Early detection and rehabilitation of functional recovery for acutely injured anterior cruciate ligament deficient individuals using clinical and biomechanical outcomes.

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Abstract

BACKGROUND: The purpose of this study was firstly to evaluate functional recovery following anterior cruciate ligament (ACL) rupture from acute injury over the course of rehabilitation. Insights from this analysis were then used to integrate movement feedback into rehabilitation to investigate if this resulted in improved functional outcome and participation level following this injury.
METHOD: In the initial modelling phase a prospective repeated measures longitudinal design was used to measure functional recovery from acute injury over time of 63 ACL patients and 61 matched controls, using a two dimensional (2D) video based analysis system. Time-distance variables and joint angles for gait, jog, distance hop and run and stop were analysed monthly. A least squares 3rd order polynomial was used to model the functional recovery of ACLD (anterior cruciate ligament deficient) individuals and functional sub-groups. A second exploratory study using a prospective cohort design compared recovery between 115 ACLD individuals randomized into movement feedback (FB) and no feedback (no-FB) rehabilitation. The feedback criterion was based on the movement data from the longitudinal analysis of functional recovery. Independent t-tests were used to evaluate group differences at 5 months post injury. Semi structured interviews evaluated the physiotherapists usage of the feedback and rehabilitation given to the ACLD patients.
RESULTS: Functional recovery was found on average to take 3 months for gait and 5 months for hopping. ACLD non-copers were distinguishable at 40 days post injury due to failure of gait variables to recover to within 'normal limits'. In study two 52 ACLD subjects were followed up at 5 months post injury. No statistically significant differences in functional performance between the FB and no-FB groups were found ($p<0.05$), for any of the movement variables for gait, one legged squat, distance hop or run and stop. Physiotherapists treating the FB group reported difficulties interpreting the movement feedback, incorporating it into rehabilitation due to its timing and identified a perceived learning effect on treatment.
DISCUSSION: Functional recovery was successfully modelled and shown to take longer than expected. This has implications for advising patients on recovery times and length of time for attendance at rehabilitation. Further clarification is required but failure of simple gait variables to recover by 40 days post injury could direct ACLD management. If the potential for recovery can be identified early then the appropriate treatment can be given. Incorporating this type of movement feedback into rehabilitation did not result in improved functional outcome or level of participation. Factors related to its application and insufficient patient numbers at follow-up may have weakened the experimental treatment effect and the power of the study. The modelling and exploratory phases of this investigation need to be revisited to identify the most relevant variables for feedback, refine functional cut-off scores, develop methods that allow feedback to be delivered immediately and more focused training for physiotherapists before progress to a randomized control trial can be considered. This study demonstrated that the clinically based video analysis system provided detailed insight at all stages of rehabilitation on the

speed, timing and completeness of recovery for functional tasks that are directly relevant to the rehabilitation goals.

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Glossary of abbreviations

ACL	Anterior cruciate ligament
ACLD	Anterior cruciate ligament deficient
ADL	Activities of daily living
AKSS	Acute knee screening service
AM	Anterior medial
ATT	Anterior tibial translation
BF	Biceps femoris
cm	Centimetre
CNS	Central nervous system
deg	Degrees
2D	Two dimensional
3D	Three dimensional
EMG	Electromyography
FB	Feedback
GRF	Ground reaction force
HDA	Hip displacement angle
HS	Heel strike
ICC	Intraclass correlation coefficient
ICF	International classification of function, disability and health model
IKDC	International knee documentation committee
J	joules
JRF	Joint reaction force
kg	Kilogram
KOOS	Knee injury and osteoarthritis outcome score
KoP	Knowledge of performance
KoR	Knowledge of results
KOS-ADL	Knee outcome score – activites of daily living
LH	Lateral hamstring
m	metre
MG	Medial gastrocnemius
MH	Medial hamstring
MLR	Medium latency response
MRI	Magnetic resonance imaging
m/s	Metres per second
N	Newtons
NHS	National Health Service
Nm	Newton meters
No-FB	No feedback
n.s.	Non significant
OA	osteoarthritis
RCI	Reliable change index
RCT	Randomised control trial
PL	Posterior lateral
ROM	Range of movement
R&S	Run and stop
SD	Standard deviation
SF-36	Short form 36

SL inj	Step length injured leg
Sl non	Step length non-injured leg
SLR	Slow latency response
TrA	Transversus abdominus
TSM	Total support moment
UHW	University Hospital Wales
UK	United Kingdom
VL	Vastus lateralis
VM	Vastus medialis
W	Watts

1.0 Introduction

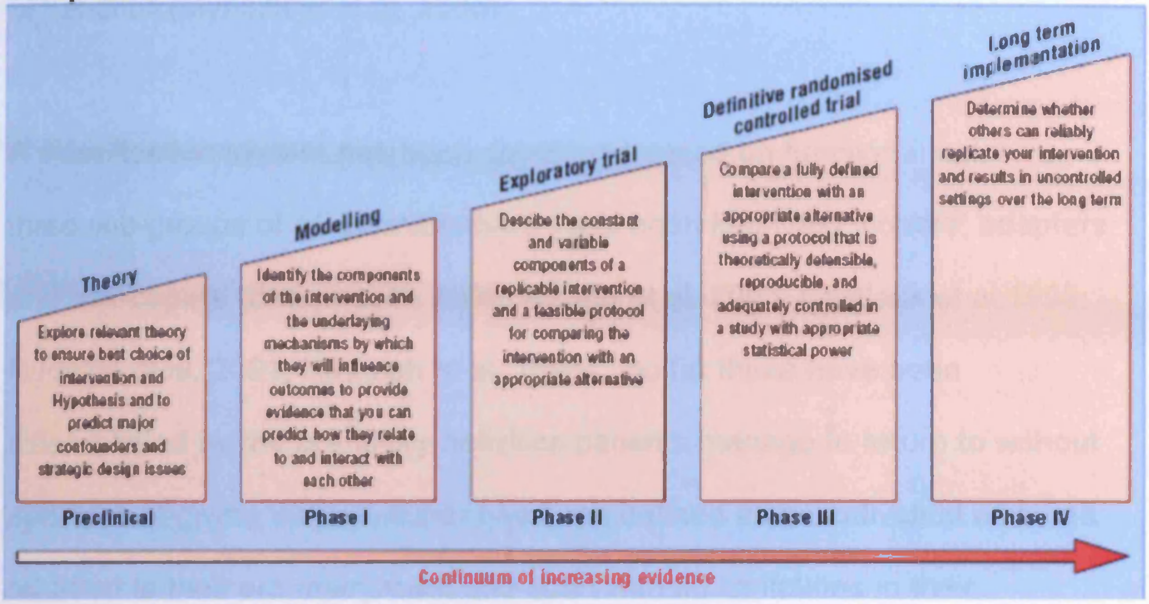
Restriction of functioning is a universal characteristic in acute and chronic pathology within musculoskeletal, neurological and internal medicine (Finger et al. 2006). Physiotherapists work across all of these specialities as a rehabilitation profession that is concerned with human movement, function and maximising potential. By applying rehabilitation techniques physiotherapy aims to help individuals with health conditions that experience or are likely to experience disability, to achieve optimal functioning in interaction with the environment and personal factors (Stucki et al. 2007; Chartered Society of Physiotherapy 2002). To receive widespread scientific credibility, rehabilitation needs to be applied to the International Classification of Functioning, Disability and Health (ICF) model, which is widely regarded as the most comprehensive model of functioning and disability within rehabilitation medicine (Wade 2005, Stucki et al. 2007). This will allow the distinct but separate entities of rehabilitation to be linked, enabling health strategies, treatment and research to be developed using a common language (Wade 2005; Lettinga et al. 2006; Stoll et al. 2005; Palisano 2006).

Within the ICF model functioning has been identified as having three components which are defined as; 'body functions and structures' which are physiological, psychological and anatomical structures; 'activities' which refers to carrying out a functional task and 'participation' relates to performing this task in a real life situation. This is all within the context of the pathology, personal and environmental factors (Stucki and Melvin 2007). Within rehabilitation the terms function, functional and functioning are commonly used in relation to structural impairments, movement adaptations and participation of everyday activities in situations that apply to the individual, which relates to the different components of the ICF model. Function refers to impairment at the structure level and relates to the 'body functions and structures' component of the model, functional relates to task deficits, adaptations and movement compensations at an 'activity ' level and finally functioning relates to 'participation' of tasks in everyday activities. To apply this model and develop functional rehabilitation the full extent of activity limitations in relation to specific health conditions need to be known and clinical methods that measure functional activities need to be developed. To have maximum impact in informing practice these methods need to measure outcome over the course of rehabilitation and provide information that can direct the content of treatment.

Physiotherapy rehabilitation is a complex intervention that is interactive and involves many components that need to be considered such as; providing information, advice and feedback, prescribing different types of exercise, giving demonstrations and performing manual techniques, at the same time as individuals may also be undergoing investigations and taking medication. This treatment will be modified by a number of factors such as; differences in the ways these techniques are applied, pathology type and individual patient factors. It is therefore essential that the main 'active ingredients' within the treatment are defined and effectiveness evaluated (Whyte 2006). This will enable development of rehabilitation techniques for evidence based practice in a healthcare system where economics of treatment are important (Wade 2005, Whyte 2006). If this is not done then rehabilitation will continue to be made up of a number of components but will be applied with a lack of understanding of what contributes to recovery. Because the ICF places such a large emphasis on functioning and maximising participation is regarded as the common treatment goal of rehabilitation (Stucki et al. 2005; Scheuringer et al. 2005; Stoll et al. 2005; Raine 2007, Wade 2005), it is essential that rehabilitation methods are developed in line with this, so the functional component of rehabilitation may need to be developed further.

A proposed research framework for the design and evaluation of complex interventions such as rehabilitation was developed by Campbell et al. (2000). Five distinct phases have been identified in this framework to make sure that the intervention is fully defined, developed and evaluated before long term implementation; these phases are demonstrated in Figure 1. The pre-clinical phase deals with exploring the underlying theory and developing hypotheses. This is followed by a modelling phase to identify components of the intervention and then an exploratory trial to compare the intervention with an alternative. This may be done using a cohort design or pragmatic randomised trial before progressing to a definitive randomised control trial. Depending on the findings progression between phases will not necessarily be linear; phases may need to be repeated to identify other treatment components. As an example, research that has evaluated muscle dysfunction and its treatment in patients with low back pain has developed in a similar way as that proposed in the framework by Campbell et al. (2000). In the modelling phase research focused on; muscle dysfunction in patients with low back pain and the pattern of these compensations in abdominal and spinal muscle groups (Hodges & Richardson 1996; Hodges & Richardson 1999), how these compensations related to pain (Hodges et al. 2003; Moseley & Hodges 2005) and the validity of ultrasound as a tool to measure muscle activation was also evaluated (Ferreira et al. 2004). In the exploratory trial phase numerous studies have evaluated the use of ultrasound as a feedback tool to improve muscle performance (Henry & Westervelt 2005; Teyhen et al. 2005; Teyhen et al. 2007). Recently there have been further studies to refine this feedback by manipulating the feedback schedule of the ultrasound (Herbert et al. 2008). The direction this research now needs to take is to develop randomised controlled studies on low back pain patient groups evaluating the success of these methods at the level of patient participation (Henry & Teyhen 2007). For this group of studies on low back pain there is a clear direction on how the research has evolved, with other groups of patients with musculo-skeletal disorders this is less apparent. Therefore the concepts identified above need to be explored and applied elsewhere, specifically to the management of individuals with acute rupture of the anterior cruciate ligament.

Figure 1 Sequential phases of developing randomised control trials of complex interventions



Rupture of the ACL is a common knee injury presenting at emergency departments and it is a particularly significant injury because it frequently results in activity restriction during activities of daily living and during sport. Its incidence varies between populations, sports and clinic locations but it has been found to be as high as 7.8 per 100 players in national league football (Brophy et al. 2007) and within a general population attending an emergency department 0.81/1000 inhabitants per year (Frobell et al. 2007). This isn't an injury that is just confined to sporting populations; Frobell et al. (2007) found that 75% of ACL ruptures were associated with sport; therefore a substantial 25% occurred during daily life activities. The immediate consequences of ACL rupture is pain, swelling and instability which contribute to loss of function. Later other deficits contribute such as movement adaptation, muscle weakness, reduced motor control and knee instability. In the long term, rate of return to pre-injury activity without any restriction in performance (full functional recovery) has been found to be as low as 16% in a general population (Strehl & Eggli 2007) but as high as 82% return to pre-injury level of handball (Myklebust et al. 2003).

A classification system has been developed based on functional outcome, three sub-groups of ACLD individuals have been identified; copers, adapters and non-copers (Button et al. 2006; Alkjaer et al. 2003; Eastlack et al.1999; Rudolph et al. 2001; Rudolph et al. 1998). So far these have been differentiated by the pre-injury activities patients manage to return to without episodes of giving way. A coper has been defined as an individual who has returned to their pre-injury work and sport with no limitations in their performance. An adapter is someone who has reduced or changed their work or sport to prevent their knee fully giving way. Non-copers are individuals who fail to return to their pre-injury sport or work and experience full giving way with work, activities of daily living (ADL) and light non pivoting sports (Alkjaer et al. 2003; Eastlack et al. 1999; Rudolph et al. 2001).

If an ACLD individual wants to return to high demand activities or experiences repeated giving way episodes then surgical reconstruction is often regarded as the optimal treatment (Marx et al. 2003; Francis et al. 2001; Mirza et al. 2000). This procedure is not without its limitations; studies evaluating surgical outcome have found persistent functional limitations (DeVita et al. 1997; Mattacola et al. 2002; Ferber et al. 2004 and Hooper et al. 2002) and a varied ability to return to pre-injury activities, ranging from 65% to 92% (Gobbi & Francisco 2006; Aglietti et al. 1997; Svensson et al. 2006 and Nakayama et al. 2000). This indicates that although surgical management is considered superior to non-surgical management, there are still a proportion of individuals that are unable to regain full function and to return to their pre-injury activities.

Not all individuals therefore progress to have an ACL reconstruction, within the United Kingdom (UK), a proportion of individuals who are mainly recreational athletes will choose conservative management because; they do not want to undergo surgery, it is not a convenient time in their lives due to work or family restraints, they are satisfied with the level of function they achieve with conservative management or it is not recommended based on their clinical signs and rehabilitation goals (de Roeck & Lang-Stevensson 2003; Fitzgerald et al. 2000b). Others will choose to have an ACL reconstruction but are required to wait due to surgical waiting lists so will require rehabilitation during this time to achieve a safe but maximal level of functioning (Francis et al. 2001; Marx et al. 2003). Conservative rehabilitation is a commonly utilised treatment modality; amongst orthopaedic surgeons 80% agree that physiotherapy is useful in the management of the ACLD knee and that 85% of their patients attend pre-operative physiotherapy (Marx et al. 2003; Francis et al. 2001).

Published theoretical models of ACLD rehabilitation and research based programs have a deficit approach to rehabilitation whereby interventions focus on underlying structure or process deficits (Sugden 2007). This includes functions such as; muscle strength, motor control, proprioception and range of motion (ROM) (Fitzgerald et al. 2000b; Manal & Snyder-Mackler 1996). In these programs function is integrated into rehabilitation through goal setting;

teaching of functional skills tends not to be advocated until the later stages of rehabilitation and is in relation to sport. An enhanced functional approach to rehabilitation would focus more on relearning a progression of functional skills (Sugden 2007) throughout rehabilitation and use feedback about movement adaptations whilst performing these activities to direct treatment; utilising an enhanced functional approach to rehabilitation. A number of different types of tools are available and appropriate for use within the clinical environment to provide this information. These tools range from joint specific symptom and function scales and questionnaires (Barber-Westin et al. 1999; Roos et al. 1998) to functional tests (Itoh et al. 1998; Hurd et al. 2008a), observational analysis (Kawamura et al. 2007; McGinley et al. 2006) and instrumented 2D video based movement analysis system (McLean et al. 2005). The limitation of the scales and questionnaires and functional tests is that they result in an overall score or measurement that provides information on outcome but not specific detail on how the performance was achieved, which is needed to inform and guide rehabilitation techniques. For example an ACLD individual is able to hop the same distance as their uninjured leg but are they using altered strategies to achieve this such as reduced ability to balance on landing or using restricted knee joint range of motion. Observational analysis does provide detail on functional performance but its accuracy and reliability is poor (Kawamura et al. 2007; McGinley et al. 2006). Instrumented two dimensional video analysis overcomes some of the limitations of the above tools making it appropriate for clinical usage. Some of its advantages are that it is reliable (McLean et al. 2005), it has flexibility allowing simultaneous analysis of a wide range of time-distance variables and joint angles for a number of functional activities, it generates knowledge of result and performance data to guide rehabilitation technique, it is relatively inexpensive, quick to use, easy to store and simple to apply and interpret. One further consideration is the adequacy of the system to be used for fully evaluating the pathology with reliability and accuracy. Despite the 2D video system fulfilling so many of the requirements of a clinical movement analysis system it is still relatively infrequently utilised (Coutts 1999). One of the major difficulties of using it within the clinical setting is what to compare individual performance against; the uninjured limb or 'normal' data if available from the literature. Most of the studies that have evaluated movement performance in ACLD subjects have been confined to the laboratory setting and used three dimensional (3D) movement analysis systems which are not readily transferable to the clinical setting. Some of the limitations for their clinical usage are; time restraints, expense and lack of individuals with sufficient knowledge to operate the system and interpret the data within the clinical setting. Even though 3D motion analysis systems have been used in the majority of studies that have analysed movement strategies in ACLD individuals, only 2D joint angles and kinetic data is often presented. Therefore the researchers have rarely utilised the full capacity of the movement analysis system they have available. In addition comparable accuracy has been found for using a 2D model compared to a 3D model for calculating knee and hip moments (Alkjaer et al. 2001).

By measuring functional performance patient recovery can be evaluated and data regarding functional outcome and performance can be used as feedback to the treating physiotherapist and patient. This can be used to direct rehabilitation content and ensure that treatment is tailored to the individual, with the ultimate aim of improving an individual's level of participation. The value of using movement feedback as a tool to facilitate the learning of novel tasks in uninjured individuals and functional recovery in neurological patients has been demonstrated (Tzetzis & Votsis 2006; Cirstea et al. 2006; Hurley & Lee 2006) but its use and effectiveness within ACLD rehabilitation has not been considered. Because maximising functional performance and safe participation level are the treatment goals of ACLD rehabilitation, then using movement feedback would appear to be an important rehabilitation component that could influence outcome, so suitable research designs to evaluate feedback effectiveness are required. If this is considered in relation to the complex intervention research framework proposed by Campbell et al. (2000), studies in the modelling phase are required to evaluate movement compensation strategies over time, from acute injury and over the course of rehabilitation, using a system that measures functional outcome. These findings can then be used to develop feedback and its effectiveness at altering performance can then be evaluated in an exploratory trial.

In summary, maximising an individual's optimal level of functioning is the ultimate rehabilitation goal. To assist this process it is essential that clinical tools are developed so that functional performance can be evaluated and recovery modelled. If functional deficits are identified through this process then this information can be used as feedback within rehabilitation to inform treatment and try to improve an individual's level of functioning. This involves a change in emphasis within rehabilitation away from functional deficits and directing it instead towards a functional movement approach that is based on performance data.

2.0 Literature Review

This literature review firstly aims to provide an overview of the main deficits that are associated with ACL rupture; knee instability, movement compensation strategies during functional activities and long term reduction in level of participation compared to pre-injury. These correspond to deficits at the 'function/structure', 'functional/activity' and 'functioning/participation' levels. The second aim is to review the literature surrounding rehabilitation programmes for ACLD knees and the use of external feedback as a tool in motor learning to improve knee stability and functional performance. Based on this review of the literature a suitable framework for measuring functional recovery in the clinical setting will be developed and rehabilitation approaches that incorporate movement feedback on functional performance.

To identify appropriate published studies to include in the literature review a search strategy was designed and carried out in 3 stages. In stage 1 a limited search of Pubmed was performed to identify a preliminary set of papers and keywords contained in the titles and abstracts of published studies. The initial search terms for this stage included: ACL and rehabilitation; ACL and movement analysis; feedback and skill acquisition. In stage 2 further keywords identified and terms were used to develop a more extensive search strategy, these needed to be slightly modified and adapted to suit the differing terminology of each database. Both truncation symbols and wildcards were employed for the keyword searches to ensure that no relevant articles were missed. Two searches were undertaken for this stage for each database which can be seen in Appendix 1, along with the keywords used. Search was carried out using the following databases:

- CINAHL
- Medline
- EMBASE
- AMED
- Cochrane Library (including Cochrane DSR, Dare and CCTR)
- SCOPUS

The search was restricted to articles published between the years 1998-2007. This criterion was used because few relevant publications were available prior to this date. The numbers of references retrieved for each of the databases are summarized in Table 1.

Table 1 Summary of the number of references retrieved for each of the databases searched.

Database	**Total Number of References: search 1**	**Total Number of References: search 2**
CINAHL	87	40
Medline	1083	72
EMBASE	259	129
AMED	259	7
Cochrane	80	36
SCOPUS	288	91

These references were imported into Endnote and all duplicates removed. This left a total of 1574 references. The remaining references were then assessed for relevance to the study based upon the information provided in the title, abstract and subject terms. Full text documents were retrieved for the remaining references which were critically appraised for quality. The inclusion and exclusion criteria for which studies were included is summarised in Table 2.

Table 2 Inclusion and exclusion criteria for the full test articles

Study inclusion criteria	**Study exclusion criteria**
ACLD population with conservative management	Case studies
Evaluation of functional performance for gait, jog, run, hop, deceleration, run and direction change, side step	Non-English papers
ACLD long term outcome	Functional activities not relevant to this study such as stair climbing
ACLD rehabilitation	Causes of ACL injury
ACL and knee stability	Animal ACL studies
Feedback, motor learning and skill acquisition in healthy individuals and presence of pathology	ACLD adolescents and children under 16 years
Feedback and rehabilitation	

Following this filtering process a total of 231 references remained. For stage 3 of the literature search reference lists and bibliographies of relevant papers were searched and relevant articles retrieved. Some studies outside the dates of the original time frame were included because their content was directly relevant to the research aims and key findings.

