1) = [];

function [R] = remo21(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
  t = (lcs(a:(a+3),:));
  x = t(2,1);
  y = t(3,1);
  r = m*y*x;
  R = [R;r];
end
R(1) = [];

function [R] = remo22(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
  t = (lcs(a:(a+3),:));
  x = t(2,1);
  z = t(4,1);
  r = m*((x^2)+(z^2));
  R = [R;r];
end
R(1) = [];

function [R] = remo23(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
  t = (lcs(a:(a+3),:));
  y = t(3,1);
  z = t(4,1);
  r = m*y*z;
  R = [R;r];
end
R(1) = [];

function [R] = remo31(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3);
  t = (lcs(a:(a+3),:));
  x = t(2,1);
  z = t(4,1);
  r = m*z*x;
  R = [R;r];
end
R(1) = [];

function [R] = remo32(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
  t = (lcs(a:(a+3),:));
  y = t(3,1);
  z = t(4,1);
  r = m*z*y;
  R = [R;r];
end
R(1) = [];

function [R] = remo33(lcs,m)
nrows = size(lcs,1);
[R] = [1];
for a = 1:4:(nrows-3)
  t = (lcs(a:(a+3),:));
  x = t(2,1);
  y = t(3,1);
  r = m*((x^2)+(y^2));
  R = [R;r];
end
R(1) = [];

function [Remote] =
remote(remote11,remote12,remote13,remote21,re
mote22,remote23,remote31,remote32,remote33);

nrows = size(remote11,1);
[Remote] = diag(ones(3,1));
for a = 1:nrows
  r11 = remote11(a);
  r12 = remote12(a);
  r13 = remote13(a);
  r21 = remote21(a);
  r22 = remote22(a);
  r23 = remote23(a);
  r31 = remote31(a);
  r32 = remote32(a);
  r33 = remote33(a);
  r = [r11,-r12,-r13;-r21,r22,-r23;-r31,-r32,r33];
  Remote = [Remote;r];
end
Remote(1:3,:) = [];

% Whole body Tensor of Inertia calculation in each
frame
function [WBI] = whole(Local,Remote);

nrows = size(Local,1);
[WBI] = diag(ones(3,1));
for a = 1:3:(nrows-2)
  l = Local(a:a+2,:);
  r = Remote(a:a+2,:);
  w = l+r;
  WBI = [WBI;w];
```

```
end
WBI(1:3,:) = [];


% Matrices of Ixx, Iyy and Izz over time
function [Ixx,Iyy,Izz] = princaxes(WBI);

nrows = size(WBI,1);
[Ixx] = [1];
[Iyy] = [1];
[Izz] = [1];
for a = 1:3:(nrows-2)
    m = WBI(a:(a+2),:);
    ixx = m(1,1);
    iyy = m(2,2);
    izz = m(3,3);
    Ixx = [Ixx;ixx];
    Iyy = [Iyy;iyy];
    Izz = [Izz;izz];
end
Ixx(1) = [];
Iyy(1) = [];
Izz(1) = [];
```

Appendix J Efficiency Program

```
function    [disp,dist,e] = efficiency2(data)

st = data(1,:);
fin = data(size(data,1),:);
disp = fin-st;
length = norm(disp);

dist = lengthcurve(data);
e = dist/length;
```

Appendix K Orientation Angle Program

```
function
[lankle,lknee,lhip,lshoulder,lelbow,lwrist,rankle,rk
nee,...

rhip,rshoulder,relbow,rwrist]=orient(thoraciclcs,pel
vislcs,...

thoraciclcsb,pelvislcsb,lhandlcsb,lforelcsb,lhumlcs
b,rhandlcs,...

rforelcs,rhumlcs,lfootlcsb,lshanklcsb,lfemurlcsb,rfo
otlcs,rshanklcs,rfemurlcs)
% matlab function to calculate the relative
orientation of the distal
% segment relative to the proxmal segment at the
major joints