2.1 ACL and Knee Joint Stability

The anterior cruciate ligament is recognised as having a major part to play in knee stability but before evaluating this role it is important to have a basic understanding of the knee anatomy and to define the concept of joint stability with particular reference to the knee. The knee is made up of the tibiofemoral and patellofemoral joints, which are bony articulations between the tibia and femur and the patella and femur respectively. It is the function of the tibiofemoral joint that has been most widely evaluated following ACL rupture due to the ACL's location within the tibiofemoral joint and the altered mechanics that result following its injury (Markolf et al. 1995; Zantop et al. 2007). Due to the relatively flat surface of the tibial plateau and the highly curved femoral condyles there is relatively poor tibiofemoral joint congruity; this is improved by menisci that are located within the joint space, increasing the concavity of the tibial plateau. There are four major ligaments associated with the knee joint; the intra-articular anterior and posterior cruciate ligaments which are primary restraints to anterior and posterior translation and secondary restraints to rotation. The extra-articular collateral ligaments are located medially and laterally crossing between the femur and tibia and are the primary restraints to varus and valgus joint motion respectively. A detailed illustration of the knee anatomy is given in Figure 2. The location of the ACL as seen by magnetic resonance imaging (MRI) is demonstrated in Figure 3. The major muscle groups that span the knee joint are the quadriceps which are knee extensors and hamstrings and gastrocnemius which function as knee flexors. The role of the muscles is to generate co-ordinated movement and joint stability (Kai-Nan 2002). This understanding of the anatomy of the knee is required to fully appreciate the components of joint stability.

Figure 2 Anatomy of the knee joint

(http://darkwing.uoregon.edu/~athmed/aclrehab/main.html)

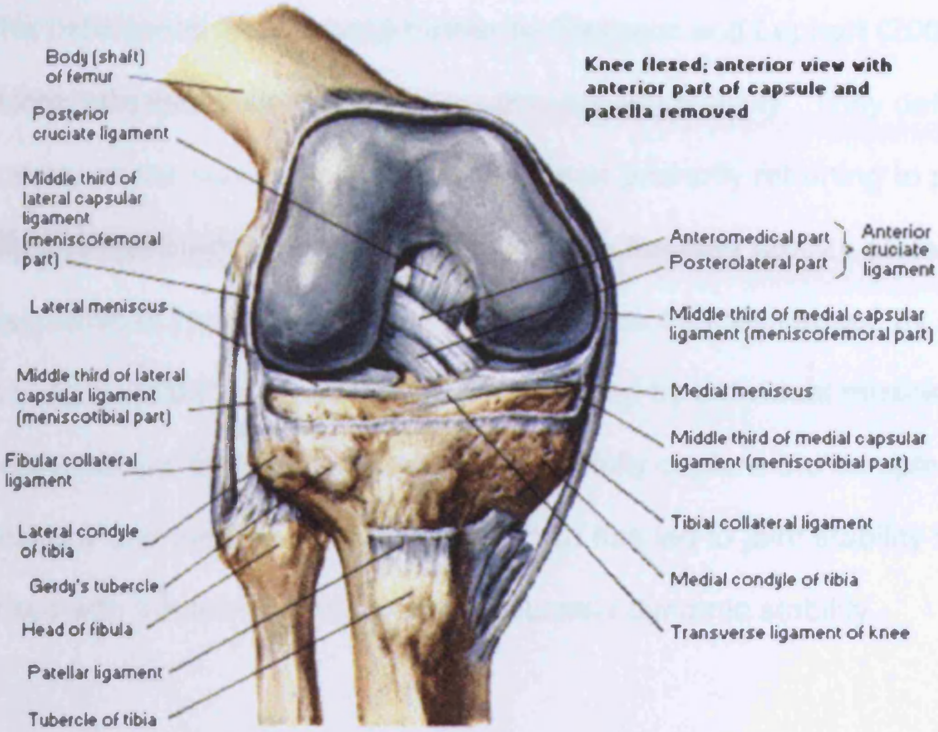
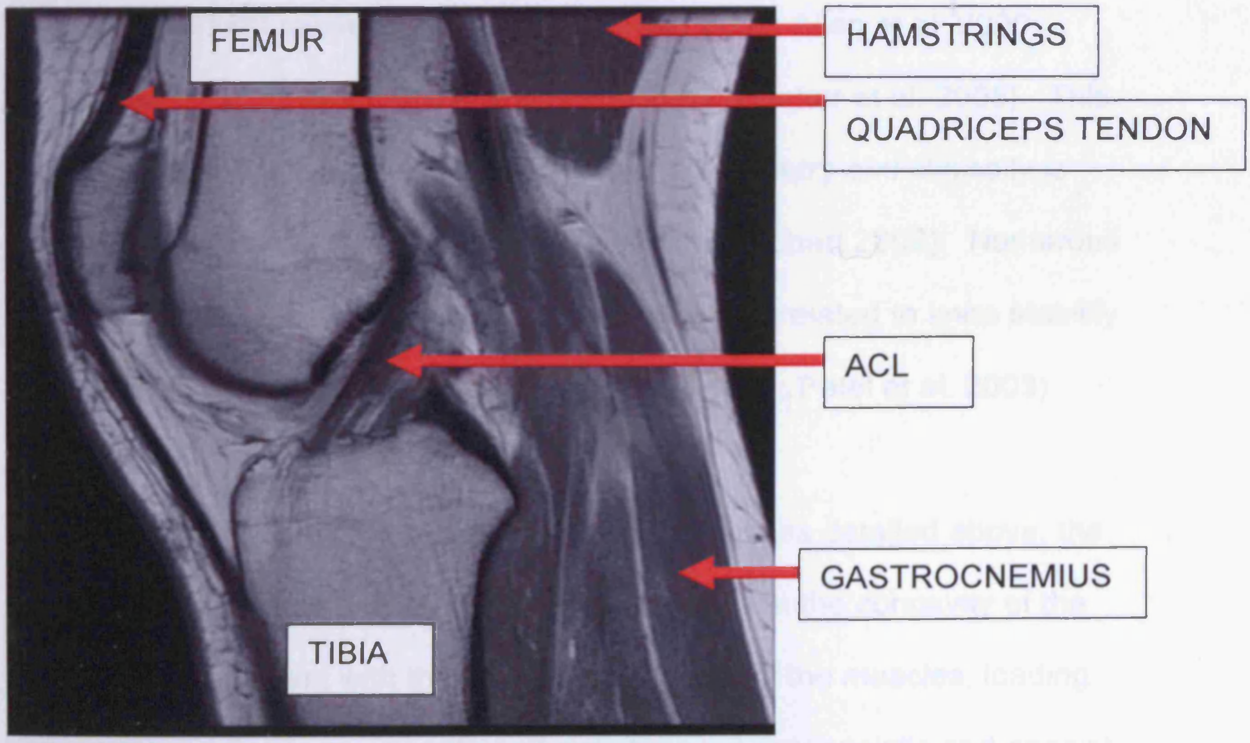


Figure 3 MRI scan sagittal view of the joint demonstrating location of the ACL and major muscle groups contributing to dynamic knee stability



This image is from the radiology archive, Cardiff and Vale NHS Trust

One basic definition of joint stability is the ability of a joint to maintain an appropriate functional position throughout its range of motion (Enoka 2002). This definition is taken a step further by Riemann and Lephart (2002) who incorporate forces as a mechanism of achieving stability. They define joint stability as the state of the joint remaining or promptly returning to proper alignment through an equalisation of forces. Kai-Nan (2002), states in their discussion of joint stability that the resultant joint forces caused by external loading must be balanced by forces generated by individual muscles. These definitions are limited because they do not fully capture the complexity of the anatomy and mechanisms involved, which has led to joint stability being linked with the terms passive and functional / dynamic stability.

Passive stability relates to the joint stability in relation to the non-contractile joint structures such as; the bony geometry, articular cartilage, menisci, ligaments and joint capsule (Riemann & Lephart 2002; Allen et al. 2000; Freeman & Pinskerova 2005; Liu & Maitland 2003; Dhaher et al. 2005). This is often assessed by specific ligament tests or arthrometry and clinically is described as the amount of joint laxity (Riemann & Lephart 2002). Numerous studies have also confirmed that passive stability is unrelated to knee stability during functional activities (Snyder-Mackler et al. 1997; Patel et al. 2003).

Functional stability incorporates the passive restraints as detailed above, the concavity-compression mechanism generated between the concavity of the joint surface interacting with the compressive forces of the muscles, loading and gravity and finally co-ordination of simultaneous antagonistic and agonist muscle activity (co-contraction) acting on the joint during movement, to further increase compression and therefore joint stability (Lephart & Fu 2000; Halder et al. 2001; Kui-Nan 2002). Knee instability is a common symptom following ACL rupture and will often present to the patient as episodes of knee 'giving way' which they will report subjectively. Therefore to understand knee instability and episodes of giving way it is firstly important to understand the ACL's role in the ACL intact knee.

The ACL is recognised as acting as a primary restraint to anterior tibial translation (ATT) and a secondary restraint to internal rotation and valgus loading (Markolf et al. 1995; Fukunda et al. 2003; Gabriel et al. 2004 and Zantop et al. 2007). Anatomically it has 2 distinct bundles; the anterior medial (AM) and posterior lateral (PL) and the in situ force within each bundle vary depending on where in the range the knee is. Most of the studies evaluating the tension patterns of the ACL have been carried out on human cadaver knees and have evaluated the ACL as a whole. More recently there has been renewed interest in evaluating the tensioning pattern of the ACL but by evaluating the separate role of the AM and PL bundle. A recent study by Zantop et al. (2007) explored the synergistic role of the AM and PL bundles in human cadaver knees. They found that ATT was increased at higher flexion angles with isolated transection of the AM bundle and at low flexion angles with resection of the PL bundle. Resection of the PL also resulted in a further increase in ATT with combined rotatory loading at low flexion angles. Similar findings were also reported by Gabriel et al. (2004); they found that the in situ forces in the PL bundle to combined loading were greater nearer to full extension and for the MA bundle were greater at slightly higher flexion angles. The reason for this renewed interest is the drive to improve surgical outcome by changing the reconstruction technique from a single to double bundle graft.

From a rehabilitation standpoint this research has increased our understanding of the loss of mechanical stability of the knee, particularly at the low flexion angles. It helps explain why this combined loading state, during functional activities such as rapid direction change during running, is such a problem for an ACLD knee (Houck & Yack 2003). The resulting knee motion can result in ACLD individuals experiencing a pivot shift phenomenon, which is anterior tibial dislocation and subsequent relocation of the tibia on the femur (Hoshino et al. 2007). In patients this is associated with the subjective report of giving way (Kocher et al. 2004). By understanding the role of the ACL during functional activities, appropriate rehabilitation programs can be designed and advice given to the patient about maintaining knee stability.

Other anatomical factors that contribute to knee joint stability can change following ACL rupture. Altered tibial slope angle in an ACLD knee can result in increased translation and reduced effectiveness of the hamstring to contribute to stability (Liu & Maitland 2003). It was therefore proposed that an individuals' tibial slope angle should be considered when determining an individuals' likely outcome with ACLD. Meniscal tears frequently occur in conjunction with ACL rupture and unstable symptomatic tears are surgically resected. Significant loss of meniscal tissue will result in reduced stability of the ACLD knee and increased stress within the secondary stability restraints (Allen et al. 2000).

In maintaining joint stability it is not just the physical role of the ACL but also its sensory role that is of great importance both at a spinal and supraspinal level. There is evidence of direct and indirect methods that ligament mechanoreceptors mediate reflex muscle contractions (Dhaher et al. 2005). At a spinal level a direct reflex has been found between the ACL and the hamstring muscle, during anterior tibial translation and through electrical stimulation intra-operatively. The reflex evoked is multi-phasic with a short (SLR) and medium (MLR) latency response. The SLR (20ms) is a monosynaptic hamstring stretch reflex mediated by 1a afferents that have direct connections to the alpha motor neurones causing the hamstring muscle to contract, to oppose the ACL loading. Even though this reflex has a short latency it is still too slow to have a protective role and prevent ACL injury during rapid movement (Krogsgaard et al. 2002). The MLR has an even slower response (50-80ms) and is mediated by group II afferents, which have direct effects on the gamma motor neurone pool and therefore muscle spindle activity. Muscle spindles have a number of roles in maintaining joint stability through the co-ordination of muscle stiffness and muscle response, position and movement sense (proprioception), monitoring and feed forward control (Friemert et al. 2005; Sjolander et al. 2002; Dhaher et al. 2005). It achieves this whilst receiving afferent input from the joint receptors which will be modulating the muscle spindles behaviour. To understand this, a more in depth description of muscle spindle function is required.

2.1.1 Muscle spindle

Muscle spindles are intrafusal fibres monitoring muscle stretch and feeding back this information to the CNS. They are situated between and parallel to the main (extrafusal) fibres of the skeletal muscles. The small intrafusal fibres are innervated by efferent gamma motor neurones that emerge from the ventral cord. It is these gamma motor neurones that the reflex activity of the ligament afferents interacts with. When the gamma motor neurones are innervated by the CNS they cause the intrafusal fibres to contract resulting in the 1a afferent fibres firing more rapidly. The information from the 1a afferents is sent to alpha motor neurones in the same muscle and through ascending pathways to sensory areas within the brain. The alpha motor neurones are innervated from higher motor centres within the brain in addition to the1a afferents from the spindle. If the 1a afferents are firing more due to stretch, this is fed back to the alpha motor neurones who respond by increasing their output and contracting to oppose this stretch. With the stretch 1a inhibitory inter-neurones are also excited which inhibit the alpha motor neurone of the antagonistic muscle. Activity in the 1a afferent is determined by the length and rate of stretch of the (extrafusal) muscle fibres and the amount of tension in the intrafusal fibres, which is determined by the gamma efferent fibres. Like the alpha motor neurones the gamma motor neurones receive and integrate input from descending supra-spinal pathways and joint afferents by group II afferents (Sjolander at al. 2002; Schmidt & Lee 2005). Through continuous modulation within the gamma muscle spindle system, muscle stiffness (the change in force over length) is controlled. This will be altered in response to signals from joint afferents, which will also have an effect on intrinsic muscle stiffness.

The ACL is a secondary restraint to other motions in the knee besides ATT and functions as a unit with other structures and their afferents to maintain stability. The combined importance of joint afferents from structures in addition to the ACL and resulting muscular responses were demonstrated in a study by Dhaher et al. (2003) during a valgus stress to the knee joint. They found increased reflex mediated activity in many muscle groups around the knee, indicating a generalised co-contraction strategy to support the knee. Following ACL rupture there is evidence that these reflex responses are not absent because other knee ligaments and the joint capsule are still present but the reflexes demonstrate an increase in the latency for both the SLR and MLR. In both the ACL intact and ACL deficient individual the limitation of this response is that it is too slow to act as a protective mechanism during everyday activities, especially fast sporting manoeuvres. During a weight bearing anterior tibial translation force in ACLD knees the medium latency responses were found to be longer (Melnyk et al. 2007 and Beard et al. 1994). This delay was even more marked in patients who were classified as non-copers but didn't have strength defects. There was no difference in passive stability between the copers and non-copers. Therefore this provides further indirect evidence that the altered stretch reflex excitability, which is related to dynamic knee stability, may be more important for the development of giving way and functional performance than the passive knee stability (Melnyk et al. 2007). If the system is less effective at providing feedback due to injury then the threshold for experiencing knee giving way in normally non-vulnerable situation may be reduced.

Feedforward control is another response that contributes to co-ordinated movement. This mechanism involves sending information ahead of the movement that prepares the system for the upcoming motor command or readies the system for the receipt of some particular kind of feedback information (Schmidt & Lee 2005). This has an important role in error detection and correction; if the function of the SLR and MLR is altered then this will reduce the effectiveness of this mechanism (Krogsgaard et al. 2002), resulting in altered muscle co-ordination strategies, possibly increasing ACLD individuals' vulnerability to giving way and altering functional performance (Roberts et al. 1999a; Ferber et al. 2002; Sinkjaer & Arendt-Nielson 1991). Evidence to support loss of muscle co-ordination in ACLD individuals is discussed more fully in chapter 2.1.3.

All the responses to stimuli discussed in the previous sections have been autogenic but voluntary responses that are processed at the higher centres can also be used to promote functional knee stability. These responses are even slower, taking from 80 to 100ms; they are processed in the higher centres and can involve any of the muscles (Schmidt & Lee 2005). Due to the slow reaction time, which is the interval between the onset of a signal and the initiation of the response (Magill 2007), voluntary response are not effective in protecting the knee joint once an external event happens. Critical events for ACLD individuals include stepping on uneven ground, responding quickly to an unexpected event or avoiding an opponent during sport. Voluntary anticipatory responses can be effective for anticipating when a change of movement is required ahead of an event (Besier et al. 2001) but will be less efficient if a second stimulus arrives during the reaction time to the first stimulus because the reaction time to the second stimulus will be delayed (Lephart & Fu 2000). For ACLD individuals if they are aware that they are vulnerable to giving way during twisting movements and high speed direction changes then they can anticipate this to try and avoid a giving way event and protect the knee. The problem with using anticipation as a protective response is that by focusing attention at knee stability, it could affect other aspects of an ACLD individual's movement performance and participation. Based on Fitts and Posners (1967) 3 stage model of motor learning then with practice and as an individual learns to use cues from the environment, then the attention or learned responses will move from being cognitive to automatic, which should be reflected in their performance and participation. Not all individuals will reach this stage; their ability to do so may be related to factors such as their ability to detect errors and correct performance, the amount, type and quality of the practice and instructions received and the type or combination of damage to the knee (Magill 2007). In conclusion the SLR and MLR responses have been found to demonstrate increased latency as a result of ACL rupture. This could result in less co-ordinated muscle activity and altered movement strategies and knee stability. To protect the knee from instability learned or anticipated responses may be required to maximise functioning.

2.1.2 Reduced proprioception in the ACLD knee

Proprioception refers to an individuals' perception of joint position and movement characteristics such as direction, velocity and location in space (Magill 2007). This has been found to be reduced in individuals with ACL rupture (Reider et al. 2003; Carter et al. 1997; Fischer-Rasmussen & Jensen et al. 2000; Pap et al. 1999), as a result of damage to sensory receptors in the ACL and any other knee structures that were simultaneously injured (Roberts et al. 2004; Friden et al. 1999) and as a result of any pain and swelling that an individual may be experiencing (Hurley 1997). Loss of proprioception following ACL rupture could contribute to knee instability; indirect evidence of this is that individuals experiencing the greatest amount of functional instability and lowest functional performance also have the poorest proprioception (Roberts et al. 1999b; Katayama et al. 2004). For instance proprioception is recognised as one factor that will predict shorter hop distance as a measure of functional performance (Roberts et al. 2007). Proprioception cannot be considered in isolation for causing loss of functional performance and reduced functional stability, it is one of many factors which include loss of muscle strength; altered muscular activation and altered central programming (Courtney & Rine 2006). Clearly the ACL has an important sensory and physical role in regulating joint stability in combination with other knee structures. The muscles surrounding the knee also have an important role in knee stability but their function can be compromised following ACL rupture which will now be discussed.

2.1.3 Overview of the role of muscles in providing dynamic stability

Within the ACL intact knee the role of the quadriceps, hamstrings, gastrocnemius and soleus muscles as contributors to joint stability and protection of the ACL have been the most widely researched. A wide range of methods have been used to evaluate their role including; 3D modelling solutions (Shelburne et al. 2005); EMG modelling (Doorenbosch & Harlaar 2003); cadaveric knees with load cells (Markolf et al. 2004); sagital plane video fluoroscopy and EMG during closed and open chain activities (Issac et al. 2005); EMG with isokinetics, isometrics and functional activities (Kellis & Baltzopoulos 1999; Issac et al. 2005). Despite the varying methods the consensus is that the hamstrings muscle acts synergistically with the ACL to oppose anterior tibial translation, protect the ACL and counteract large quadriceps forces (Kellis & Baltzopoulos 1999, Li et al. 1999, Imran & O'Connor 1998, Markolf et al. 2004; Isaac et al. 2005). The effects of the hamstrings have been found to be most pronounced near 90 degrees of flexion, where the angle of pull of the hamstrings is nearly parallel to the tibial plateau, allowing the hamstrings to displace the tibia posterior (Markolf et al. 2004). This role could be compromised at low flexion angles below 20 degrees of flexion, where the angle of pull of the hamstrings will not allow this mechanical advantage (Markolf et al. 2004). In contrast at low flexion angles below 30 degrees the line of pull of the quadriceps is such that significant increases in ATT have been found (Li et al. 1999). The gastrocnemius and soleus function to create a posterior shear force of the tibia on the femur and control anterior rotation of the tibia (Courtney & Rine 2006). These muscle groups provide a stabilising role through a combination of appropriate;

antagonistic co-contraction (Kingma et al. 2004; Fagenbaum & Darling 2003; Shelburne & Pandy 1998); recruitment pattern (Houck et al. 2007) and timing and amplitude of the muscle (Rozzi et al. 1999; Houck & Yack 2003; Shelburne et al. 2006). This activity in turn is dependent upon factors such as the joint angles, body alignment, velocity, load and phase within the task being performed (Shin et al. 2007a; Withrow et al. 2006; McNitt-Gray et al. 2001).

The key area for investigation regarding the stabilising role of the muscles has been their ability to control/reduce excessive ATT. In an isokinetic study and step up task using EMG on ACLD patients, increased hamstrings co-contraction was found to be related to reduced ATT (Yanagawa et al. 2002) and increased hamstrings activity maintained ATT to within the same range as ACL intact individuals (Isaacs et al. 2005). Using a computer model of gait Shelburne et al. (2005) found that by increasing the hamstring activation ATT could be reduced, although this resulted in a reduced extensor moment. Reducing quadriceps activity to restore ATT range was not possible because it resulted in a complete elimination of the extensor moment which is required for gait and knee stability. Both the quadriceps and hamstrings have an essential role providing muscular support during side cutting to support valgus and varus movements, through co-activation (Lloyd et al. 2005). This overview of the role of the muscles in knee stability is confined to controlled environments or single plane activities. For a more extensive understanding of the role of the knee muscles that is more informative to the rehabilitation of ACLD knees it is important to understand muscle activity in relation to performance of functional activities. This includes identifying adaptation in timing and amplitude of activity and the relationship between muscle strength deficits and functional performance. This will be discussed in depth in chapter 2.2 on movement compensation strategies.

2.1.4 Muscle strength deficits

Muscle strength deficits are a common finding following ACL rupture (Tsepis et al. 2006; Chmielewski et al. 2004; Snyder-Mackler et al. 1995; Keays et al. 2001; Patel et al. 2003; Roberts et al. 2007). In addition quadriceps atrophy, reduced strength and control have been found to be a distinguishing characteristic of non-copers (Williams et al. 2005; Courtney & Rine 2006). Similarly hamstring weakness has been found in low functioning ACLD individuals (Tsepis et al. 2006) but comparison of these findings with other studies is limited due to the novel method of sub-classifying groups; using the Lysholm score (Lysholm & Gillquist 1982). The limitations of this method are detailed on page 82. In a recent study by Hurd et al. (2008b) no difference in quadriceps strength was found between potential copers and non-copers. This finding may be because individuals were enrolled on a rehabilitation program immediately and their participants were high level athletes pre-injury.

Muscle weakness may persist after ACL rupture as a result of the pain and swelling and subsequent inactivity that accompanied the acute phase post injury (Hurley 1997; Torry et al. 2000; Sterling et al. 2001). As a result of the joint damage abnormal articular afferent information can cause reduced alpha motoneurone excitability and decreased voluntary quadriceps activation, if this is persistent and severe enough then this could result in muscle atrophy and weakness (Hurley 1997). This reduction in voluntary quadriceps activation has been found to be worse in individuals who had more joint damage in combination with the ACL rupture (Hurley et al. 1994). If muscle function is not restored through rehabilitation then this could result in altered patterns of neuromuscular activation, resulting in loss of functional joint stability, poor muscle co-ordination and functional performance (Sterling et al. 2001; Tsepis et al. 2006; Chmielewski et al. 2004; Snyder-Mackler et al. 1995; Keays et al. 2001; Patel et al. 2003; Roberts et al. 2007). It may also mean that as individuals try to return to activity they may experience early onset of muscle fatigue. Based on the biomechanical responses of the knee to fatigue in uninjured ACL intact individuals, muscle fatigue could result in; further movement adaptation, greater predisposition to giving way and further injury. In non-injured subjects fatigue resulted in longer latency of the monosynaptic reflex, reduced EMG amplitude of the short and medium latency responses of the hamstrings and increased ATT which represents a loss of dynamic stability of the knee (Melnyk & Gollhofer 2007). In ACLD individuals who already have compromised stability of the knee this may further increase their risk of giving way. In addition during landing activities ACL intact but fatigued individuals demonstrated less contribution from the knee to total support moment and more from the ankle and hip (Coventry et al. 2006; Orishimo & Kremenic 2006). This is the same strategy that was found in ACLD individuals during deceleration tasks and therefore underlying muscle deficits could be responsible for these adaptations. Clearly, reduced strength is common in ACLD individuals but will not be found in all individuals and regaining full muscle strength is an important rehabilitation goal.

2.2 Movement Compensation Strategies following ACL Rupture

A number of studies have analysed functional activities to try and identify the form of altered movement strategies adopted by ACLD individuals. If identified they can be addressed in rehabilitation, used to identify individuals who are not recovering or discriminate between high and low functioning ACLD individuals and may also increase our understanding of joint loading that could be detrimental to cartilage and predispose to degenerative changes (Barrance et al. 2007). Several different approaches have been used in terms of methodology and ACLD population recruited. The most common approach has been to evaluate patients performing functional activities using a 3D motion analysis system comprising of cameras, force platforms and software to calculate biomechanical variables that can be grouped into kinematics, kinetics and electromyography. Kinematics is a description of motion independent of the forces causing that movement (Winter 2005). In the current study this term has been subdivided into the domains of linear and angular kinematics. In this thesis linear kinematics includes the time-distance variables of velocity, cadence, step length, step time and hop distance wheras angular kinematics includes joint angles. Kinetics is a description of motion that includes consideration of force as a cause of motion and electromyography (EMG) is the measurement of action potentials in muscle fibres and provides insight into which muscles are responsible for a movement (Enoka 2002, Winter 2005). Definitions of all the biomechanical variables that are discussed in this literature review are defined in Table 3. The kinetic variables reported in most of the studies analysing performance in ACLD individuals have been calculated using inverse dynamics, an approach to determine the forces and moments acting on a system based on the kinematics of the motion (Enoka 2002). The results of studies analysing motion in ACLD individuals will now be evaluated in turn for gait, jogging, distance hop and run and stop (R&S); functional activities that are commonly incorporated into rehabilitation, to analyse if common movement adaptation strategies can be identified for ACLD individuals.

Table 3 Definitions of biomechanical variables.

VARIABLE	DEFINITION
Velocity	This is the rate of change in position of an individual with respect to time (Enoka 1994).
Step length	The distance between the occurrence of a gait event and its next occurrence on the other leg (Enoka 1994).
Cadence	This is the number of steps an individual takes per minute (Enoka 1994).
Symmetry index	This is the symmetry in step lengths (SL) between the injured and uninjured legs.
Force (N)	Effect of one body on another that causes the bodies to accelerate relative to an inertial reference frame (Enoka 1994).
Ground reaction force (GRF)	An external force measured under the area of the foot and provided by the support surface. This is 3D consisting of a vertical, medial-lateral and anterior-posterior component (Winter 2005; Enoka 2002).
Joint reaction forces (JRF)	The net force transmitted from one segment to another due to muscle, ligament and bony contacts that are exerted across a joint. This consists of a compressive component (along the axis of the segment) and shear (perpendicular to the long axis of the segment or along the articular surface) component (see for example Enoka 2002).
Moments (Nm) Internal and external moments	The turning effect of a force about a point; the product of the force and the perpendicular distance from its line of action to this point. Internal moments represent the net effect of all muscle activity at a joint. For example a positive internal knee extensor moment represents extensor muscle dominance. Internal moments should not be confused with external moments which are computed only by the use of the resultant GRF and its perpendicular distance to the joint centre. An external knee flexion moment would be balanced by a net internal extensor moment (Simonsen et al. 1997; Enoka 2002).
Total support moment (TSM)	The sum of the moments generated at the ankle, knee and hip (extensor positive). If this support moment is positive one or even two joints may show flexor muscle dominance without resulting in collapse of the whole extremity (Winter 1980; Simonsen et al. 1997).
Work (J)	Energy change over a period of time as a result of force acting through a displacement on the direction of the force (Enoka 2002).
Power (W)	The rate of doing work; the rate of change in energy; the product of force and velocity. A system absorbs power when it does negative work and produces power when it does positive work (Enoka 2002).
Quadriceps avoidance	An external extension moment at the knee in stance (Berchuck et al. 1990). Alternatively it has been defined as an absence or reduction of an internal extensor moment in the knee, representing a reduction of quadriceps activity or net increase in hamstring activity. This can occur during the stance phase of gait in ACLD individuals causing a reduction or loss of the biphasic extensor/flexor moment pattern found in healthy subjects

2.2.1 Gait

The majority of the research has centred on gait analysis so this chapter has been sub-divided into gait analysis in acute and chronically injured ACLD individuals and gait performance in the different functional sub-groups; copers, adapters and non-copers. Although traditionally gait has not been considered a challenging activity for ACLD knees, it is the one activity that all individuals have to be able to perform to carry out essential activities of daily living. Recent renewed interest in ACLD gait analysis has occurred with recognition that there are 3 different functional sub-groups of ACLD individuals and non-copers in particular experience knee instability with walking. There are some difficulties when trying to identify common gait compensation strategies between studies. The main problems are; differences in the chronicity of patients recruited; sub-grouping patients using different criteria; small sample sizes; adopting different inclusion criteria for what pathology is acceptable in combination with the ACL rupture; using different methods to normalise the data; inconsistency with what variables have been evaluated and analysing different phases of the gait cycle. This may partly be responsible for the lack of consensus on what gait adaptations are utilised by ACLD individuals. Analysis of gait time-distance variables in particular gait velocity is essential because firstly it reflects change in gait performance (Coutts 1999) and secondly, velocity has been found to exert a direct influence on gait joint angles (Lelas et al. 2003; Hanlon & Anderson 2005; Kirtley et al. 1985) and other components of gait (Voloshin 2000), so to understand resulting patterns gait time-distance data is required.

2.2.1.1 Early v late ACLD gait compensation strategies

Gait compensation strategies are expected initially post injury in response to swelling and pain which can cause reduced extensor moments, altered muscle co-activation, joint compressive forces, ground reaction forces and work (Torry et al. 2000; Palmieri-Smith et al. 2007; Shrader et al. 2004; Robon et al. 2000). Recovery is expected over a period of 4-6 months (Kvist 2004a) during which pain and swelling decline, functional stability of the knee improves and after this time individuals should be achieving their maximum functional ability. Compensation strategies after this time point are considered long term adaptations to the injury.

Only four studies have been carried out comparing gait performance between acutely injured ACLD subjects and uninjured controls. The methodology and key findings of these studies are summarised in Table 4 and will now be described in turn for gait time-distance variables, joint angles and kinetics before the implications of these findings are discussed. The only study to demonstrate any adaptation in gait time-distance variables was conducted by Knoll et al. (2004). Both male and female ACLD subjects were found to walk with a reduced step length and step base compared to uninjured controls. In contrast, Georgoulis et al. (2003) did not find any statistically significant differences between the uninjured and control subjects for cadence and velocity. DeVita et al. (1997) measured velocity, step length and cadence, finding similar means to control subjects but didn't perform a statistical analysis. Finally, Lewek et al. (2002) did not report on time-distance variables, it is unknown if any were measured. For knee joint angle a stiffening strategy with reduced knee flexion excursion was noted in the ACLD subjects by Knoll et al. (2004) and DeVita et al. (1997), compared to healthy subjects. In direct contrast no difference in sagittal joint angles were noted by Lewek et al. (2002) or Georgoullis et al. (2003). Increased internal rotation at initial swing was found by Georgoullis et al. (2003) but the clinical significance of this for ACLD gait is not apparent. A mixture of muscular compensation strategies were found for the acutely injured ACLD individuals. Lewek et al. (2002) found that ACLD individuals had a decreased internal knee extensor moment, which would represent decreased quadriceps activity. Because the data for this study was collected up to 6 months post injury this could be a result of neuromuscular adaptation due to reduced voluntary muscle activity in the acute phase post injury (Sterling et al. 2001). Reduced quadriceps activity of the vastus medialis and vastus lateralis (VM and VL) was also found by Knoll et al. (2004); this was based on a descriptive analysis of EMG rather than a statistical analysis, which is required to draw firm conclusions from this study. Due to the acuteness of when this analysis was conducted the mechanism for this quadriceps avoidance could be due to alpha motor neurone inhibition due to pain and swelling (Sterling et al. 2001). In contrast Devita et al. (1997) found an increased knee internal extensor moment ($p<0.001$) in the ACLD individuals that persisted throughout stance instead of demonstrating a normal biphasic pattern (Perry 1992). So in this study there was no evidence of reduced quadriceps activity but no EMG variables were collected to directly support this finding. The increased internal knee extensor activity may reflect increased co-activation required to stabilise the injured knee as it maintained a more flexed positioning and reduced excursion. For the hamstring muscle, which is considered of major importance to functional knee stability only Knoll et al. (2004) found an increase in hamstring activity based on descriptive analysis of the EMG. This would counteract the reduced quadriceps activity that this group of authors reported and would be required to provide functional knee stability. It is clear that acutely injured ACLD individuals can adopt a number of different strategies to stabilise the knee, encompassing adaptations to time-distance variables, joint angles and kinetics and the interactions that exist between these variables. Compensation strategies may vary so much between these studies because of differences in the timing of when studies were carried out. The acute phase is potentially a period of rapid change due to recovery of acute symptoms so small differences in the timing of the analysis could make significant differences to gait performance. The time from injury to analysis for the studies included varied from 12 days to within 6 months post injury, which is a large range. Other explanations for the difference in findings may be due to equipment. In the study by Knoll et al. (2004) subjects walked on a treadmill, which controlled velocity across all subjects. Imposing a set speed, rather than letting individuals walk at their preferred speed could in itself have resulted in gait differences between the studies. There has also been a lack of consistency between investigations for which gait variables have been measured and how they have been analysed. For example mean knee angles during stance were evaluated by DeVita et al. (1997), whereas knee flexion at a particular time point (heel strike) were evaluated by Georgoulis et al. (2003). Differences in methods may also have resulted in different findings, for example using EMG compared to calculating muscle moments. The strength of the study by Lewek et al. (2002) is that they measured and calculated both types of data to evaluate muscle activity. The overall implication is that a number of different strategies can be adopted by acutely injured ACLD individuals which may be the response to the acute symptoms, reduced joint stability or neuromuscular adaptation. Further studies are warranted on acutely injured ACLD subjects to understand the longer term implications of early compensation strategies. In particular further insight into time-distance and joint angle adaptations are required because these variables are clinically relevant to inform rehabilitation and easy to measure in the clinical setting. The four studies to date have not made a thorough analysis of them.

Table 4 Data tables for studies that have analysed gait in ACLD subjects following acute ACL rupture

STUDY AUTHORS	SUBJECTS	METHOD	MAIN FINDINGS
DeVita et al. 1997	9 ACLD 10 controls No ligament damage Varying athletic ability Analysed 2 wks post injury	2 camera movement analysis, inverse dynamics and EMG. Early to mid stance analysed NO statistical analysis of time distance variables T-tests for kinematics and kinetics	ACLD: cadence 119, step length 0.74, velocity 1.48m/s. Mean knee angle 23 degrees, hip 9.7 degrees. CONTROLS: cadence 120, step length 0.75, velocity 1.50m/s. Mean knee angle 17.8 degrees, hip 4.5 degrees ACLD: injured knee significantly more flexed ($p<0.01$), hip more flexed ($p<0.01$), extensor torque throughout stance (should be bi-phasic), less positive power knee ($p<0.01$)
Georgoulis et al. 2003	13 ACLD, 21 ACL reconstruction, 10 controls No ligament damage Analysis 1 to 5 wks post injury	6 camera movement analysis	No group differences ACLD v controls for; cadence (109 steps/min), velocity (1.31 v 1.18 m/s), knee flexion heel strike (3.41 v 2.3 degrees) ($p>0.05$) ACLD v control; increased internal rotation during initial swing (9.6 v 0.3 degrees $p<0.003$)
Knoll et al. 2004	21 ACLD, 51 controls Isolated ACL injury ACLD subdivided into acute and chronic but not statistically analysed separately. Time from injury to measurement 12 days acute, 28.2 mths chronic.	EMG Ultrasound device for kinematics Treadmill walk	ACLD step length: males 478.1 mm, females 396.1, uninjured males 513.3, females 470.7 ($p<0.0046$ males, $p<0.0038$ females) ACLD step base: males 30.1 mm, females 11.25, uninjured males 41.9, females 39.0 ($p<0.0034$ males, $p<0.0028$ female). Reduced knee excursion all phases of gait. ACLD peak knee extension: males 2.4 degrees, females 6.1, uninjured males 5.5, females 7.3 ACLD peak knee flexion: males 40.9 degrees, females 42.58, uninjured males 53.2, females 57.3 (descriptive analysis only) EMG ACLD biceps femoris activity more intense (descriptive analysis only) ACLD VM and VL limited activity (descriptive analysis only)
Lewek et al. 2002	10 ACLD, 10 controls, 18 ACLR (sub-divided into strong and weak) Analysis 6 months from time of injury. All ACLD subjects participated regularly in sports	Cross sectional comparative study Early stance phase analysed EMG and 6 camera movement analysis system, inverse dynamics	ACLD weaker than ACL recon strong group ($p=0.000$). No group diff in knee flexion angle at HS ($p=0.729$) ACLD internal moment moment at peak knee flex trend towards being reduced ($p=0.021$). No difference EMG gastrocnemius, VL, lateral hamstrings ($p>0.05$).

Far more studies have been carried out evaluating gait in chronically injured ACLD individuals, the populations, methodology and main findings for these studies are summarised in Table 5. For time-distance variables no compensations were found in subjects with ACLD injured knees (Snyder-Mackler et al. 1995; Muneta et al. 1998; Roberts et al. 1999a; Patel et al. 2003 and Ferber et al. 2004; Ferber et al. 2002 and Torry et al. 2004; Wexler et al. 1998). For sagittal joint angles a large number of studies found that ACLD individuals adopted an overall strategy of reduced flexion excursion through stance, also known as a knee stiffening strategy (Snyder-Mackler et al. 1995; Muneta et al. 1998; Roberts et al. 1999a; Patel et al. 2003; Ferber et al. 2004). In contrast both Ferber et al. (2002) and Torry et al. (2004) did not find any altered joint angles. There is some difficulty comparing results between studies because of differences in analysis. Some of the investigations have only analysed or reported on limited phases of the gait cycle; for example Wexler et al. (1998) reported decreased extension at terminal stance, which has not been evaluated elsewhere. Muneta et al. (1998) and Berchuck et al. (1990) analysed specific phases of the gait cycle whereas Ferber et al. (2004) evaluated the average position through stance. Based on the number of studies that have found reduced knee excursion as a compensation strategy and their overall methodological quality it can be concluded that this is a common kinematic compensation strategy in chronic ACLD subjects. More recently the range of ATT and rotation at the knee has been evaluated (Andriacchi & Dyrby 2005). There is still much work to be done on this but the early evidence indicates that

ACLD individuals reduce external rotation and ATT at terminal swing, which could decrease their stability when accepting weight onto the limb at initial contact (Andriacchi & Dyrby 2005). The advantage of this is that it would counteract against a pivot shift type of movement that occurs during an episode of giving way. At the hip joint an increase in flexion during stance has been noted (Ferber et al. 2002; Ferber et al. 2004). Accompanying muscular compensations have been analysed directly using EMG and indirectly by calculating joint moments. From the EMG studies altered timing and longer duration of hamstrings, quadriceps (Roberts et al. 1999a; Ferber et al. 2002; Sinkjaer & Arendt-Nielson 1991) and gastrocnemius (Sinkjaer & Arendt-Nielson 1991) have been found. This may indicate a generalised co-activation strategy to stabilise the knee. There is limited evidence of altered magnitude of muscle activity (Ferber et al. 2002; Sinkjaer & Arendt-Nielson 1991). Mixed responses have been found for the knee moments; a number of studies have found no alteration to knee moments (Roberts et al. 1999a; Ferber et al. 2002; von Porat et al. 2006); whilst other studies differ in their conclusion as to whether there is increased or decreased extensor moments (Ferber et al. 2004; Muneta et al. 1998; Patel et al. 2003; Andriacchi & Dyrby 2005; Berchuck et al. 1990). An alternative approach to identifying altered movement strategies has been used by Torry et al. (2004). ACLD individuals were stratified according to whether they used a hip or knee strategy. A hip strategy could be recognised by a normal biphasic moment pattern at the knee, increased hip extensor output, decreased knee extensor output and normal knee joint angle. A knee strategy involved increased knee stiffness, a flexed knee gait that is accompanied with a dominant knee extensor moment pattern with increased VM and (biceps femoris) BF later in stance. An alternative strategy that has not been explored in the literature is an ankle strategy to stabilise the knee. Like the hip strategy this may result in normal knee joint angle and reduced knee extensor moments but increased plantar flexor ankle moment to compensate. This could occur in conjunction with increased hip extensor moments. This fits the concept of total support moment proposed by Winter (1980), whereby a reduction in extensor moment at the knee can occur as positive moments are maintained at the ankle or hip.

Based on all of these studies a late compensation strategy that emerges is one in which individuals stabilise the knee by stiffening it and limiting their range of motion. A number of muscular adaptations are available that appear to be related to altered timing as opposed to magnitude of activity. This could indicate a strategy of generalised co-contraction to stabilise the knee. Overall a predominantly internal extensor moment pattern has been found at the knee, which may indicate that it is most common for ACLD individuals to use a knee strategy. This does not mean that quadriceps avoidance does not occur but it would not appear to be the most frequent muscular compensation to stabilise the knee. More analysis of the ankle and hip joint is required because compensations may occur at these joints as forces are transferred away from the knee. Adaptations at these joints may be more common in the presence of quadriceps avoidance to maintain a positive total support moment of the lower limb. For clinical movement analysis a combination of gait variables is required to more fully evaluate movement strategies. To inform practice this needs to include a combination of variables which as a minimum includes time-distance variables and joint angles for the ankle, knee and hip.

Table 5 Data tables for studies that have analysed gait in ACLD subjects with a chronically ruptured ACL.