% Wrist
[Tlwrist] = posetrans(lforelcsb,lhandlcsb);
[lwrist] = rotzxy(Tlwrist);
% [lwrist] = continuity(lwrist);
[Trwrist] = posetrans(rforelcs,rhandlcs);
[rwrist] = rotzxy(Trwrist);
% [rwrist] = continuity(rwrist);

% Elbow
[Tlelbow] = posetrans(lhumlcsb,lforelcsb);
[lelbow] = rotzxy(Tlelbow);
% [lelbow] = continuity(lelbow);
[Trelbow] = posetrans(rhumlcs,rforelcs);
[relbow] = rotzxy(Trelbow);
% [relbow] = continuity(relbow);

% Shoulder
[Tlshoulder] = posetrans(thoraciclcsb,lhumlcsb);
[lshoulder] = rotyxy2(Tlshoulder);
% [lshoulder] =
[lshoulder(:,1:2),lshoulder(:,3)+90];
% [lshoulder] = continuity(lshoulder);
[Trshoulder] = posetrans(thoraciclcs,rhumlcs);
[rshoulder] = rotyxy2(Trshoulder);
% [rshoulder] =
[rshoulder(:,1:2),rshoulder(:,3)+90];
% [rshoulder] = continuity(rshoulder);

% Hip
[Tlhip] = posetrans(pelvislcsb,lfemurlcsb);
[lhip] = rotzxy(Tlhip);
% [lhip] = continuity(lhip);
[Trhip] = posetrans(pelvislcs,rfemurlcs);
[rhip] = rotzxy(Trhip);
% [rhip] = continuity(rhip);

% Knee
[Tlknee] = posetrans(lfemurlcsb,lshanklcsb);
[lknee] = rotzxy(Tlknee);
% [lknee] = continuity(lknee);
[Trknee] = posetrans(rfemurlcs,rshanklcs);
[rknee] = rotzxy(Trknee);
% [rknee] = continuity(rknee);

% Ankle
[Tlankle] = posetrans(lshanklcsb,lfootlcsb);
[lankle] = rotzxy(Tlankle);
% [lwrist] = continuity(lankle);
[Trankle] = posetrans(rshanklcs,rfootlcs);
[rankle] = rotzxy(Trankle);
% [rwrist] = continuity(rankle);

% figure
% plot(lwrist)
% title('lwrist')
% legend('z','x','y')
% figure
% plot(rwrist)
% title('rwrist')
% legend('z','x','y')
% figure
% plot(lelbow)
% title('lelbow')
% legend('z','x','y')
% figure
% plot(relbow)
% title('relbow')
% legend('z','x','y')
% figure
% plot(lshoulder)
% title('lshoulder')
% legend('y','x','y')
% figure
% plot(rshoulder)
% title('rshoulder')
% legend('y','x','y')
% figure
% plot(lhip)
% title('lhip')
% legend('z','x','y')
% figure
% plot(rhip)
% title('rhip')
% legend('z','x','y')
% figure
% plot(lknee)
% title('lknee')
% legend('z','x','y')
% figure
% plot(rknee)
% title('rknee')
% legend('z','x','y')
% figure
% plot(lankle)
% title('lankle')
% legend('z','x','y')
% figure
% plot(rankle)
% title('rankle')
% legend('z','x','y')


function [Tpd] = posetrans(Tp,Td)
%posetrans: Matlab function to calculate the pose
transformation matrix
%from two coordinate systems
%Tpd - transformation matrix describing the distal
coordinate system with
% respect to proximal coordinate system
```

```
Tpd = eye(4);
nrows = size(Tp,1);
for a = 1:4:(nrows-3)
   Rp = (Tp((a+1):(a+3),2:4));
   Rd = (Td((a+1):(a+3),2:4));
   rpd = Rp'*Rd;
   Pp = Tp(a+1:a+3,1);
   Pd = Td(a+1:a+3,1);
   ppd = Rp'*(Pd-Pp);
   Ta = [1,0,0,0;ppd,rpd];
   Tpd = [Tpd;Ta];
end
Tpd(1:4,:) = [];


function [out]=rotzxy(Tdata)
%
% programma voor het berekenen van de rotaties
z,x, en y res. rond de Z-,
% x- en y-as uit de gegeven matrix R.