STUDY	SUBJECTS	METHOD	FINDINGS
Andriacchi & Dyrby 2005	ACLD 9 subjects injured and non-injured knee, 9 controls. Average analysis 127 months post injury	4 camera, 3D movement analysis	At terminal swing reduced external rotation and ATT at terminal swing (p<0.05). Average position through gait cycle offset towards internal rotation (p<0.05) compared to healthy knee. Offset in the rotational position were positively correlated to the magnitude of the flexion moment (balanced by a net quads moment) p<0.05.
Berchuk et al. 1990	16 ACLD 10 controls Included ACLD with meniscal tears	2D movement analysis, optoelectronic digitiser	Increased external extension moment at heel strike and at mid stance (quadriceps avoidance) p<0.05. Reduced knee flexion at mid-stance p<0.05. No difference in hip moments of maximum hip flexion angle (p>0.05)
Ferber et al. 2002	10 ACLD 10 controls Isolated ACL injury	4 camera 3D Movement analysis, inverse dynamics, EMG	Velocity, cadence and step length not reported on. No difference in stance time (p>0.05). No difference in knee kinematics p>0.05. ACLD Hip significantly more flexed involved leg HS to first ½ stance p<0.05. No difference knee moments through stance p>0.05. ACLD Increased hip moment to mid stance p<0.05, then switched to significantly reduced hip flex moment for rest of stance p<0.05. ACLD knee power absorption significantly less late stance (p<0.05). ACLD larger hip power generated mid stance (p<0.05). ACLD EMG VL slower time to peak mid stance (p<0.05) and greater biceps femoris early stance (p<0.05).
Ferber et al. 2004	10 ACLD 10 controls Isolated ACL injury	4 camera 3D Movement analysis, EMG inverse dynamics,	Velocity, cadence and step length not reported on. No difference in stance time (p>0.05). ACLD greater average knee and bilateral hip flexion angle than controls (p<0.05) Greater ACLD non-injured and control knee extensor angular impulse, extensor moment and power absorption non-injured leg (p<0.05).
Muneta et al. 1998	12 ACLD injured versus non-injured	1 camera system, force platform, 2D analysis	Reduced injured leg maximum internal knee flexion moment (p=0.030) (quadriceps avoidance). Greater knee flexion in injured leg at heel strike (p=0.031)

STUDY	SUBJECTS	METHOD	FINDINGS
Patel et al. 2003	44 ACLD 44 controls	Cross-sectional study 1 optoelectic camera and force platform	Reduced external knee extension moment v controls at late stance, no p values given for independent t-tests. Greater knee flexion angle at late stance ($p<0.05$)
Roberts et al. 1999	18 ACLD 10 controls	5 camera, 3D motion analysis system, EMG	No significant group difference for cadence, stride length and stride speed ($p>0.05$) Maximum knee extension reduced, maximum knee internal and external rotation increased ($p<0.05$). Trend for slight increase in flex early stance No difference in internal knee extension moment ($p>0.05$) Overall 94% ACLD individuals had longer duration of quads activity, 94% had longer medial hamstring activity, 83% had increased lateral hamstring activity and 83% had increased gastrocnemius activity in ACLD
Shelburne et al. 2005		3D model based on forward dynamic simulation, previous EMG data	ATT increased throughout stance for ACLD subjects. Peak ATT at contra lateral toe off, coinciding with peak extensor moment ATT levels could not be resorted just by reducing magnitude of quadriceps activity, but could restore by increasing hamstring magnitude
Sinkjaer et al. 1991	14 ACLD subjects 16 controls Average 46 months post injury	EMG and treadmill	Earlier onset times for ACLD all inclines; VM, VL, medial hamstrings, lateral hamstrings, medial gastrocnemius. ACLD subjects longer bursts of VL, VM, lateral hamstrings and medial gastrocnemius. No difference in EMG amplitude in ACLD subjects during level walking.
Snyder-Mackler et al. 1995			Subjects with weak quads tendency to hold knee in slight knee flexion at Hs and continue t o flex only slightly so have a reduced flexion excursion.
Torry et al 2004	16 ACLD 8 controls Isolated ACL tear 2yr+ since injury. Sub-divided; presence of a biphasic extensor moment (Gp A) or an all extensor moment (Gp B)	5 camera 3D motion analysis system, force platform, EMG	POOLED ACLD DATA: No difference velocity ACLD (1.4m/s) v control (1.4m/s) or for any hip, knee or ankle kinematics, moments or EMG ($p>0.05$). No subjects demonstrated quadriceps avoidance. SUB-DIVIDED ACLD DATA: Gp A; increased ROM throughout stance, larger hip extensor impulse with greater contribution to the support moment ($p<0.05$), no diff in knee kinematics to controls ($p>0.05$), lower knee extensor moment that contributed to extensor moment than gp B ($p<0.05$). GpB; compared to controls and gpA more flexed at the knee and ankle through stance ($p<0.05$), less knee excursion ($p<0.05$), no kinetics differences ($p>0.05$), 3rd quartile stance greater VM and BF activity, less gastrocnemius activity than Gp A ($p<0.05$).

von Porat et al. 2006	12 ACLD males, soccer players 12 controls		No gait kinematic, kinetic or time distance variable differences ACLD v control (p>0.05); velocity 1.39 v 1.32 m/s p=0.2, step length 0.71 v 0.71 p=0.8, peak knee flexion at loading response 18 v 17 degrees p=0.5, internal knee extensor moment p=0.6
Wexler et al. 1998	30 ACLD subdivided according to time from injury; 0-2.5yr, 2.5-7.5, 7.5+ no additional ligament damage 30 controls	2 camera optoelectronic digitiser, force platform	Decreased external knee flexion moment mid-stance (quadriceps avoidance in all but 1 subject) for each ACLD time interval (p<0.001). Maximum external flexion moment during stance was significantly reduced in ACLD subjects (p<0.001). Terminal stance significantly increased external knee extension moment (p<0.03) chronic ACLD only. Decrease in terminal knee extension with chronicity (p<0.01) and compared to controls (p<0.03).

2.2.1.2 Sub-group analysis; copers versus non-copers

The main findings of all the studies that have analysed gait in ACLD sub-groups are listed in Table 6. None of the studies comparing time-distance gait variables between copers and non-copers have found any differences between sub-groups in ACLD populations with acute or chronic ruptures. All ACLD non-copers, regardless of chronicity, walked with decreased knee flexion at heel strike (HS) and peak knee flexion (Rudolph et al. 1998; Rudolph et al. 2001; Hurd & Snyder-Mackler 2007), a joint stiffening approach. The strategy for copers is less well established as both increased and decreased peak knee flexion angles have been documented (Alkjaer et al. 2003; Chmielewski et al. 2001). Reduced ATT has been found in non-copers but the method of sub-grouping into high and low functioning sub-groups according to Lysholm, which is a score evaluating knee symptoms and function, is unique to this investigation (Kvist 2004b). No differences in hip joint angles have been documented. Based on an anlysis of joint moments a reduced extensor moment in the knee of non-copers was found by Rudolph et al. (1998) and Alkjaer et al. (2003). This is hypothesised to represent a reduction in quadriceps activity to promote knee stability. No evidence of quadriceps avoidance in non-copers was found by Hurd & Snyder-Mackler (2007); or Rudolph et al. (2001). There is an overall consensus of no reduction in total support moment following ACL rupture but non-copers have been found to have a greater relative contribution from the hip (Rudolph et al. 2001; Alkjaer et al. 2003; Hurd & Snyder-Mackler 2007). EMG analysis also provides support for a number of different strategies following ACL rupture. The exact muscular compensations in copers and non-copers are not completely defined as relatively few studies have been conducted and there is no agreement between the investigations for their results. Non-copers have been found to walk with increased amplitude of soleus (Rudolph et al. 2001) and hamstrings (Hurd & Snyder-Mackler 2007) and decreased amplitude of quadriceps and soleus have been reported by Hurd & Snyder-Mackler (2007). Increased duration of activity has been found for hamstrings and medial gastrocnemius (Rudolph et al. 2001). There is no consensus as to whether non-copers walk with increased or decreased co-activation levels between the quadriceps and hamstrings (Alkjaer et al. 2003; Hurd & Snyder-Mackler 2007). Overall non-copers have a gait pattern which is most distinctly different from copers and controls and in general adopt a strategy of stiffening the knee by using less flexion and reducing ATT. The disadvantage of this strategy is that it will not permit adaptability when faced with different task and environmental demands, which could result in instability limiting functioning. There is also a small amount of evidence from 2 studies that the hip contributes more to the total support moment and the knee less further work is required to clarify this. This is not a good strategy for maintaining knee stability, particularly during demanding sport manoeuvres. There is no consensus on moment or EMG muscular adaptations, despite a number of studies evaluating these variables. For clinical movement analysis this indicates that a system that allows evaluation of kinematics is required as a minimum. This raises the question of how similar is the gait of copers and healthy subjects?

Rudolph et al. (2001) concluded that potential copers move like control subjects using similar ROM, moments and muscle activation patterns but a number of studies have found results to challenge this (Alkjaer et al. 2003; Chmielewski et al. 2001; Rudolph et al. 1998; Courteny & Rine 2006; Sinkjaer & Arendt-Nielsen 2001) . Increased peak knee flexion angle was demonstrated by Alkjaer et al. (2003) and less knee flexion by Chmielewski et al. (2001). Kinetic analysis has found lower knee extensor moments in copers compared to controls (Rudolph et al. 1998 and Chmielewski et al. 2001), with increased moment contributions from the hip and ankle (Alkjaer et al. 2003; Chmielewski et al. 2001). Courteny & Rine (2005) found that copers demonstrated greater hamstrings activation and less gastrocnemius activation compared to adapters and controls. Their results must be interpreted with caution due to the very small sample size of 3 subjects in the coper and 4 subjects in the non-coper groups. Sinkjaer & Arnet-Nielsen (2001) found that individuals with good stability had earlier gastrocnemius activation but they used the Lysholm score to sub-classify patients into functional sub-groups instead of the more common method of what pre-injury activity individuals have been able to return to without instability. Therefore, copers move in a similar manner to healthy subjects but they do not walk without movement compensation strategies. They do not demonstrate time-distance or knee kinematic adaptations but overall appear to use lower knee extensor moments, with a greater contribution from the ankle or hip to the total support moment and greater hamstring activation. Using lower knee moments and higher hip and ankle moments is a strategy used by healthy subjects when they are fatigued (Orishimo

& Kremenic 2006; Coventry et al. 2006) and therefore is not a good strategy to maintain functional stability of the knee, particularly during high demand sporting manoeuvres. This will be discussed further in the section below on distance hop. Overall the quality of the data collection methods has been good, with the majority of the studies using 3D movement analysis systems in case control and cross-sectional studies. Investigators have almost always used uninjured controls in addition to the uninvolved limb to compare against the ACLD involved leg. The main limitation of studies has been the small number of subjects in the ACLD sub-groups, particularly the copers, resulting in the statistical analysis having low power and reducing the likelihood of finding statistically significant sub-group differences.

The literature evaluated up to this point has been concerned with looking for differences in performance between groups for biomechanical variables. There has been no consideration of other factors that evaluate skilled performance, such as movement adaptability when encountering different environments and situations (Sterigou et al. 2004). If ACLD can only move in a particular way then they may be prone to instability or will have to adapt by reducing their performance level. This was taken into consideration by Houck et al. (2007) and they used cluster analysis to identify preferred muscle activation strategies VL, MH and LH in ACLD individuals. This revealed that (76-93%) control subjects used 3 muscle activation patterns, whereas copers and non-copers had preference for only one muscle activation pattern for MH but a different pattern each, that they used >2 times more frequently than controls. This also applied to VL for the copers. In addition non-copers also exhibited for MH and LH their own distinct pattern compared to copers and controls. This suggests that ACLD subjects use different muscle activation strategies for these muscles than controls. Their preference for only one muscle strategy indicates that they may be less able to adapt to varying movement conditions, possibly increasing their chances of instability.

Table 6 Summary of studies which have analysed gait compensation strategies in ACL sub-groups

STUDY	SUBJECTS	METHOD	FINDINGS
Chmielewski et al. 2001 ACUTE	11ACLD potential copers, compared to uninjured side and controls Analysed on average 3.4 wks post injury	3D mov't analysis ,6 camera system	ACLD potential copers v uninjured controls copers; copers reduced involved leg peak knee flexion (p=0.019), reduced vertical GRF at loading response (p=0.023) but no difference in moments (p>0.05), had significantly reduced involved knee support moment at peak knee flexion (p=0.021) and increased involved ankle support moment (p=0.017). Injured v uninjured side; injured had reduced involved peak knee flexion angle (p=0.04).
Hurd & Snyder-Mackler 2007 ACUTE	21 ACLD non-copers (11.4 wks post injury)	weight acceptance and mid stance (not going to discuss) 6 camera 3D motion analysis system EMG	Non-copers injured limb lower flexion excursion range (p<0.001) therefore lower peak knee flexion angle (weight acceptance p=0.041, mid-stance p=0.028). Lower injured knee moment at peak knee flexion (weight acceptance p=0.003, mid-stance p=0.038). Less contribution from knee to TSM and greater contribution from the hip (weight acceptance p=0.009) and ankle (midstance p=0.008). Injured limb lower limb hamstrings more active (p<0.1). No difference gastrocnemius or tibialis anterior (p>0.1)
Alkjaer et al. 2003 CHRONIC	19 males ACLD: (9 copers, 10 non-copers) Isolated ACL Pre-inj hard pivoting sport 6m+ inj 19 male controls (10 EMG)	5 camera 3D movement analysis system EMG	No group differences in time distance variables; velocity (p=0.195), step length (p=0.222), cadence (p=0.486) copers sig increase peak knee flex in 1st half stance v controls (p=0.039) Peak hip extensionn moment sig larger in copers than non copers (p=0.004) and controls (p=0.0001). At a given peak flexion angle the knee extensor moment was significantly larger in controls than non-copers (p=0.016). No significant difference EMG co-activation (p=0.3818) or EMG amplitude VL,VM, semi-tendinosis or biceps femoris (p>0.05)

Courtney & Rine 2006 CHRONIC	17 ACLD (3 copers, 10 adapters, 4 non-copers), 7 controls. Mean 72 months post injury	Treadmill walk EMG	Slow level walking adapters had earlier onset of gastrocnemius so relative latencies for gastro/tibialis anterior ($p=0.014$) and hamstrings/tibialis anterior ($p=0.06$) Fast inclined walking copers more hamstring and less gastrocnemius amplitude ($p=0.011$). Trend For diff hamstring/gastrocnemius latency due to earlier gastrocnemius onset adapters and hamstrings copers, also resulted in difference in hamstring/tibialis latency in copers ($p=0.07$)
Kvist 2004b CHRONIC	22 ACLD; 11 well functioning and 9 poor functioning	potentiometers	No difference between good and poor functioning groups for knee flexion angle at loading response or initial contact ($p>0.05$). Poor functioning group had (16%) less ATT in injured compared to non-injured leg. Good functioning group had (24%) more ATT in the injured leg compared to non-injured leg. This difference was statistically different between groups ($p=0.003$)
Rudolph et al. 1998 CHRONIC	16 ACLD (8 non-copers, 8 copers)	5 camera motion analysis inverse dynamics	No difference in velocity; non-copers 1.87m/s v copers 2.13m/s ($p=0.126$) Non-copers less knee flexion at heel strike ($p=0.041$), trend loading response ($p=0.079$), no difference ankle angles ($p>0.05$) Lower knee extension moment ($p=0.044$) and power ($p=0.016$) in copers and non-copers injured v non-injured
Rudolph et al. 2001 CHRONIC	21 ACLD (11 copers, 10 non-copers) Non-copers within 8 months injury 10 controls	3D movementt analysis 6 cameras, EMG	No difference velocity ($p>0.05$). Non-copers involved leg reduced peak knee flex angle ($p<0.05$), reduced knee moment at this time ($p<0.05$) but not total support moment – more hip contribution. Non-copers higher activity in soleous ($p=0.020$), earlier onset ($p=0.004$) and longer duration of medial gastrocnemius ($p=0.019$), lateral Hamstrings longer duration ($p=0.005$), onset to peak longer ($p=0.002$). VL activity earlier peak in copers

Based on this review of the literature for gait adaptations in ACLD individuals it appears that movement compensation strategies do exist but the only consistent finding is that ACLD individuals tend to walk with a reduced range of knee flexion. This has been interpreted as a stiffening strategy to stabilise the knee. Overall the altered gait presentation in chronic ACLD individuals is most similar to the non-coper sub group; this is probably due to the high number of individuals that have a poor functional outcome over time. Therefore the non-coper strategy is likely to dominate the findings of studies that have been conducted on generalised groups of ACLD individuals. Comparison and transferability of the results between studies is often difficult because of the many options that are available for analysing the data such as; which variables to evaluate in which phase of the gait cycle and the method to use for sub-classifying ACLD individuals. Based on all the studies that have been conducted to date more investigation is required on hip and ankle compensation strategies, early evidence indicates they are present but they are not yet clearly defined. In addition because adaptation of knee joint angle appears to be a widespread compensation, it is important that clinical movement analysis systems are available to measure this. This adaptation appears to become more clearly organised over time and is more apparent in chronically injured ACLD individuals. This means that studies are needed that model the development of these gait patterns over time, at present it is not known how long it takes for these adaptations to develop. Greater insight into this will identify when rehabilitation is likely to be most effective in facilitating recovery of function. It would appear that rehabilitation should aim to retrain ACLD individuals to walk like uninjured controls because copers move in a more similar manner to healthy subjects. Of particular importance is to rehabilitate individuals to be able to use a wide variety of movement patterns to promote functional knee stability. To achieve this clinical methods that incorporate movement analysis into treatment are required.

Movement compensation strategies for other functional activities that are considered more challenging to the ACLD knee will now be discussed. Far fewer studies have been conducted analysing these activities, particularly hopping because of the risk of individuals experiencing knee instability.

2.2.3 Jogging

Jogging potentially poses a greater challenge to ACLD knees because it generates higher impact and muscular forces that need to be generated and controlled. Being able to jog is commonly set as a goal within ACLD rehabilitation but surprisingly it has evaluated in relatively few studies, these are summarized in Table 7. This means that jogging movement adaptations have been less thoroughly explored than gait compensations and may be one of reasons for more consistency within the literature. There is some evidence that ACLD copers and non-copers jog at a slower velocity with shorter stride lengths than controls (Rudolph et al. 2001), which the same authors had previously found as a trend in non-copers (Rudolph et al. 1998). There is a high consensus for reduced range of knee excursion throughout stance and reduced peak knee flexion, regardless of sub-group (Lewek et al. 2002; Rudolph et al. 2001; Rudolph et al. 1998; Chmielewski et al. 2001; Patel et al. 2003). Based on the kinetic analysis there is an overall agreement in the literature for reduced internal knee extensor moments during stance for all ACLD individuals (Lewek et al. 2002; Patel et al. 2003, Berchuck et al. 1990) and for non-copers when individuals have been sub-grouped (Rudolph et al. 2001). Total support moment was not found to be reduced in the non-copers but there was a greater contribution from the internal hip extension moments (Rudolph et al. 2001); which could indicate a strategy of compensating at the hip joint. Muscle activity studies have found greater activity in lateral hamstrings for acutely injured ACLD subjects (Lewek et al. 2002) and a chronic population of non-copers (Rudolph et al. 2001); which in conjunction with the reduced knee range may indicate a strategy of stiffening the joint and using increased co-contraction, particularly of the hamstrings to stabilize the joint.

In summary, although the literature for jogging in ACLD individuals is limited in number, the quality of the studies is good in terms of data collection methods and control group for comparison. Some investigators have measured external instead of internal moments (Berchuck et al. 1990) or normalized moments to body weight (Lewek et al. 2002) and some studies have normalized time-distance variables to leg length (Rudolph et al. 1998; Rudolph et al 2001), making comparison between studies difficult. There is a limited number of studies that have analysed jogging so they have not been sub-divided to allow identification of acute, chronic or sub-groups movement strategies, instead an overall movement adaptation has been identified of; reduced time-distance variables, reduced knee range through stance, reduced net internal knee extension moments, greater contribution from the hip internal extensor moment to the total support moment and greater lateral hamstring activity to stiffen the joint using increased co-contraction. The combination of jogging movement adaptations detailed has been found consistently between studies, this means that for this activity set criteria based around these variables could be applied to determine success of jogging functional performance in the clinical setting. This would include time-distance variables and joint angles, which could be measured using relatively inexpensive and quick to use equipment. The greater consistency of movement adaptations found for jogging unlike gait could be because jogging is a more challenging activity for knee stability and as an activity becomes more challenging then less variability in movement patterns will be demonstrated (Davids et al. 1999; Jordan et al. 2006; Li et al. 2005; Sterigou et al. 2004).

Table 7 Jogging

AUTHORS	SUBJECTS	METHODS	LIMITATIONS
Berchuck et al. 1990	16 ACLD 10 controls Included ACLD with meniscal tears	2D movement analysis, optoelectronic digitiser	No difference in jogging speec (2.8m/s both groups, $p>0.05$). No difference mid-stance knee flexion (44 degrees $p>0.05$). ACLD injured knee significant reduction in peak moments mid stance peak external flexion moment ($p<0.05$)
Chmielewski et al. 2001	11 ACLD potential copers v uninjured side and controls Analysed ave 3.4 wks post injury	3D mov't analysis ,6 camera system	ACLD knee more extended at initial contact than controls (13.03 v 16.34 degrees, $p=0.033$) and less peak knee flexion (43.03 v 46.11, degrees, $p<0.035$) No difference in moments or total support moments ($p>0.05$) or vertical GRF ($p>0.05$).
Lewek et al. 2002	10 ACLD, 10 controls Analysis 6 mths post inj. All ACLD subjects participated in pivoting sport.	Cross sectional comparative study Early stance analysed EMG and 6 camera movement analysis, inverse dynamics	ACLD jogging velocity 3.33 m/s/leg v uninjured 3.75 m/s/leg ($p=0.485$). ArCLD tend peak knee flexion ($p>0.063$), significantly reduced internal knee extension moments ($p=0.014$). Lateral hamstrings significantly more active in the ACLD involved limb ($p=0.029$).
Patel et al. 2003	44 ACLD 44 controls	Cross-sectional study 1 optoelectic camera, force platform and inverse dynamics	Peak external extension moment was not significantly different between groups ($p>0.573$)
Rudolph et al. 1998	16 ACLD 8 non-copers, 8 copers)	5 camera motion analysis inverse dynamics	Non-copers 3.587 m/s/leg copers 3.823 m/s/leg ($p=0.343$). Non-copers less knee flexion at initial contact ($p=0.044$) and less peak knee flexion stance ($p=0.012$), lower GRF ($p=0.009$).
Rudolph et al. 2001	21 ACLD (11 copers, 10 non-copers) Non-copers within 8 months injury 10 controls	3D movement analysis 6 cameras, EMG	Non-copers (4.137 m/s/l) and copers (4.041 m/s/l) slower jogging velocity than controls (4.745m/s/l, $p=0.03$). Lower peak knee flexion angle ($p=0.05$), lower knee moment ($p=0.021$), no difference total support moment (higher hip contribution $p=0.030$). Higher magnitude of non-coper involved hamstrings ($p=0.017$), lower vastus lateralis and medial gastrocnemius co-contraction ($p=0.041$).

2.2.4 One legged squat

This is an activity that has been infrequently evaluated in ACLD subjects but is frequently used as an early neuromuscular control exercise (Fitzgerald et al. 2000b), is considered to reflect sporting postures (Zeller et al. 2003) and is used as an assessment of strength and muscle control around the knee and pelvis (Zeller et al. 2003; Kvist 2005). The only study to fully evaluate one legged squatting in ACLD subjects was conducted by Kvist (2005), using a computerized goniometer and electromyography. They found that the maximum knee flexion for the injured leg was consistently less than for the uninjured limb. In terms of muscle activity the activity of the hamstrings and gastrocnemius was low throughout the whole flexion phase and higher during the extension phase. The highest magnitude of activity was found for the quadriceps was during the first half of the extension phase and was 72% of the maximal voluntary contraction. There was no difference between injured and uninjured limbs. No studies have defined any adaptations in frontal plane knee motion or sagital plane ankle range during the one legged squat for ACLD subjects, although differences have been found between males and females for healthy subjects (Zeller et al. 2003). Therefore there is still much analysis required of one legged squat but it would be reasonable to expect that ACLD individuals will demonstrate a reduced knee flexion angle during a one legged squat.

2.2.5 Distance hop and run and stop movement compensations

Both distance hop and run and stop are functional activities that are considered a challenge to the ACLD knee; in particular during the deceleration phase. When performing this activity large vertical impact forces are generated and joint reaction forces up to four times body weight (Zhang et al. 2000; Simpson & Pettit 1997; Steele & Brown 1999). To control the knee flexion large extensor moments occur along with high levels of muscle activity to stabilize the lower limb and absorb and transfer forces.

2.2.5.1 Distance Hop

Several investigations have noted shorter hopping distances in the injured leg of ACLD individuals compared to their uninjured leg or control subjects; 155cm v 163cm $p<0.01$ (Gauffin et al. 1990), 96cm v 116cm $p<0.05$ (Scavenius et al. 1999), 115cm v 135cm $p<0.04$ (Gustavasson et al. 2006). Only one investigation has evaluated hopping distance in functional sub-groups and in this study copers were found to hop a similar distance as uninjured controls (Rudolph et al. 2000). This could not be evaluated statistically because there were an insufficient number of non-copers that could hop (only 4 out of the 10 non-copers). A shorter hop distance is proposed to indicate an incomplete functional recovery (Barber et al. 1990) and this information used alongside other clinical data may indicate for a particular individual that it is not advisable to return to higher demand sporting activities at present (Gustavsson et al. 2006). Measuring hop distance on its own does not provide additional information about important factors such as muscle control and joint angles that could be used in rehabilitation to improve performance. However hop distance has been found to be dependent on a number of factors in ACLD subjects, such as; lower proprioception, reduced muscle strength and increased laxity (Roberts et al. 2007). Individually these are all factors of knee function that are related to injury of the ACL but individually these factors do not provide evidence of functional performance (such as hopping) which is essential for informing about overall recovery in rehabilitation. Therefore methods that evaluate functional performance are potentially of greater relevance to direct rehabilitation.

The most extensive biomechanical analysis of distance hop with the most elaborate movement analysis system was conducted by Rudolph et al. (2000). This study aimed to compare copers, controls and non-copers. Unfortunately due to a very small sample size of 4 non-copers, 10 copers and 10 controls the analysis was limited and the conclusions drawn need to be interpreted with caution. A large number of the non-copers were unwilling to hop, this may have been because they were still in the early phase of recovery following injury; all individuals were all less than 3 months from rupture. Considering these individuals were experiencing instability and non-copers have marked gait deviations with gait it is not surprising that individuals were reluctant to perform sports specific functional activities at 3 months. In their study copers didn't demonstrate any difference in knee joint angle but the ankle did provide a higher contribution to the total support moment ($F= 8.595$, $p=0.009$). In contrast non-copers used a smaller range of knee flexion during the deceleration phase, which was accompanied with a lower peak vertical ground reaction force and lower knee extensor moments. The total support moment had a lower knee and higher hip contribution, all of this is based on descriptive analysis of 4 subjects. Transfer of moments away from the knee and generating greater contribution from the hip or ankle is also a strategy used in non-injured controls when performing fatigued hops (Orishimo & Kremenic 2006; Coventry et al. 2006). So although the knee function is crucial for hopping some of the demand is transferred to the hip, potentially making it a less destabilising activity for the ACLD knee. Therefore in ACLD individuals this hip strategy may be an indication of poor neuromuscular control at the knee and incomplete recovery. Two further studies have analysed distance hop in ACLD individuals using 2D rather than 3D movement analysis systems. These studies did not find any statistically significant differences in knee flexion angles, internal knee extensor moments, ground reaction forces or muscle activity (Gauffin et al. 1990, Muneta et al. 1998). Lack of statistical differences may have been due to different methods and analysis procedures associated with the 2D versus the 3D system. In addition, standardised hop distances of 55cm and 90 cm were used by Muneta et al. (1998); as opposed to allowing patients to hop at their own maximal distance, which may not have challenged the ACLD knee sufficiently, making comparison between studies difficult.

In summary ACLD individuals do tend to hop with a shorter distance. Evidence is limited due to the lack of studies but it is suggested that copers do not hop like healthy subjects, the use the same knee joint angle but the ankle contributes more to the total support moment. Further investigation is required but non-copers use a reduced knee range of motion during the landing phase, reduced internal knee extensor moments with increased contribution from the hip. The study by Rudolph et al. (2000) has the research design which most comprehensively evaluates hopping performance, including hip, knee and ankle joint angles and kinetics but the analysis is limited because there is no EMG data to support the moment findings and the small number of non-copers prevented statistical analysis of this group.

2.2.5.2 Run and stop

Only two studies have evaluated run and stop type activities in ACLD subjects. Based on a ball catch and landing task, Steele & Brown (1999) found that the only significant difference between ACLD and controls subjects was a significantly later onset of biceps femoris, so even allowing for an electromechanical delay (Hof 1997), peak activity was more synchronous with initial contact and high compressive and shear joint reaction forces (F=4.425 p=0.042; F=4.094 p=0.05). There was no difference in muscle burst durations, peaks, quadriceps synchronisation or tibial femoral shear force between groups (p>0.05). A lack of differences in EMG may be as a result of movement artefacts and vibration that will occur during these high impact activities and could disrupt the EMG signal. Jog and stop was evaluated by Patel et al. (2003), external moments were evaluated to indirectly evaluate muscle group activity. There was no difference in external extensor moments but there was a significantly reduced external flexion moment, which they concluded represents net reduced quadriceps activity (quadriceps avoidance). Different muscular compensation strategies were found between these studies, one reason for this may be differences in the demands of the task performed, which could have resulted in different neuromuscular responses. In the study by Steele and Brown (1999), subjects were decelerating whilst catching a ball. In contrast the subjects in the study by Patel et al. (2003) were decelerating to stop at a particular point on the force platform. Overall a limited number of studies have been conducted evaluating run and stop.

In summary for these deceleration functional activities there has only been one study that has used adequate methodology to analyse distance hop and identify compensation strategies, but their results are limited due to an insufficient sample size. Copers were found to move in a similar manner as controls but demonstrated some evidence of an ankle control strategy, through increased ankle moment contribution to the total support moment. Non-copers landed using a stiff knee with a hip control strategy. For run and stop muscular compensations may occur in ACLD individuals but like distance hopping further investigation is required to clarify and provide a better guide to rehabilitation. Although distance hop is the most widely recommended functional test for ACLD individuals no successful/unsuccessful compensation strategy has been identified.

2.2.6 Rapid direction change

Activities that involve rapid change of direction through cross over cutting and side step cut are considered the most challenging activity for the ACLD knee due to the combination of rapid deceleration, high knee extensor moments and low knee flexion angle, coupled with increased transverse plane motion (Houck & Yack 2003; Houck & Yack 2001). The number of studies that have evaluated this activity in ACLD individuals is particularly limited; this may partially be due to the low level of coping and therefore the difficulty of recruiting enough individuals that can perform this activity. Walking and a 45 degree cut and side step was evaluated by Houck & Yack (2003), using a 3D movement analysis system and inverse dynamics. ACLD Individuals with an isolated ACL tear at 5 months post injury were separated into seven high and nine low functioning individuals based on scoring over 80% in a global rating score. This classified functional level based on a single question that read, 'If I had to give my knee a grade from 1 to 100, with 100 being the best, I would give my knee a_______'. At 20% stance all ACLD individuals had less knee flexion by 2.6 to 6.6 degrees, lower extensor moments ($p<0.001$) and lower knee abductor moment ($p<0.001$), in addition the high functioning ACLD group also had more internal rotation. At 60% of stance the same strategies persisted in the low functioning group only (p<0.001). Using a similar methodology Houck et al. (2005), compared a 45 degree step cut and cross-over cut between 15 ACLD non-copers and 14 controls. A similar result was found to their previous experiment, non-copers used 1.8 to 5.7 degrees less knee flexion (p<0.043), 22-27%, lower internal knee extensor moments during weight acceptance (p<0.001) and 34-39% higher internal hip extensor moments (p<0.003). Based on the limited amount of evidence available it appears that during early stance of cutting manoeuvres ACLD individuals use a strategy to stabilise their knee by using less knee flexion, stiffening their knee and thereby reducing the range of knee motion that needs to be controlled. They also use reduced internal knee extensor and abduction moments and demonstrate greater contribution by the hip to maintain the lower limb total support moment and therefore performance.

2.2.7 Summary

For all the activities analysed it has to be concluded that many different movement adaptations can be adopted and therefore movement strategies may be specific to individuals. The most consistent movement adaptation reported across all the different functional tasks is altered knee joint angle. Kinetic compensation strategies also occur but they are less consistent for example internal knee extensor moments have been found to be increased or decreased in ACLD individuals. As the activities became more challenging then reduction in the magnitude of time-distance variables was found, for example slower jogging velocity and shorter hop distance. There was also evidence of reduced knee extensor moments with greater contribution by the extensor moments at the hip and ankle to maintain the injured limb total support moment. Based on the sub-group analysis ACLD copers were found to move in a more similar manner to healthy subjects and non-copers demonstrated greatest differences in their movement strategies compared to controls. This would suggest that rehabilitation should be aiming to help individual's perform like copers to maximise outcome. To achieve this clinical movement analysis methods need to be developed so that patients that are not recovering can be identified based on their movement characteristics and rehabilitation tailored accordingly. Based on this review clinical movement analysis could be developed around relatively simple movement variables that do not require expensive equipment, are quick to use and simple to interpret such as the time-distance variables and joint angles, allowing evaluation of individuals and their specific functional limitations.

2.3 Measuring Functional Outcome

To facilitate the treatment goal of maximising function it is essential that measures are available in the clinical setting to evaluate final participation level and functional task performance which are sub-goals of rehabilitation (Fitzgerald et al. 2000b) and therefore anticipated to change with treatment. For ACLD subjects an indirect relationship exists between participation and functional performance outcome; ACLD copers who are able to return to pre-injury activities are able to perform functional tasks such as gait and hopping in a similar manner to healthy subjects, unlike non-copers, who are unable to return to pre-injury levels of participation and have functional outcome unlike control subjects. Functional performance outcomes measured in the clinical setting will directly measure functional outcome and are indirectly related to an individual's ability to participate in activities of daily living and sport. Ideally these measures need to provide outcome data (knowledge of results) such as distance hopped and generate data on how individuals achieve this performance (knowledge of performance), for example joint angles used. This information can then be used to direct rehabilitation techniques. Before discussing methods to measure functional outcome it is first important to identify what functional activities should be measured, what movement variables to evaluate, what criteria to compare ACLD performance against and what the cut off values should be to evaluate recovery. The first two factors were discussed in chapter 2.2 and suitable activities and movement variables were identified. To maximise the use of functional outcomes a range of functional activities are required which progressively challenge the knee as an individual recovers. For ACLD subjects this may initially be non-rotational, low impact activities that are required for ADL such as gait. As an individual's level of participation increases activities need to progress to evaluate increased impact forces and rotational motion, like those encountered during sport. At this stage activities such as jogging, hopping and finally rapid direction change need to be assessed. Functional hop tests have received widespread recognition as clinically applicable activities to evaluate outcome and change in performance over time (Eastlack et al. 1999; Itoh et al. 1998; Hurd et al. 2008a). Numerous studies have demonstrated hop test validity and reliability (Reid et al. 2007; Gustavasson et al. 2006; Brosky et al. 1999). Their clinical limitation is that they provide data on outcome but the do not provide clinicians with information on how they achieved that outcome (performance measures) which could influence rehabilitation techniques. To evaluate the success of performance several methods are available. The first is to compare the injured to the uninjured leg performance by comparing their means or by calculating a limb symmetry index, which is the percentage asymmetry, with zero indicating no asymmetry. The problem with these methods is that reduced performance has also been found in the uninjured leg (Barber et al. 1990; Gauffin et al. 1990) so an individual can be judged to be performing better than they are (Barber et al. 1990). Activity outcome can also be compared to healthy subjects but to evaluate success set criterion and cut off values are needed to compare performance against and evaluate if any difference in outcome is clinically significant i.e. is a patient's score within a functional (normal) or dysfunctional range of scores, (Jacobson and Truax 1991) and therefore meaningful to treatment or function (Kendall et al. 1999). Cut-off values that have been suggested to demonstrate clinically significant differences range from being 2SD (standard deviation) to 0.5SD outside of the control mean (Jacobson et al. 1999; Kendall et al. 1999; Norman et al. 2003). It has been proposed for health related quality of life measures that individuals recovering from an acute condition may expect a complete recovery so they will demonstrate minimal change from a non-dysfunctional population and therefore the cut-off value should be set higher, close to 0.5SD than 2SD which has been proposed for chronic conditions (Norman et al. 2003). Within the psychology literature the proposed standard cut-off has been set as 1SD form the controls mean (Kendall et al. 1999). This cut-off value needs to be explored as it will be differ between populations and pathology. Other important characteristic of a functional outcome measure are that it can measure change in performance over time and distinguish between individuals that are recovering to those that are not.

The most common form of movement analysis that is used clinically is observational analysis. Several investigations have been conducted to evaluate the accuracy and reliability of this from video recordings in gait and sports specific manoeuvres and over a range of pathologies. A recent study by Kawamura et al. (2007) compared visual analysis from videotape and 3D gait analysis in patients with spastic diplegic cerebral palsy. Based on the level of inter-observer agreement for 10 specific points in the gait cycle and agreement between the visual and 3D analysis it was found that only knee flexion angle at heel strike (inter-observer agreement k=0.29 to 0.54; visual v 3D k=0.65 to 0.47) and pelvis obliquity (inter-observer agreement k=0.58; visual v 3D k=0.51) could be evaluated on a visual basis alone. The accuracy of clinical observations compared to 3D movement analysis for the push off phase of gait in stroke patients was evaluated by McGinley et al. (2006). This study found high correlations between observational ratings and ankle peak power (Pearson r=0.98). They concluded that physiotherapists can make accurate real time clinical observations of push off following stroke. These findings are confined to neurological patients and it may be even more difficult to identify these deviations in ACLD subjects whose gait may recover back to the control levels. Just evaluating power at push off is a limited assessment of gait and has limited applicability to ACL subjects. The reliability of structured observational gait analysis from video of orthopaedic patients by clinicians with varying experience was carried out by Brunnekreef et al. (2005). Fair/moderate inter-reliability was found for the structured gait analysis and was slightly higher in clinicians with the most experience (inexperienced ICC=0.42, experienced ICC=0.40, expert ICC=0.54). Intra-rater reliability was moderate/substantial and was highest in the clinicians with most experience (inexperienced ICC=0.57, experienced ICC=0.63, expert ICC=0.72). Although these findings are positive the research was carried out in a controlled environment with no distractions, unlike the clinical setting. Within rehabilitation ACLD individuals will often perform sports specific tasks which the physiotherapists will evaluate visually. Few studies have been conducted to evaluate the accuracy of observational analysis for these types of activities but a recent investigation by

Krosshaug et al. (2007) did evaluate joint angles during running and cutting manoeuvres from video sequences. Overall substantial errors were found for accuracy and precision for all the kinematic variables evaluated and there was no significant improvement in this following training. Mean error for knee flexion was (pre-training = 19 degrees, SD 14; post training =18 degrees, SD 15, p=0.30), hip flexion (pre-training=7 degrees, SD=18; post training=7 degrees, SD=19, p=0.40). Based on this, visual observation does not appear sufficient for this type of activity. Therefore visual analysis is not sufficient for analysing movement strategies for ACLD subjects due to the subtleties of gait adaptations that may be difficult to identify and observational inaccuracies that are associated with the more complex tasks that are performed in rehabilitation with these patients.

Using a single camera for video movement analysis can easily be performed in the clinical setting but as discussed previously observational analysis of video recordings is not accurate (Brunnekreef et al. 2005, Krosshaug et al. 2007). Inexpensive software can be used to allow measurement of time-distance variables and joint angles. The advantage of this method is that it provides information on outcome and how that performance was achieved. The accuracy of measuring kinematic data using a single video camera and its potential as a screening tool was evaluated by McLean et al. (2005). In their investigation frontal plane knee motion was measured during side step, side jump and shuttle run manoeuvres using a 2D and 3D movement analysis system which were then compared. Their results indicated that there was high correlation between the 2D camera and 3D system for inter subject differences and moderate correlations for within subject differences. Root mean square errors were between 1.7 and 1.5 degrees for the side jump and side step activities, which was less than the between trial variability. Greater error and lower correlations were found for the shuttle run task. They concluded that a single camera can reliably measure frontal plane knee motion for side step (r^2=0.58) and side jump (r^2=0.64) activities, having a similar potential as 3D methods for screening valgus knee angles. It may also be useful for evaluating training programs which aimed to modify movement kinematics. This study highlights the potential benefits of a 2D single camera system for clinical usage. The limitations of this study are that it is only applicable to knee motion in the frontal plane and its accuracy has not been investigated in patients with pathology. These results also only apply to this system and anyone using a 2D video camera system should test the reliability of their own set-up. Finally this study indicates that this system may only be appropriate for activities that take place perpendicular to the camera. Single camera systems have a much lower potential than the 3D system when functional activities require subject to turn away from the camera, for example running and direction change.

Numerous laboratory based movement analysis studies on ACLD subjects have demonstrated altered muscle activity during functional activities, which includes both timing and magnitude. This has often been measured using electromyography and although this information is particularly relevant to rehabilitation it is difficult to measure in the clinical setting. Obtaining a good signal and keeping noise levels at a minimum are a challenge in both the laboratory and clinical environment and adequate precautions need to be taken in both environments. With ACLD subjects sports specific activities will be evaluated, large impact forces and soft tissue and electrode movement can contribute to large amounts of noise and distort the signal (Turker 1993). If magnitude of muscle activity is going to be analysed the signal needs to be normalised and the preferred method is to use maximal voluntary contraction. To achieve this in ACLD subjects the recommended method is using a burst superimposition technique, to ensure that the contraction is truly maximal (Chmielewski et al. 2004); this involves equipment that often is not available. Because many of the activities analysed are related to sports specific manoeuvres, analysis programs will not exist and specific computer programs will need to be written, requiring specialist skills. Identification of onset and offset times can be done using a number of methods but with activities such as hopping identifying timing events related to the landing phase can be difficult because the muscles are very active even through the flight phase. Muscle activity has also been inferred from 3D movement analysis and using inverse dynamics to calculate net moments. Again this is limited due to availability of equipment and expertise (Coutts 1999). Moments are also not a direct measure of muscle activity and certain aspects of the muscle performance cannot be measured using moments such as timing or the magnitude of activity of an individual muscle within a group. Use of 3D movement analysis systems to measure kinetic data is not applicable to the clinical setting for many of the practical reasons mentioned previously.

An alternative method of evaluating function is to use specific patient rated knee scores and questionnaires such as the Lysholm score (Lysholm & Gillquist 1982), KOOS (Roos et al. 1998), Cincinnati knee rating system (Barber-Westin et al. 1999) and the IKDC (Irrgang et al. 2001). These contain sections asking the patient to rate their participation level and symptoms, their validity and reliability for use with ACLD individuals has been established (Barber-Westin et al.1999; Roos et al. 1998; Risberg et al. 1999; Marx et al. 2001). In general their main limitation is that they result in a final score which can be used to evaluate outcome but do not provide information that can be used to direct the specific content of rehabilitation, especially if treatment is being directed at a particular functional activity. A further limitation is that the Lysholm and IKDC are not sensitive to change over time and so cannot be used to monitor change over rehabilitation (Risberg et al. 1999). Ceiling effects have also been found for the Lysholm score; whereby patients can have a maximum score but they have not made a full recovery and are still experiencing limitations in their performance (Briggs et al. 2006). There is some evidence that functional scores and functional tests measure different aspects of recovery (Reid et al. 2007; Neeb et al. 1997; Mittlmeier et al. 1999). This indicates that they are best used alongside each other but the patient rated scores are not a substitute for clinical movement analysis which can provide additional information for rehabilitation (Mittlmeier et al. 1999).

In summary, a single camera 2D system which generates data on joint angles and time-distance variables for ACLD subjects during functional tasks that range from gait to complex sport manoeuvres is appropriate for the clinical setting. Criterion to evaluate the success and clinical significance of performance can be taken from uninjured control data, using an appropriate cut-off value, such as 1SD either side of the control mean (Kendall et al. 1999). Other important characteristics of a functional outcome measure are that it can demonstrate differences in performance over time and between different sub-groups. This should provide meaningful data to evaluate outcome and performance and direct treatment content.

2.4 Functional Recovery: Long Term Functional Outcome

The aim of both surgical and conservative management of ACL rupture is to achieve a stable knee that allows individuals to participate in their pre-injury sports and work or to return to an activity level that they are satisfied with. Despite this non-surgical management following ACL rupture is frequently associated with reduction in sporting level compared to before the injury, knee instability and predisposition to meniscal tears (Eastlack et al. 1999; Muaidi et al. 2007b; Meunier et al. 2007).

Numerous studies have evaluated the long term outcome of ACLD individuals and have found varying levels of recovery and the rate of return to pre-injury activity levels is not clearly established. An 82% return to pre-injury level of handball was found by Myklebust et al. (2003) for a group of handball players 6-11 years post injury. Although there was a high rate of return to activity, 60% of these individuals were experiencing instability, making them adapters as opposed to copers. Kostogiannis et al. (2007) found in a general population of ACLD individuals attending a clinic 42% of individuals were copers and returned to their pre-injury sport level. They acknowledge this is a high level of coping and attribute it to the type of conservative management that their patients received; acute arthroscopy, neuromuscular rehabilitation and advice on activity modification. Selection bias could have affected the results because all individuals were pre-screened and only those that wanted conservative management were included. The authors have described this study as a cohort design but due to the lack of a comparative group, it would be more appropriate to describe it as a longitudinal design. Engstrom et al. (1993) and Roos et al. (1995) found the level of coping to be 23% and 20% respectively in two different populations of ACLD individuals. Roos et al. (1995)

evaluated competitive football players whereas the individuals in the study by Engstrom et al. (1993) included individuals who did not participate in high demand sports pre-injury. Because of their lower pre-injury level of function in the latter study the individuals may have been expected to demonstrate a more complete recovery but this was not found. In a recent study, Strehl and Eggli (2007) found the level of coping to be as low as 16%. This is a particularly poor outcome especially because subjects were pre-screened to exclude individuals with high activity demands, concomitant damage to other structures and high level of instability acutely. Therefore their population of ACLD individuals should theoretically have been a group that responded well to conservative management. Based on these studies which represent a broad spectrum of ACLD individuals the level of coping and return to pre-injury level of function in the long term following conservative management is fairly low. Many of these studies have evaluated functional recovery within specific sporting populations and therefore their results are not transferable to a general population of ACLD individuals that may attend an Emergency Unit (Frobell et al. 2007). These studies are useful for understanding the natural history of individuals following ACL rupture but they do not identify factors that clinicians can use to predict who will perform well/poorly with conservative management. Their use in informing rehabilitation is also limited due to the time scale of follow-up, a lot of individuals will have received physiotherapy in the acute and sub-acute phase, whereas these studies have been conducted a number of years following injury. No randomised control studies have been carried comparing the outcome of conservative versus operative management of ACL rupture to evaluate outcome, which would provide the highest level of evidence. This would be difficult to carry out because an ACL reconstruction is a popular treatment choice amongst patients.