% calculate the number of rows
nrows = size(Tdata,1);

%calculate the number of frames
nframe = nrows/4;

%start out matrix
out = [1,0,0];

%Iterative loop which takes each transformation
matrix and calculates
%alpha,beta and gama for each frame of data. The
rotations are succesively
%placed in matrix out
for a = 1:4:(nrows-3)
   t = (Tdata(a:(a+3),:));
   R = [t(2:4,2:4)];
   x1 = asin(R(3,2));
sy =-R(3,1)/cos(x1);
cy = R(3,3)/cos(x1);
y1 = atan2(sy,cy);
sz =-R(1,2)/cos(x1);
cz = R(2,2)/cos(x1);
z1 = atan2(sz,cz);
if x1 >= 0,
  x2 = pi - x1;
else
  x2 = -pi - x1;
end
sy =-R(3,1)/cos(x2);
cy = R(3,3)/cos(x2);
y2 = atan2(sy,cy);
sz =-R(1,2)/cos(x2);
cz = R(2,2)/cos(x2);
z2 = atan2(sz,cz);
if (-pi/2 <= x1 & x1 <= pi/2)
  y=y1;
  z=z1;
  x=x1;
else
  y=y2;
  z=z2;
  x=x2;
end

     o=[rad2deg(z),rad2deg(x),rad2deg(y)];

   out = [out;o];

 end
 %remove 1st line of out matrix
out(1,:) = [];

     function [out]=rotyxy2(Tdata)
%
%   programma voor het berekenen van de rotaties
rond achtereenvolgens
%   de y-, z- en lokale y-as uit de rotatiematrix r.
er zijn twee
%   oplossingen: de oplossing met de kleinste
rotaties wordt uitgekozen.
%
% calculate the number of rows
nrows = size(Tdata,1);

%calculate the number of frames
nframe = nrows/4;

%start out matrix
out = [1,0,0];

%Iterative loop which takes each transformation
matrix and calculates
%alpha,beta and gama for each frame of data. The
rotations are succesively
%placed in matrix out
for a = 1:4:(nrows-3)
   t = (Tdata(a:(a+3),:));
   r = [t(2:4,2:4)];
    x1 = acos(r(2,2));
    if (x1==0) then
          y=acos(-r(3,3));
          x=x1;
          ya=0.0;
          return
    end
    cy = r(3,2)/sin(x1);
    sy = r(1,2)/sin(x1);
    y1 = atan2(sy,cy);
    cya = -r(2,3)/sin(x1);
    sya = r(2,1)/sin(x1);
    ya1 = atan2(sya,cya);
    x2 = -x1;
    cy = r(3,2)/sin(x2);
    sy = r(1,2)/sin(x2);
    y2 = atan2(sy,cy);
    cya = -r(2,3)/sin(x2);
    sya = r(2,1)/sin(x2);
    ya2 = atan2(sya,cya);
    if (0 <= x1 & x1 <= pi)
           y = y2;
           x = x2;
```

```
        ya = ya2;
  else
        y = y1;
        x = x1;
        ya = ya1;
  end
   o=[rad2deg(y),rad2deg(x),rad2deg(ya)];

  out = [out;o];

 end
 %remove 1st line of out matrix
out(1,:) = [];
```

```
function [out]=rad2deg(in)

% function [out]=rad2deg(in)
% Description:     Conversion of radians to
degrees applied to the entire matrix
% Input:  in (values in radians)
% Output:          out (values in degrees)
% Author:          Christoph Reinschmidt, HPL,
The University of Calgary
% Date:            October, 1994
% Last Changes:    November 29, 1996
% Version:         1.0

 out=in.*(180/pi);
```