There is a need for better designed cohort studies that apply to general populations of individuals with ACL rupture, take baseline group characteristics into consideration and are not subject to selection bias.

2.4.1 Fear of re-injury

Further factors that have been found to be related to a poor functional outcome but are rarely addressed in ACL rehabilitation are related to a patient's health belief status, self-efficacy and fear of re-injury (Nyland et al. 2002; Kvist et al. 2005 and Thomee et al. 2007). In a study evaluating the relationship between function and health belief it has been found that ACLD patients with low self rated functional limitations had a health status that they regarded as being more controlled by internal factors. Patients with greater functional limitations had an external health status belief (Nyland et al. 2002). Fear of re-injury was the reason given in a study by Kvist et al. (2005) as to why 24% of individuals following ACL reconstruction failed to return to sport, despite regaining mechanical stability. In ACLD subjects fear of re-injury or giving way is likely to be even greater. This may prevent them from participating in activities that it is safe for them to perform. This may also explain the large number of adapters that are reported in the literature. These individuals are not actually experiencing giving way but they have decided to reduce their activity levels due to the injury. Therefore fear of re-injury may in part explain the reduced function found in ACLD subjects and may also be a contributory factor to the altered movement strategies adopted by non-copers.

2.4.2 Secondary knee joint damage in the ACLD knee

Factors such as delayed surgical management, conservative treatment and rotational instability following ACL rupture and their relationship to meniscal tears, articular cartilage degeneration and osteoarthritis have been much debated. Rotational instability during episodes of giving way and altered translation patterns in the knee joint of ACLD individuals are thought to increase the shear forces in the knee, resulting in more meniscal tears and articular cartilage damage (von Eisenhart-Rothe et al. 2004; Maffulli et al. 2003). In addition the number of meniscal tears and articular cartilage lesions increase with the time from ACL injury (Murrell et al. 2001; Foster et al. 2005; Maffulli et al. 2003; deRoeck & Lang-Stevenson 2003; Fithian et al. 2005; Meunier et al. 2007) and loss of the meniscus is associated with greater articular cartilage damage and therefore indirect evidence of predisposition to future osteoarthritis (OA) (Murrell et al. 2001; Meunier et al. 2007). Having an ACL reconstruction does not eliminate the risk of OA; high rates have been found in patients that have undergone surgical management (Fithian et al. 2005; Meunier et al. 2007; Kessler et al. 2008). This indicates that rehabilitation to improve functional stability of the knee in delayed reconstruction patients and those undergoing conservative management is essential to reduce the risk of associated meniscal tears, articular cartilage damage and predisposition to OA.

2.4.3 Screening examinations

Different screening examinations have been proposed to differentiate between individuals who will have a good outcome from conservative management from those that will not. Fitzgerald et al. (2000a) classified patients as rehabilitation candidates for conservative management if they achieved a global rating of 60% or higher, had no more than one episode of giving way since injury, obtained a KOS-ADL score of 80% or higher and a timed hop test of 80% or higher. Successful outcome was defined as the ability to return to pre-injury activity without experiencing giving way. They found that 79% returned to pre-injury activity and 21% failed, which is a better outcome than has been reported elsewhere (Strehl & Eggli 2007; Roos et al. 1995; Myklebust et al. 2003). This scheme doesn't guarantee success at predicting outcome for an individual but using it could increase the probability of selecting the correct pathway of care. Similar variables were evaluated by Eastlack et al. (1999), significant differences were found for each variable between copers and non-copers. Four factors explained 66% of the variance between the groups but the contribution of each variable is not reported. The sensitivity of identifying non-copers was 97%. The effectiveness of the screening examination designed by Fitzgerald et al. (2000a) and an accompanying treatment algorithm have been evaluated over a period of 10 years (Hurd et al. 2008a). They found that 63 of 88 potential copers were able to return to pre-injury activity without surgery and concluded that it was a successful tool for classifying individuals who want to be managed conservatively. Although this patient management tool is valuable it would be difficult to implement within the NHS. This is because there is not widespread availability to early reconstruction for all the categories of ACLD patients that this scheme recommends. In addition because early surgical management in the NHS is not readily available the population of ACLD patients that are referred for rehabilitation will be different to that in the study by Hurd et al. (2008a); there will be more patients with concomitant injuries that would have been excluded with the treatment algorithm, which may affect outcome. The final limitation is that these investigations have only included athletes that participate in activities that involve high levels of jumping and cutting, such as basketball, football and racket sports. Therefore their results cannot be generalised to the ACLD population of the NHS, which also includes individuals that participate in low demand sports such as running and fitness training or individuals that are sedentary.

A treatment algorithm was also developed by Fithian et al. (2005). This classified a patient into high, moderate and low risk requirement for surgical reconstruction and within each group an individual was further sub-divided into early reconstruction, late reconstruction or conservative management. This classification was based on joint laxity and pre-injury activity level. It is difficult to interpret the success of conservative management and the treatment algorithm due to the way the data is presented; there is a surgical bias to how the results have been interpreted. Although not discussed in their interpretation, it appears that the algorithm was fairly successful at determining non-surgical treatment because within the low risk conservative group instability was only 11% and the overall return to activity was 52% for all the non-reconstructed patients. This was a higher rate than that reported for the surgical groups and a higher rate of return to activity than many of the long term follow-up studies discussed previously. These results are affected by selection bias because sub-grouping into surgical or conservative treatment was down to surgeon discretion. In direct contrast to the work of Fithian et al. (2005), pre-injury activity level and passive anterior laxity were not found to contribute to early knee function after ACL rupture (Hurd et al. 2008b). These same authors concluded that using the screening examination developed by Fitzgerald et al. (2000a) that combines hop tests, KOS-ADL, giving way and global rating makes a greater contribution to differentiating patients into appropriate management type than traditional outcome measures of passive stability and activity level. The screening tool by Fitzgerald et al. (2000a) includes functional measures that relate to performance, whereas passive stability relates to function at the structure level only (relating to the ICF). Therefore there is a need to develop functional methods that can classify potential rehabilitation patients within the NHS and provide data that can direct treatment towards achieving rehabilitation goals.

In addition to the limitations of implementing each of the individual screening tools for patient management, within the NHS there is a more generalised problem of surgical waiting lists. Although an individual may be identified as a coper or non-coper early they may still have to wait for surgical reconstruction. This places greater emphasis on physiotherapy to help patients regain knee stability and improve functioning. Therefore screening tools not only need to be able to sub-group individuals and provide information on their recovery, they also need to generate information to direct rehabilitation. None of the current screening tools provide feedback that can be applied to rehabilitation. Tools need to be available to the clinician during the recovery phase (first 6 months following injury) that identify which sub-group a patient belongs to and which aspect of their performance is lacking so treatment can be directed at this. Monitoring the recovery of functional tasks fulfils this role because these activities are often set as rehabilitation exercises and as treatment milestones, making them directly relevant to clinical practice. No studies to date have monitored the recovery of functional activities over time and the length of time for their recovery. These are issues that are often of prime concern to the patient when undertaking a rehabilitation program.

2.5 Rehabilitation

Rehabilitation of acutely injured ACLD subjects aims to return individuals to the highest level of activity that they are safely able to perform without experiencing symptoms of instability, pain or swelling. Published guidelines that focus on the content of ACLD rehabilitation use a combination of a deficit and functional rehabilitation approach. In a deficit approach treatment addresses factors such as reduced proprioception (Reider et al. 2003), altered muscle responses (Roberts et al. 1999b; Ferber et al. 2002), altered hamstring reflex timing (Beard et al. 1994; Melnyek & Gollhofer 2007), muscle strength deficits (Tsepsis et al. 2006), movement adaptations (Rudolph et al. 1998, Rudolph et al. 2000) and fear (Kvist et al. 2005) to achieve functional goals (Fitzgerald et al. 2000b) and maximise functioning (Sugden 2007). In a functional approach the emphasis is on teaching functional skills to improve functioning without trying to resolve any structure or process deficit (Sugden 2007), this is emphasised in late stage ACLD rehabilitation when there is a focus on relearning manoeuvres for return to sport (Kvist 2005). In the early stage after injury treatment often centres on resolution of acute symptoms and normalisation of gait. Activities to regain full range of motion, strengthen, maintain cardio-vascular endurance, proprioception and improve neuromuscular control all begin as soon as the patient is able to tolerate, which is a deficit approach to rehabilitation. Functional activities are incorporated into programs and with ACLD individuals and as mentioned previously there is particular emphasis on sports specific manoeuvres (Fitzgerald et al. 2000b; Kvist 2004a). Rehabilitation is progressed according to symptoms such as pain, swelling, ROM, giving way, strength and biomechanical principles (Manal & Snyder-Mackler 1996; Fitzgerald et al. 2000b; Kvist 2004a). The progression of functional goals is based around increasing impact forces and gradual introduction of medial/lateral and rotational forces that challenge the stability of the ACLD knee. This progression includes return to gait, jogging, hopping, side stepping and rapid directional change during sporting manoeuvres (Fitzgerald et al. 2000b). Other rehabilitation modalities utilised include; goal setting, providing feedback, manipulating practice conditions, providing advice and monitoring recovery. Overall rehabilitation is a complex intervention, with so many components it is important to identify which are responsible for influencing treatment outcome so that their benefit can be maximised. A limited number of studies have evaluated the effectiveness of specific rehabilitation programs with ACLD individuals. Those which have evaluated the effectiveness of a specific rehabilitation program can be sub-divided into three categories, based on the content of their rehabilitation:

1. Comparison of a perturbation training program compared to standard rehabilitation (Fitzgerald et al. 2000c; Chmielewski et al. 2005).
2. Effectiveness of supervised rehabilitation versus unsupervised (Zatterstrom et al. 2000; Ageberg et al. 2001).
3. Closed versus open chain exercise rehabilitation program (Tagesson et al. 2008).

The effectiveness of each group of studies will be discussed in turn and their overall contribution to the treatment of ACLD individuals presented.

2.5.1 Perturbation rehabilitation studies

The content of the perturbation rehabilitation programs conducted by Fitzgerald et al. (2000c) and Chmielewski et al. (2005) have focused almost entirely on balance retraining using a motorised platform, tilt board and roller board. Progressions focused on changing the direction of destabilising forces and reducing the base of support. The standard rehabilitation consisted of strengthening using resistance machines, cardio-vascular training and agility and sport specific exercises. Each subject had to attend a total of 10 rehabilitation sessions, 2-3 times per week and took 5 weeks to complete. Both of these studies only included individuals that participated in level sports 1 and 2 sports (Daniel et al. 1994) and had no other ligament injuries or repairable meniscal tears. The findings of each of these studies will now be discussed in turn.

Fitzgerald et al. (2000c) evaluated the success of a perturbation rehabilitation program using a randomised control trial. Twenty eight subjects were recruited onto the investigation and twenty six completed the intervention, 14 in the standard and 12 in the perturbation rehabilitation, so the drop out rate was low. They found a 50% failure rate of standard rehabilitation due to episodes of giving way and rehabilitation was significantly more unsuccessful than the perturbation training (chi square=5.27, $p<0.05$). Overall ADL score, global rating scale and cross-over hop all improved over time for both groups by the end of treatment and there was no difference between groups ($p>0.05$) but the standard rehabilitation group were unable to maintain this improvement and demonstrated a decline in outcomes by 6 months post rehabilitation (ADL and global rating score $p<0.03$, single limb crossover hop $p<0.05$). They concluded that the perturbation group was better prepared for negotiating the destabilising forces encountered on return to full sporting activities.

This study is valuable because it is one of the few investigations that have attempted to evaluate the effectiveness of a specific rehabilitation program and to progress the content of rehabilitation by evaluating a specific type of exercise. Its major limitation is that the treatment groups may not have been matched for the time since injury of its subjects or the amount of rehabilitation, training and return to sports preparation that individuals did themselves before recruitment onto this investigation. Although all subjects had to be within 6 months from injury this is a phase of rapid recovery for ACLD individuals and so large variations in ability and amount of training completed independently would be expected. For example subjects may have been able to fulfil the screening examination as early as 4 weeks post injury, conversely those recruited at 4-6 months post injury may have been in the final stages of preparing to return to sport or have returned. It would potentially make a big difference to treatment outcome if all the individuals who were at a greater distance from time of injury were in the perturbation group and more acutely injured in standard rehabilitation. No statistical analysis was undertaken to evaluate that groups were matched for demographic variables and the descriptive statistics indicate large differences in group mean weights (mean 78.9kg SD 13.4 and mean 83.6 SD 16.1), which may have altered performance. Other factors could have contributed to their result, such as blinding. There is no mention as to whether the patient, the person supervising the rehabilitation and the data collector were aware of the content of different treatments or if the latter two people performed both jobs. Finally there was no attempt to evaluate why the standard rehabilitation group demonstrated deterioration at long term follow-up. Individuals choosing to reduce their functioning for factors unrelated to their knee injury could have resulted in altered function at this time. Differences in group muscle strength were not evaluated and may also explain differences in function at the final follow-up. This investigation has used a deficit approach to rehabilitation to improve sensori-motor control and co-ordinated movement patterns but based on the results of this one study there is insufficient evidence to support this.

Perturbation training was re-evaluated by Chmielewski et al. (2005), using a clinical trial research design. In this investigation 17 potential ACLD copers were compared before and after the training program to an unknown number of healthy subjects, who also underwent perturbation training. The content of the exercise program was very similar to that used by Fitzgerald et al. (2000c) with only minor changes to the exercises. The outcome measures evaluated focused on the movement strategies adopted during the preparatory interval and weight acceptance phases of gait by both the patient and healthy subjects. Their results demonstrated that prior to training ACLD copers used lower peak knee flexion angles (19.81 v 24.28 degrees p=0.016) and stiffened their knees with higher co-contraction for locked (VL-LH 41.69 v 30.40 p=0.034, lateral (VL-MG 16.35 v 11.13 p=0.018; VL-LH 51.95 v 34.70 p=0.008) and anterior (VL-MG 15.70 v 11.27 p=0.044) platform positions. After perturbation training the potential copers knee flexion angles increased (mean 20.78 degrees p=0.046) and muscle co-contraction decreased for the lateral condition (preparatory phase VL-LH 31.25 degrees p=0.73; weight acceptance VL-VH 42.55 p=0.092) and anterior platform condition (preparatory phase VL-LH 20.90 degrees p=0.093; weight acceptance 41.64 p=0.052) so that there were no differences between them and the healthy subjects for these variables (p>0.05 for the kinematics and p>0.1 for co-contraction). One of the limitations of this study is that the alpha level for the co-contractions was set very low without any justification so many of these findings would not be significant if an alpha level of p<0.05 had been used. A further limitation is that no attempt was made to compare descriptively or statistically if these two subject groups were matched for demographic variables. Although the perturbation training appeared to improve the ACLD potential coper response to destabilising forces, it is not clear how this transferred into success at returning to sport or other activities. These findings only apply to this rehabilitation exercise but it would have been even more valuable to evaluate if these improvements in muscle co-contraction also transferred to performance of sports specific manoeuvres or functioning, which is of greatest importance to the patient. This study has taken on a deficit approach but practicing a progression of functional activities under different conditions that are problematic to ACLD individuals may have had the same favourable muscular response without requiring specialist equipment. A 3D movement analysis system was used as an outcome measure to evaluate compensation strategies and for the reasons mentioned previously it would be difficult to transfer this system to the clinical setting but the potential value of measuring kinematics had been demonstrated and could be measured using a 2D system.

The findings of both of these studies have limited ability to be generalised to patients treated within the NHS. This is because their results are only applicable to level 1 and 2 athletes, whereas the patient mix in the NHS is predominantly recreational athletes and individuals who regularly participate in exercise but not cutting and pivoting sport. The findings are also limited to potential copers who form the smallest sub-group of patients following ACL rupture and do not reflect a more generalised population of ACLD patients encountered in the UK, making their findings difficult to apply. In addition these authors did not include individuals with any additional ligament damage or repairable meniscal tears, which further restrict the applicability of the results. What these studies do contribute is to demonstrate that biomechanical variables can change with rehabilitation so their application could be more widespread during treatment to directly evaluate recovery of functional activities and performance.

2.5.2 Supervised versus unsupervised rehabilitation

A comparison of supervised versus unsupervised rehabilitation was carried out and reported by Zatterstrom et al. (2000) and Ageberg et al. (2001). The same cohort of patients were used in both of these studies but symptoms and functional outcome were reported at 3 and 6 months by Zatterstrom et al. (2000), whereas Ageberg et al. (2001) reported on differences in postural control at 3 years following injury. One hundred consecutive patients from a population with varying sporting levels and a mixture of ACL pathology including additional meniscal and ligament sprains were randomised into the study. Unsupervised treatment involved initial instruction on range of motion exercises and muscle strengthening. Supervised rehabilitation comprised information sessions, active movements, and closed chain weight bearing exercise without compensatory movements, postural control in ADL and sport activities. Group exercise sessions were held twice a week for 50-60 minutes for 5-8 months. Sessions became less frequent after 4-6 months and more sports specific exercises were added. Training concluded when muscle postural reaction were clinically evaluated as coming without delay and equivalent to the non-injured side. By 3 months nearly 50 % of the unsupervised group had been transferred to the supervised training. This supervised group also demonstrated better isometric flexion (p=0.006) strength at 3 months and extension strength at 12 months (p=0.03) and isokinetic work at 3 months (extension p=0.002, flexion p=0.006) and 12 months (extension p=0.06, flexion p=0.01). Hop distance demonstrated significantly more improvement in the group of supervised patients with most knee damage than the unsupervised group with most knee damage (p=0.04). There were no treatment group differences at 12 months for Tegner scale (p>0.05) or Lysholm score (p>0.05) (Zatterstrom et al. 2000). At 3 years post injury postural control for all ACLD patients regardless of treatment group was impaired for single leg stance compared to controls. Hop distance recovered to control level in the supervised group but remained significantly shorter in the non-supervised training group (p=0.003) (Ageberg et al. 2001).

Limitations of this investigation are that neither of these reports has analysed the return to sport rate and to what extent patients had to modify sporting activity due to instability. Failure to report this is somewhat surprising because the patient goal is often to return to as high a level of function as possible. No account has been made of what happened to the patients that were lost to follow-up between 12 months and 3 years, was it due to being unable to trace patients or was it due to these individuals undergoing reconstructive surgery? The large number of patients that were transferred between the groups could have introduced bias into the investigation and affected the outcomes reported. Patients would no longer have been blinded and may just have performed better because they were aware of transferring to a more informed, intensive and constructive rehabilitation program. The statistical analysis performed was not always appropriate to fulfil the study aims. For example at 3 and 12 months paired t-test were used to evaluate differences in hopping distance over time within a group and no between group analyses were performed. It would have been informative to have carried out an analysis between groups over time, therefore it would have been more appropriate to use a mixed design repeated measures ANOVA. The non-supervised rehabilitation does not appear to be an effective option in the early stage following injury because so many patients had to be transferred into the supervised treatment. The strengths of this investigation are that it was carried out on a population of ACLD patients that reflects the population treated within the NHS of varied activity level and pathology.

2.5.3 Closed versus open chain exercise

The effectiveness of a rehabilitation program combining neuromuscular control exercises with either closed or open chain quadriceps strengthening exercises in ACLD individuals was evaluated by Tagesson et al. (2008) in a randomised control trial. Twenty one patients were randomly allocated to the closed chain (squat) and twenty two to the open chain (seated knee extension) strengthening rehabilitation. Physiotherapist's monitored rehabilitation weekly but patients in both groups were independently asked to perform 3 sessions of rehabilitation a week and for each exercise, 3 sets of 10 repetitions. The method for increasing the load for the strengthening exercises was the same between groups; the progression went from 50 to 60% to 70-80% of one repetition maximum of the uninjured leg. As patients were able walking, cycling and running were added and in the latter stages sports specific activities, this was the same between groups. Compliance was monitored with exercise diaries. Both groups were closely matched for demographic variables, injury, sports and time from injury. At the end of 4 months of rehabilitation there were no group differences for swelling and passive range of motion ($p>0.05$). The open chain quadriceps rehabilitation group had significantly greater isokinetic quadriceps strength than the closed chain group ($p=0.009$) but there was no difference between groups for the 1 repetition squat test ($p=0.525$), single leg vertical jump ($p=0.444$) or for distance ($p=0.362$), Lysholm score ($p=0.826$), maximal tibia translation during Lachman's (p=0.882), gait (0.750) or single legged squat (p=0.766). They concluded that open chain quadriceps exercise led to significantly greater quadriceps strength compared with closed kinetic chain quadriceps exercise, so may be needed in rehabilitation to regain good muscle torque. Overall this was a well designed trial that attempted to evaluate a rehabilitation program that reflected clinical practice by combining neuromuscular control, strengthening and functional activities. The effectiveness of one component of this rehabilitation, (the strengthening component) was evaluated and the most effective method of improving muscle torque was demonstrated but this program did not result in on overall improvement in performance of functioning. Other strengths of this study were the low drop out rate (3 closed chain participants and 4 open chain participants) and similar compliance rates with exercise. Unlike the perturbation program proposed by Fitzgerald et al. (2000c) it is a rehabilitation program that is easy to apply within the NHS; it doesn't require specific equipment that is not readily available and doesn't require a high number of supervised treatment sessions that may also be difficult to deliver within the NHS time pressures. One limitation of this investigation is that no protected ROM was used because there is a risk of increased ATT in the range from 30 degrees of flexion to full extension due to high unopposed quadriceps contractions (Li et al. 1999). But in terms of regaining function it may be problematic to avoid strengthening in that range because many functional activities such as initial contact of walking and jogging occur at low flexion angles (Perry 1992; Chmielewski et al 2001).

All of the studies presented above which have evaluated ACLD rehabilitation have had a deficit approach to either or both their treatment components and outcome measures applied. Based on these studies there is still insufficient evidence assessing which treatment components maximise functioning, which is the ultimate treatment goal. There is some evidence that rehabilitation can result in improved movement strategies and function but this requires further exploration and possibly development of a more functional approach to rehabilitation. This means that rehabilitation might benefit from simple movement analysis methods being available within the clinical setting to evaluate individual performance during functional activities. This would provide the physiotherapist and patient with feedback about recovery, success of rehabilitation and indicate what rehabilitation is required.

2.6 Feedback

During movement an individual draws on information about the success or errors of a performance that can be used to alter their movement strategies (Magill 2007). This feedback can come from internal and external sources. Intrinsic feedback refers to a person's own sensory-perceptual information that is generated as a result of movement being performed. Several sources are available to an individual such as vision, proprioception and sound (van Vliet & Wulf, 2006). External feedback is provided from an external source and is additional to internal feedback. This can also be administered in several formats such as visual, verbal, auditory and tactile feedback (McNair et al. 2000; Lam & Dietz 2004; Yoo & Chung 2006; Goebl & Palmer 2008; Haguenauer et al. 2005). External feedback can be used as a rehabilitation tool to supplement the internal feedback and facilitate recovery during rehabilitation and is acknowledged as a valuable tool for enhancing performance in; sport, learning new skills in uninjured individuals and to facilitate motor learning in neurological rehabilitation (Tzetzis & Votsis 2006; Cirstea et al. 2006; Hurley & Lee 2006; Liebermann et al. 2002).

Despite the diverse background to the literature concerning feedback little work has been carried out on its value of enhancing rehabilitation in patients with ACL rupture. It is potentially a valuable treatment tool with ACLD individuals because these subjects will experience an alteration to the intrinsic feedback due to the loss of the sensory role of this ligament (Davids et al. 1999); therefore supplementary external feedback may assist motor learning and recovery. In addition the goal of rehabilitation for these individuals is to maximise function and participation level. Feedback could be used to help them achieve this by evaluating movement adaptations that were discussed in chapter 2.2 and providing information to the treating clinician and patient on recovery and guide progression of rehabilitation and treatment content. Only one study to date has used external feedback to attempt to alter muscle strategies during gait in ACLD individuals to improve knee stability, this was done by providing feedback to the patient (Sinkjaer & Arendt-Nielsen 1991). Two individuals with poor knee stability according to the Lysholm score were trained using visual and verbal feedback to alter their muscle strategies for gastrocnemius. They were then sent away with a 12 week rehabilitation program. When they were re-measured they did demonstrate altered strategies of their gastrocnemius muscle and had improved knee stability according to the Lysholm score (pre-training scores 67 and 70, post training scores 85 and 90). Although the authors attribute this to the altered muscle timing this improvement could have been due to other positive outcomes of performing a rehabilitation program such as strengthening. Based on this study the role of feedback in achieving this outcome is unknown and needs further evaluation. Overall this is a poor quality design to evaluate the effectiveness of treatment with the low subject numbers, lack of control group and analysis. For the best application of external feedback some of the following need to be considered: what information is to be conveyed; mode of feedback and scheduling. Each of these will now be discussed in turn.

2.6.1 What information to include in external feedback

External feedback can be in two forms; knowledge of result and/or knowledge of performance. Knowledge of result (KoR) is external feedback about performance outcome or goal. For example, single leg hop for distance is a functional activity commonly evaluated in ACLD individuals to monitor progress and outcome. Informing an individual about the distance hopped in centimetres would be KoR. Knowledge of performance (KoP) is external feedback about the movement characteristics that led to the outcome (van Vliet & Wulf 2006). For example, for hopping this may be information about the joint angles, moments and muscle activity. Generally an individual will always have some intrinsic KoR available to them and circumstances when none is available are rare (Russell & Newell 2007). To supplement this, external feedback of both KoR and KoP have been found to be beneficial in skill acquisition within healthy subjects using KoR of an upper limb barrier knock down tasks (Badets & Blandin 2004); KoR of an upper limb task depressing switches (Badets & Blandin 2005), KoP of a throwing task (Janelle et al. 1997) and KoP on shooting accuracy (Mononen et al. 2003). Ideally a combination of KoR and KoP will be included in the feedback.

2.6.2 Feedback schedule

Feedback schedule refers to how often the feedback should be given, should it be after every trial or after blocks of trails or training sessions? Several studies have addressed this issue. In two separate experiments evaluating different types of activities individuals who received KoR on less than 50% and 33% of trials had a more stable performance on an upper limb task (Badets et al. 2006) and better performance on a barrier knock down test (Badets & Blandin 2004). In both of these experiments control subjects received feedback on 100% of trials. Similar findings have also been noted when individuals only received feedback on trials with errors. Reduced variability and greater accuracy was found during an upper limb timing task (Badets & Blandin 2005) and better performance of a difficult Badminton task (Tzetzis & Votsis 2006).

Other investigators have analysed the effect of having a less rigid schedule of when the performer receives feedback letting them decide when they want the feedback (self control feedback). Chiviacowsky & Wulf (2005) demonstrated that individuals preformed better at an upper limb delayed transfer test ($F_{1,41}$=4.98 p=0.05). Janelle et al. (1997) demonstrated that the self control group performed better throwing the ball with the non dominant hand (throwing form $F_{3,40}$=49.80 p<0.001; error measures on a retention test $F_{3,40}$=6.99 p<0.001). The strength of all of these investigations is that they evaluated the success on feedback on delayed retention and transfer tests.

Recently the effectiveness of ultrasound imaging feedback schedule on learning and performance of a lumber multifidus muscle activity was evaluated in a randomised control trial (Herbert et al. 2008). One group received KoR after every trial and in the other group summary feedback after a block of trials. Both groups improved over the training sessions and maintained improvement at a one week retention test. At the long term retention test the group that had summary feedback had the best performance (p=0.4). This was a well designed and executed study, its main limitations are that there is no transfer test and there was a small sample size of 15 subjects per group which dropped to 11 and 12 subjects per group at final follow-up.

The overall conclusion for feedback schedule on healthy subjects is that feedback after every trial is not necessary and allowing the performer to decide when they receive feedback is the most effective. This conclusion is based on experiments carried out on a range of unrelated tasks on healthy subjects, further investigation is required to evaluate if this also applies on patients with musculo-skeletal pathology.

2.6.3 Mode of feedback

Within the literature numerous studies have evaluated the effectiveness of providing feedback to facilitate motor learning for both healthy subjects, patients with neurological pathology and to a lesser extent individuals with musculo-skeletal injuries, using verbal, auditory and visual feedback (Cirstea et al. 2006; Yoo & Chung 2006; Tzetzis & Votsis 2006; Kernodle et al. 2001, Henry & Teyhen 2007). Due to the volume of studies that have evaluated feedback the ones included in this literature review are those that have evaluated performance of lower limb tasks in injured and uninjured individuals and sporting manoeuvres in uninjured individuals, as this reflects activities that are most relevant to ACL rehabilitation and the effects of this pathology. Within these studies success of the feedback method is usually measured by evaluating outcome performance variables such as kinematics and performance errors at the end of learning, on delayed testing (retention test) and on transfer testing of a similar but different activity. Success in delayed and transfer tests is particularly important for rehabilitation because it provides some evidence of training benefits between sessions and transfer of skill between a clinical and non-clinical environment. These studies will now be discussed in turn.

For an overhand throwing activity in the non-dominant arm of a group of novices Kernodle et al. (2001) demonstrated that verbal instruction on error correction was as effective as verbal instruction on error correction with video for throwing outcome and skill retention. Both groups improved over time (Throwing outcome group x trial $F_{7,175}=9.74$, $p<0.05$) but there was no difference between groups, they concluded that using video was of no additional benefit to verbal instruction in early learning but may be more effective later on. Tzetzis & Votsis (2006) demonstrated the effectiveness of verbal instructions in 3 different formats for improving performance of a difficult badminton skill ($F_{4,90}$=25.89, p=0.001). The verbal instructions were found to be even more effective when coupled with information on performance errors and how to correct them ($F_{2,45}$=23.71, p=0.001). Lam & Dietz (2004) evaluated the effectiveness of using acoustic feedback to train individuals to walk over obstacle with minimum foot clearance and found improvement with practice and training ($p<0.05$). This was effectively transferred to other walking conditions, no difference in foot clearance was found between conditions ($p>0.05$). The major limitation of these studies is that they did not have a control group receiving no feedback to evaluate if practice alone was enough to improve performance in early learning. In a study by McNair et al. (2000) the benefits of auditory of landing noise was more effective than imagery or controls receiving no external feedback ($p<0.05$) in reducing impact forces when jump landing from a height. The weakness of this investigation is that patients had to generate their own feedback and no retention or transfer tests were evaluated. Finally, for soccer kicking task, Janelle et al. (2003) found that verbal information in addition to visual cues resulted in less error and more form on retention and transfer trials compared to five other learning conditions; discovery learning (control group), verbal instruction, video model with verbal cues, video model with visual cues, video model with visual and verbal cues and video model only (Absolute error $F_{5,54}$=13.8, $p<0.001$; variable error $F_{5,54}$=16.8, $p<0.001$). This investigation has been designed better than the other studies discussed so far. The strengths of this investigation are that individuals were randomly assigned a group, a control group was included, statistical analysis confirmed matching at baseline and they evaluated a number of different forms of feedback with delayed assessment but a transfer test was not included. Not all investigations have found verbal instruction and feedback to be of benefit. Haguenauer et al. (2005) found no additional benefit of providing novices with verbal instructions in addition to demonstration when learning a complex ice skating task, both groups improved with practice regardless of feedback (jump height no group effect or interaction, but improvement with repetition ($F_{1,15}=9.32$, $p<0.01$). Like the study by Kernodle et al. (2001), their subjects were also novices and were in the early stages of learning. The difference between these investigations is that individuals learning the ice skating task were given generalised rather than individual specific instructions. It may therefore have been the type of instruction that was of no benefit, rather than feedback instruction itself being of no benefit. In addition the subjects in the ice skating task were evaluated immediately after one trial. This means they were in the very early stages of learning and may have been receiving too much information. Finally the analysis used did not evaluate skill retention which may have demonstrated benefits. The strength of this investigation is that it included a control group who received no instruction feedback.

The value of verbal feedback has also been evaluated in patients with neurological conditions. Using a double blind randomised controlled trial, Cirstea et al. (2006) found that verbal feedback containing both KoP and KoR resulted in improved performance of a reaching task over time ($F_{2,66}=14.63$, $p<0.0001$) but subjects that received the KoP only feedback performed even better (faster $F_{2,66}=2.77$, $p<0.001$, less segmented $F_{2,66}=6.06$, $p<0.01$ and more consistent $F_{2,66}=4.09$, $p<0.05$). Severity of cognitive impairment was found to be an important factor in improvement so although this is not applicable to ACLD patients other factors may be important such as amount of secondary tissue damage and pre-injury participation level. Yoo

& Chung (2006) evaluated the effect of visual feedback plus mental practice on symmetrical weight bearing training in people with hemiparesis. They found that visual feedback on its own resulted in improvement of symmetrical weight bearing but this improved even further with mental practice ($p<0.05$). The improvement was evaluated after treatment and at a one hour follow-up, which is a short retention period. The study design was a single subject experimental design but the positive findings warrant developing this study further, into a research design with a higher level of evidence, such as a randomised clinical trial. Another single subject design was carried out by McGraw-Hunter et al. (2006). Brain injured individuals watched a video of themselves as they cooked. As they practiced the tasks they were then given prompts and feedback. Evaluations of practice were made before, after, at 2 and 4 weeks follow-up and on a transfer test. Three of the four individuals achieved the improvement criterion and were able to transfer this to a novel task. The research design used means that this study only provides a low level of evidence but the strength of this experiment is that it is directly evaluating and directing treatment at participation outcomes which relate to the patients overall treatment goal.

In subjects with musculo-skeletal pathology external feedback has been used to alter muscle activation strategies in the presence of low back pain (Henry & Teyhen 2007; Tsao & Hodges 2007), patello-femoral joint pain (Ng & Li 2008; Dursun et al. 2001; Yip & Ng 2006). Feedback methods used included rehabilitative ultrasound imaging and EMG. Tsoa & Hodges (2007) used rehabilitation ultrasound imaging to train nine individuals with low back pain to perform isolated voluntary transversus abdominus (TrA) contractions. This was incorporated into a rehabilitation program that patients had to perform themselves over a four week period. After 4 weeks of training the onset of TrA was earlier and its co-efficient of variation lower during averaged gait and findings were still present at 6 months follow-up ($p<0.05$). This investigation also demonstrated associated self reported reduction in pain and improvement in function. This study is not a randomised controlled trial and does not advocate this rehabilitation program as being sufficient to treat patients with low back pain but suggests that it does address a common impairment with low back pain of delayed activity of TrA. This investigation did not have any control group so the improvement may be due to other factors in addition to the feedback. A randomised controlled trial to evaluate the effectiveness of real time EMG feedback with exercise and exercise alone (control group) on the VL/VM activity ratio was carried out on subjects with patello-femoral pain (Qi & Ng 2007). The training program of both groups was the same. These investigators found that the group who had EMG biofeedback had significantly greater EMG VM/VL ratio ($p=0.0017$) at the end of 8 weeks training, compared to no significant difference in the control group ($p=0.355$). Although the real-time EMG training feedback appeared effective, its clinical application is limited because there was no attempt to relate these muscular changes to improved participation or pain reduction. In a randomised control trial, Dursun et al. (2001) found that VM and VL muscle performance improved in a group of patients who underwent an exercise training program with EMG biofeedback compared to a control group who just received exercise, but there was no difference between groups for self reported pain or function. The strength of this study is the research design and no subject drop-outs occurred. The study limitations are that there is no mention of blinding of the patient, researcher or clinician, there is no detail of the randomisation process and there was also no evaluation of functional performance, retention or transfer to related functional tasks. The effectiveness of an EMG visual feedback exercise program compared to a standard exercise program was also evaluated by Yip & Ng (2006), in a double blinded randomised clinical control trial that they classified as a pilot trial, the reason for the latter is unknown. Both groups improved for isokinetic peak torque (p=0.005), work output (p=0.0037) and patella alignment (p=0.001-0.014); there was no significant reduction in pain and no difference between groups (p>0.05). This study is limited because there was no assessment if patients complied with the exercise program, no delayed retention test, transfer test or evaluation of changes in participation level. The strength of this investigation is its study design did permit the effectiveness of feedback as the active treatment component to be evaluated.

In summary, for uninjured subject's external feedback as a tool to improve performance seems to be of value although a limited number of studies have been designed to adequately compare FB to no-FB. Further clarification is also required as to which is the most effective mode to apply feedback. In patient groups preliminary findings suggest that external feedback has potential to improve performance but for neurological patients there have not been a sufficient number of investigations of sufficient quality. In patients with patello-femoral pain several randomised controlled trials have been conducted to evaluate feedback but limitation in their design in terms of evaluating functioning, retention and transfer tests mean that further research is required. No sufficient studies evaluating feedback have been carried out on ACLD individuals.

2.7 Literature Review Summary

Based on this review of the literature numerous movement compensation strategies have been identified in ACL individuals during functional activities which appear to be most pronounced in individuals with the poorest functional outcome. What this literature has not explored is the recovery of movement variables over time, to inform clinical practice about time required and which variables and activities could guide rehabilitation based on their recovery. There is also a need to establish a criterion on which to evaluate recovery and method of interpreting the clinical significance of any findings. Two dimensional video methods are relatively simple, inexpensive and can be used to evaluate adaptations for time-distance variables and joint angles but to date they have not been adopted in clinic based research in ACLD subject to evaluate functioning. Current approaches to ACLD rehabilitation have had a deficit focus, which has also been reflected in studies that have evaluated the effectiveness of specific components of conservative treatment. The effectiveness of strength training, supervision and perturbation has been evaluated and their value in improving functional activity performance established but this has not been related to increased participation level the ultimate goal for the patient. There are also limitations to applying some of these rehabilitation programs because they have not been validated on the type of ACLD population seen within the NHS or require resources that are not readily available. Feedback as a tool to improve performance has been evaluated using a range of modalities and populations. There are an insufficient number of studies that have compared FB to no-FB across all populations, to truly evaluate its effectiveness. The most common trial design has been to compare different types of feedback but no one method has emerged as the most effective. Therefore further evaluation of the effectiveness of feedback as a rehabilitation tool and the type of feedback provided to physiotherapists is required.

In patient populations there has not been a sufficient number of studies evaluating the effects of feedback on retention or transfer test or evaluating outcomes that relate to improved participation.

2.8 Objectives and Hypotheses

Based on this review of the literature the objectives of this study are:

1. To measure functional recovery longitudinally from acute injury and over the course of rehabilitation for a range of functional activities using a 2D clinical movement analysis system.
2. To evaluate if providing physiotherapists with movement feedback on ACLD patient functional performance over the course of rehabilitation results in an overall superior functional outcome.

The research framework used to evaluate these objectives is based on that proposed by Campbell et al. (2000) for evaluating complex interventions. Objective 1 of the current investigation corresponds to phase one of this framework, illustrated in Figure 1. Recovery will be modelled over time starting from time of injury for selected time-distance variables and joint angles of functional activities that progressively challenge knee stability. Recovery will be evaluated against the performance of uninjured control subjects. An ACLD subject will be classified as performing within 'normal limits' when their recovery for a particular variable is within 1SD of the control mean. If recovery of a variable falls outside of this then the difference in the control and ACLD performance will be considered clinically significant (Kendall et al. 1999). Based on this model of functional recovery an exploratory trial (phase 2 of the research framework) will be developed to evaluate objective 2. The component of rehabilitation to be evaluated in part 2 of the research will be the effectiveness of providing treating physiotherapists with movement feedback on ACLD functional performance.

Hypotheses and null hypotheses for the second objective are:

H1: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will achieve a significantly better functional outcome for the gait time-distance variables in Table 8 than those patients whose physiotherapists do not receive movement feedback.

Ho1: There will be no difference in gait time-distance variables between ACLD patients treated by physiotherapists in the feedback rehabilitation and no-feedback rehabilitation programs.

Table 8 Hypothesis 1: expected outcomes for gait time-distance variables for FB- rehabilitation group

Gait time-distance outcome variables for the FB-rehabilitation
Faster gait velocity
Longer injured and non-injured and step length
Higher cadence
More symmetrical step lengths

H2: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will achieve a significantly better functional outcome for gait kinematic variables in Table 9, than those patients whose physiotherapists do not receive movement feedback.

Ho2: There will be no difference in gait joint angles between ACLD patients treated in the feedback rehabilitation and no-feedback rehabilitation programs.

Table 9 Hypothesis 2: expected outcomes for gait joint angle variables for the FB-rehabilitation group

Gait kinematic outcome for FB-rehabilitation
Larger hip displacement angle of the injured and non-injured leg
Increased knee extension at heel strike
Increased dorsi-flexion at heel strike

H3: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will have a significantly better functional outcome for one legged squat variables in Table 10, than those patients whose physiotherapists did not receive movement feedback.

Table 10 Hypothesis 3: expected outcomes for one legged squat variables for FB rehabilitation group

One legged squat variables for FB rehabilitation
Larger maximum knee flexion angle
Increased range of ankle dorsi-flexion at maximum knee flexion
Increased knee valgus angle at maximum knee flexion

H4: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will achieve a significantly better functional outcome for distance hop variables in Table 11, than those patients whose physiotherapists do not receive movement feedback.

Ho4: There will be no difference in distance hop between ACLD patients treated in the feedback rehabilitation and non-feedback rehabilitation programs.

Table 11 Hypothesis 4: expected outcomes for distance hop variables for FB rehabilitation

Hop variables for FB rehabilitation
Increased injured and non-injured leg hop distance
Increased knee range during take-off phase
Increased knee range during the deceleration phase
Increased ankle range during the take-off phase
Increased ankle range during the deceleration phase

H5: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will achieve a significantly better functional outcome for run & stop variables in Table 12, than those patients whose physiotherapists do not receive movement feedback.

Ho5: There will be no difference in run & stop between ACLD patients treated in the feedback rehabilitation and non-feedback rehabilitation programs.

Table 12 Hypothesis 5: expected outcomes for distance R&S for FB rehabilitation

R&S outcome variables for FB rehabilitation
Increased knee range during take-off phase
Increased knee range during the deceleration phase
Increased ankle range during the take-off phase
Increased ankle range during the deceleration phase

H6: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will achieve a significantly better functional outcome for the Cincinnati knee rating system and SF-36 than those patients whose physiotherapists do not receive movement feedback.

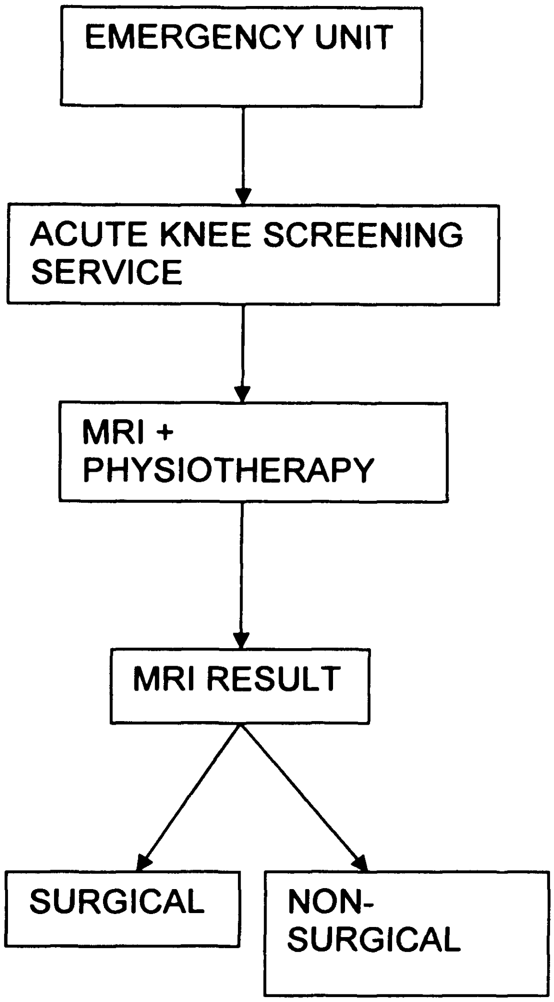
Ho6: There will be no difference in the Cincinnati knee rating system and SF-36 between ACLD patients treated in the feedback rehabilitation and no-feedback rehabilitation programs.

3.0 Methods

To investigate the objectives identified at the end of chapter 2, the study was divided into two parts; the first part modelled functional recovery using a prospective longitudinal design and the second part was aimed to evaluate the effectiveness of providing movement feedback using a prospective cohort design. Because each part used a different research design and ACLD sample these differences will be identified first. This study took place within the clinical setting recruiting for both part 1 and 2 from the large population of patients with knee injuries receiving assessment at the University Hospital for Wales (UHW) for the Cardiff & Vale NHS Trust catchment area. The movement analysis outcome measures and data collection protocols were the same for both parts and will be described mainly with part 1 of the study. The final section covers the separate analyses of each part.

It is important to state that participating in this investigation did not affect the overall medical or physiotherapy management of individuals with an acute ACL rupture. Patients who attended the Emergency Unit at the UHW with an acute knee injury, swelling, restricted mobility, loss of knee extension, instability or locking were referred to the Acute Knee Screening service (AKSS) for assessment. The AKSS is an extended scope physiotherapist led clinic based within the Emergency Unit at UHW and provides a link between the emergency unit, trauma and orthopaedics and physiotherapy. Most ACL injuries are managed according to set guidelines and the process for the patient is set out in Figure 4. All patients who were given a provisional diagnosis of an ACL rupture based on clinical examination were routinely referred for MRI scan and physiotherapy rehabilitation. A decision about long term surgical or non-surgical management was made at approximately 12 weeks post injury and was based on MRI findings, pre-injury activity levels, instability symptoms, passive stability, success of rehabilitation and patient goals and wishes. The ultimate decision of whether an ACL reconstruction should or should not be performed was between the orthopaedic surgeon and patient.

Figure 4 Overall management following acute ACL rupture at University Hospital of Wales



In part 1 and 2 the aim of physiotherapy rehabilitation was to assist individuals back to the highest level of function that was safe for them to perform. The content of rehabilitation was not dictated to the treating physiotherapists, they decided this for themselves on assessment of the patient. Rehabilitation was based around current guidelines aimed at resolution of acute symptoms, promoting functional stability and achieving functional goals. Rehabilitation activities to achieve this include neuromuscular control exercises, strengthening of lower limb muscles, cardio-vascular training, sport specific drills and advice. Progression was governed by clinical signs and symptoms and achievement of functional goals (Fitzgerald et al. 2000b; Manal & Snyder-Mackler 1996; Kvist 2004a).

Ethical approval for this study was granted from the Caridff and Vale NHS Trust research and development committee and the South East Wales local research ethics committee. Copies of the letters of the ethical approval from both bodies are in Appendix 2 along with the patient information sheets and consent forms.

3.1 PART 1: Measuring Functional Recovery

3.1.1 Study design

A prospective longitudinal design was used to measure functional recovery of ACLD subjects from acute injury up until 6 months post ACL rupture with a follow up after 12 months. Subjects were measured approximately monthly over the course of their rehabilitation, with a minimum of 3 movement analysis recording sessions. The number of days from injury to the date of each recording session and the activities analysed at each session were noted for inclusion in the analysis. A control group of subjects without a history of knee damage were recruited from the same catchment area to provide normative data.

3.1.2 Subject inclusion and exclusion criteria

Patients attending the AKSS were considered for inclusion in the study if they had an acute ACL injury on clinical assessment that was later confirmed by

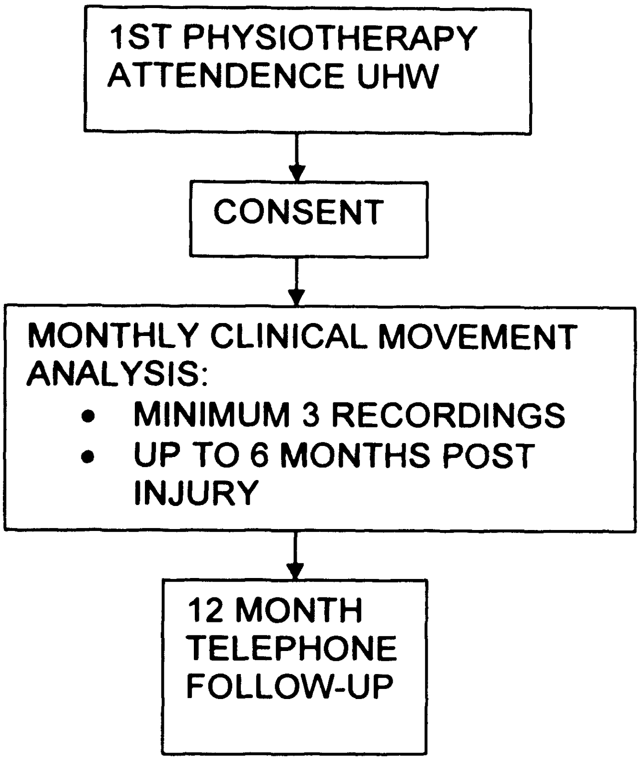
MRI. ACLD participants were excluded from the study if they were under eighteen or over fifty years of age, had other relevant neurological or musculo-skeletal pathology, required an urgent knee arthroscopy, had combined ACL and posterior cruciate ligament injuries, had a repairable meniscal tear or a concomitant fracture. However, ACL injuries combined with MCL tears or asymptomatic meniscal tears were included. These combined injuries did not require urgent surgical management and previous studies have concluded that this combination does not result in a worse outcome long term than a single ACL injury (Buss et al. 1995). There are six physiotherapy catchments within the Cardiff and Vale NHS trust which are based on geographical areas and treatment capacity of each individual physiotherapy department. Subjects were only included if they lived in the UHW catchment for physiotherapy. Patients living outside of this were referred to their local physiotherapy department for treatment.

Control subjects were recruited to match the ACLD subjects for age, height, mass, gender and activity levels. They were healthy and did not have any pathology which prevented then performing the functional activities, previous knee surgery or known knee ligament ruptures.

3.1.3 Subject recruitment and visits

Over the recruitment period from May 2001 to November 2003, 281 individuals attended the AKSS at the University Hospital of Wales and by clinical examination were diagnosed with an acute ACL rupture. Sixty three ACLD individuals fulfilled the inclusion criteria and were therefore invited to participate in the study. The main reason why the other 220 patients were not included was because they did not live in the UHW physiotherapy catchment area. The process for patients participating in this study following referral to physiotherapy is given in Figure 5.

Figure 5 Flow chart of the research process for ACLD subjects



On the patients initial attendance to physiotherapy they were given the study information sheet and asked if they would consider taking part in the investigation. Data collection started once they had returned a completed consent form. Clinical movement analysis included recordings of gait, jogging, run and stop and distance hop during clinical visits. These activities were chosen as they progressively challenge the ACLD knee in terms of impact and muscular forces. Due to acute knee symptoms post ACL rupture the only activity that individuals could initially perform was walking but as pain, swelling, muscle inhibition, functional instability and restricted ROM resolved then they could progress to jogging, run and stop and finally distance hop.

It was essential for the main analysis that patients attended for a minimum of 3 recordings of gait over their treatment so that recovery could be modelled using a 3^{rd} order polynomial, this is discussed in depth in chapter 3.5.2. These visits needed to be at least one month apart and data collection for individual patients was complete by approximately 6 months post injury; the majority of patients had been discharged from physiotherapy by this time. At 12 months post injury patients were followed up with a telephone questionnaire that evaluated their current functional ability and their knee stability during ADL and sport. Based on this information compared to their pre-injury activity participation level, individuals could be sub-classified into functional copers, adapters and non-copers. To reiterate, the definitions for each of the individual sub-groups are: a coper is an individual who has returned to their pre-injury level of work and sport with no limitations in their performance. An adapter is someone who has reduced their work or sport level or changed activities to prevent their knee fully giving way. Non copers are individuals that fail to return to their pre-injury activities and are experiencing episodes of full giving way with work, ADL or low demand, non pivoting sports (Alkjaer et al. 2003; Eastlack et al. 1999; Rudolph et al. 2001).

Only 42 subjects were eligible to be included in the final analysis, 21 were excluded because they did not have a minimum of 3 gait analyses or were not contactable for the telephone follow-up at 12 months post injury. A total of sixty one control subjects without a history of knee damage and meeting our inclusion criteria were recruited from the same catchment area as the patients.

3.2 Data Collection for Part 1 and Part 2

3.2.1 Preparation

All clinical movement analysis data collection took place in the physiotherapy gym at UHW by the same researcher in part 1 and 2. Prior to data collection two, one metre long sticks, with reflective markings at either end were placed parallel to each other and one metre apart on the floor of the gym. This distance was measured from the centre of the reflective marker on one stick to the centre of the reflective marker on the parallel stick. These sticks were located at the centre of the area for clinical movement analysis. These did not interfere with the subject's ability to complete the tasks but were required for data processing. One camera was placed opposite the sticks at a distance of 6 metres so that all functional activities were recorded in the sagittal plane. For 1 legged squat an additional camera was placed perpendicular to the sticks so this activity could also be recorded in the coronal plane. Both cameras were mounted on tripods 1 metre high. To ensure high quality video footage for data processing it was essential that the researcher aligned the camera perpendicular to the subject's plane of progression and that the sticks were completely horizontal in the camera viewer. Any deviation from this would result in distortion of the joint angle with either an over or under estimation of the angles when the video was processed and analysed. This set up is demonstrated in Figure 6.

Figure 6 Experimental set up demonstrating stick position on the ground and subject filling the view finder of the camera.

3.2.2 Clinical Examination

On arrival the patient firstly underwent a brief clinical examination. They were asked about knee symptoms of pain, swelling and knee giving way. Their current activity level was established and they were asked if they had attended physiotherapy, if they were still attending and if they did not attend at all what their reasons were. If they had been listed for a surgical procedure this was noted, along with any other concerns they might have about their knee. The MRI scan result was taken off the hospital database. The objective examination included a palpation, assessment of swelling using the sweep test and the presence of a positive test noted. Passive range of motion was visually assessed and documented. Stability was evaluated using the pivot shift and Lachman's test. This information was used to help evaluate which activities it was safe to allow the individual to perform.

3.2.3 Demographics

Height was measured using a SECA height measure which was fixed to the wall. Mass was measured in kg using SECA weight scales. Leg length was not measured as previous research has found a strong correlation with height and concluded that they can be used interchangeably (van der Walt & Wyndham 1973). Other demographic information that was collected about individual subjects was: age, gender and pre-injury activity level. For the latter that patient was questioned about what activities they regularly participated in. Individuals were classified as having a high demand activity level if they participated in contact sports or non-contact sport that involved pivoting and landing. A low demand activity level was defined as non-contact activities with low impact and no pivoting.

3.2.4 Collecting video footage of the functional activities

Before individuals could be videoed performing functional activities they needed to dress in shorts and trainers so that the lower limb was visible for the video processing stage. Activities to be recorded were then described to the individual and practiced. Standardized instructions were given to all subjects about how to perform each of the tasks, these were:

1. WALKING: Walk at your comfortable walking speed through the sticks to the other end of the walkway. I will tell you when to turn around and

walk back. This will be repeated so you perform 3 trials in either direction.

2. ONE LEGGED SQUAT: Balance on your affected leg, bend your knee as far as you can keeping your balance and then straighten your knee maintaining your balance, repeat five times.
3. JOGGING: Jog at your comfortable jogging speed through the sticks to the other end of the walkway. I will tell you when to turn around and jog back.
4. DISTANCE HOPPING: Take off from the limb being tested and land on the same leg. Hop as far as you can and land keeping your balance on the one leg until I tell you to stop. This will be repeated so there are 3 trials for each leg.
5. RUNNING TO A STOP: Jog down the walkway and stop when I tell you too balancing on your testing leg, keeping your other foot off the ground until I tell you that you can put it down. This will be repeated so there are 3 trials for each leg.

During the practice trials the researcher was able to watch the activities in the camera viewer and evaluate whether the subject was adequately filling the screen. If they weren't then the zoom function could be used on the camcorder. It was essential to maximize the size of the person in the viewfinder so that during data processing alignment of the onscreen goniometer would be more accurate to measure joint angles.

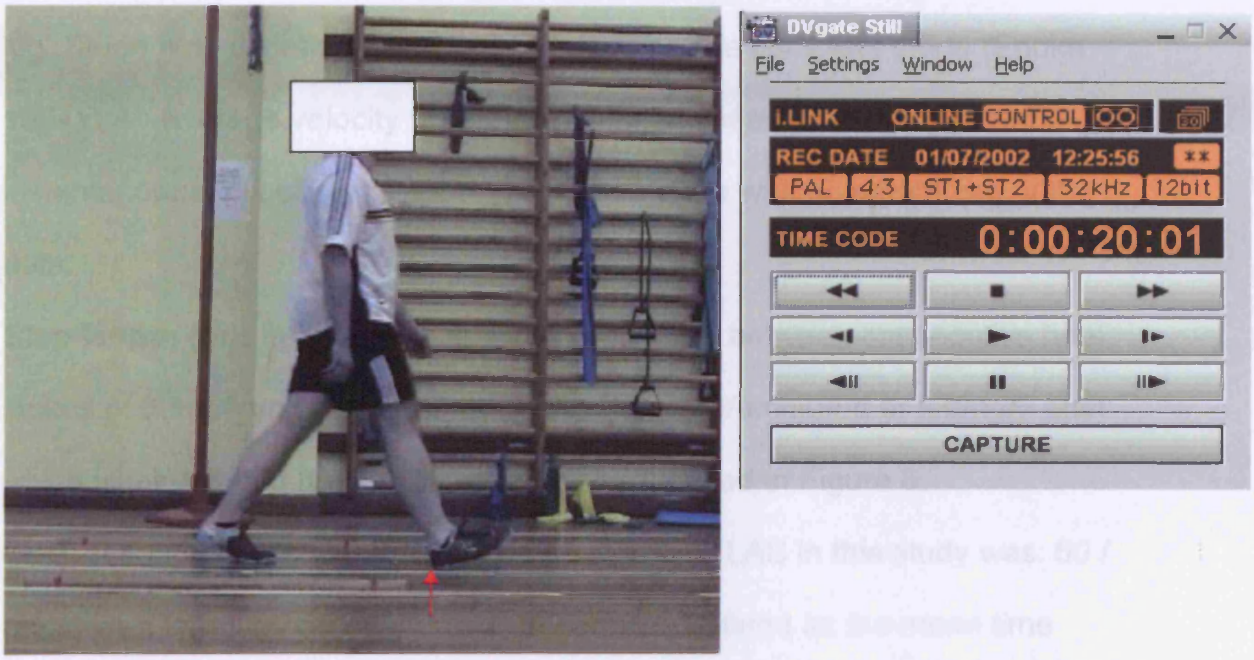
Throughout data collection each trial needed to be assessed by watching the activity through the camera view finder to check that it had been performed correctly or that the correct phases had been videoed. For a gait trial to be classified as successful then 3 heel strikes needed to be captured, with 2 of these being for the leg closest to the camera. The same classification was used for jogging. For distance hop and run and stop a failed trial occurred when the subject didn't keep balance for sufficient time or if they took multiple steps or hops to stabilize on one leg. All individuals were able to participate in the walk and one legged squat but not all individuals could progress to data collection of the more challenging functional activities; jogging, distance hop and run and stop.

3.3 Data Processing

3.3.1 Time-distance variables

All data was processed using a SONY VAIO FX105 laptop with DVGate Still and Mathworks MATLAB software, version 6.5 as a two stage process. For stage 1 individual frames corresponding to events of interest were saved from the video and stored as JPEG files. For gait analysis these frames were 3 heel strikes of the subject walking in either direction and for hopping 2 frames corresponding to pre take off and landing. Temporal information of these events was obtained in frames from the time code display in DVGate Still; this is displayed in Figure 7. DVGate Still software played the video at a resolution of 25 frames per second, which allowed for accurate identification of heel strike, particularly for gait. The time difference in frame between each of the gait events of interest was noted. This information was not needed for hopping distance because we were not measuring velocity for this activity.

Figure 7 Frame of interest and the corresponding time code of this frame



REC DATE 01/07/2002 12:25:56
PAL 4:3 ST1+ST2 32kHz 12bit
TIME CODE 0:00:20:01

For stage two of the processing a program was purpose-written in MATLAB. The two one-meter sticks were used to calibrate the area between them and create a grid so that the placement of the foot (location of the heel in contact with the floor at heel strike) relative to the calibration sticks could be measured. This spatial information was obtained automatically by the computer after the operator had indicated the heel location by means of a cross-hair displayed on the computer screen. This program corrected for any error that could have occurred due to small differences in foot placement between consecutive steps, by one foot being closer or further away from the camera than the other or not quite perpendicular to the line of the camera.

Once the temporal and spatial information was processed, the following variables were calculated by the computer:

Gait velocity (m/s): Within MATLAB the calculation used obtain this was: stride length / stride time. Stride length is defined as one complete cycle of gait; in this study this was from heel strike to the next heel strike for the same leg. Stride time is defined as the time taken for one complete stride (Enoka 1994). An average velocity was taken from two measurements per trial instantaneous velocity was not measured so there was no smoothing of the data.

Step length (m): In this study this was measured between consecutive heel strikes of the left and right leg. It is named injured/uninjured or left/right after which is the leading heel strike leg. This is depicted in Figure 6.

Cadence (step/min): The calculation used in MATLAB in this study was: 60 / mean step time. Mean step time in seconds is defined as the mean time taken for the step lengths. Sixty is the number of seconds in a minute.

Gait step length symmetry index (%): The equation used for this is (Sadeghi et al. 2000):

$$\text{Symmetry index} = \frac{(\text{SL non} - \text{SL inj})}{0.5(\text{SL non} + \text{SL inj})} \times 100\%$$

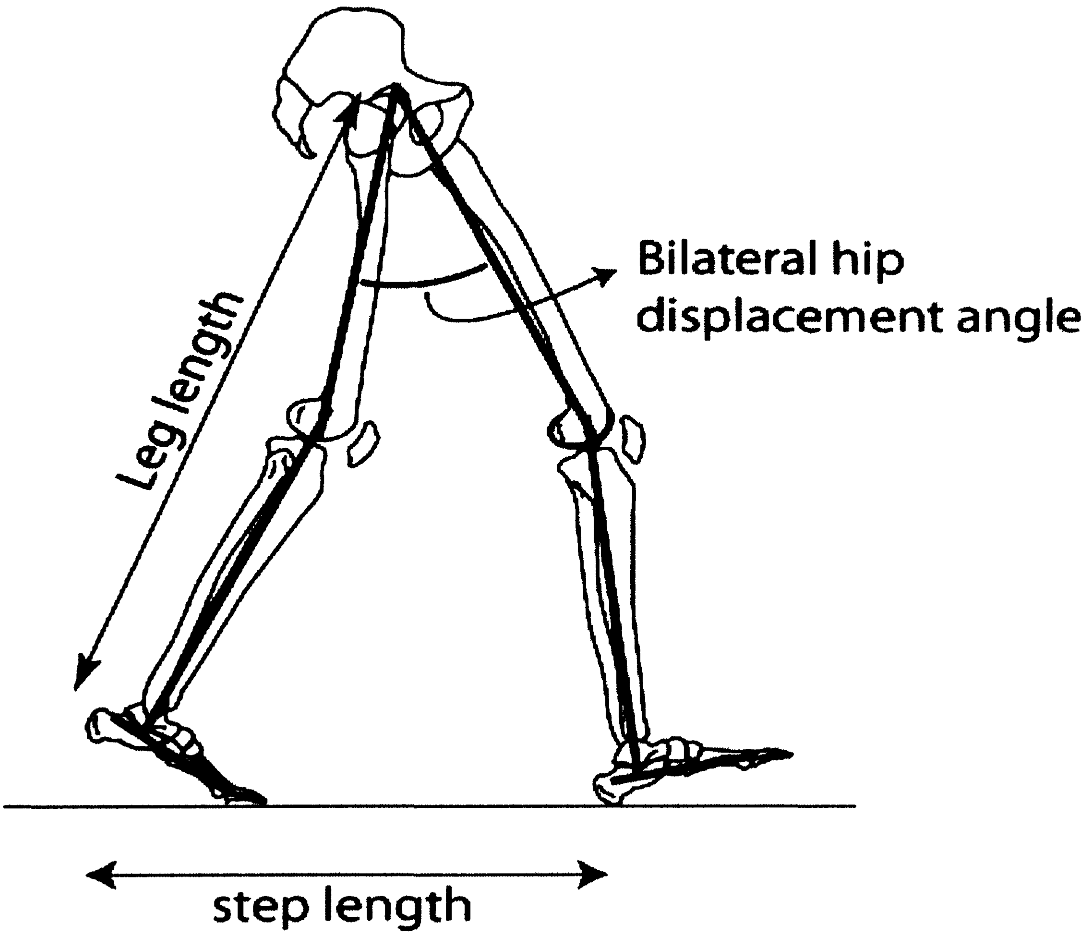
Maximal hopping distance (m): The distance between the most posterior point on the heel prior to take off when the foot is still in contact with the ground to the same point on the heel when an individual has landed and stabilized on one leg.

3.3.2 Joint angles

Ankle, knee and hip joint angles were processed using a SONY VAIO FX105 laptop and SiliconCOACH software, version 6, which allows the digital recording to be analysed at 50 frames per second. Individual AVI files were saved for each gait trial. These were then analysed frame by frame until the frame corresponding to heel strike was identified for both the injured and non-injured legs. The trailing leg was also analysed at this point and corresponded to late stance. A computerized goniometry tool was aligned over specific landmarks to obtain the joint angles which are described in Table 13. The hip displacement angle (HDA) is the difference in hip angle between the leading and trailing leg at heel strike and represents the functional hip range of motion at this time point. HDA, leg length and to a lesser degree knee joint angle all contribute to step length. HDA reflects the hip joint influence on step length without any contribution from the knee joint whose motion may be altered in patient with an acute knee injury. These relationships are visually represented in Figure 8.

There are some limitations in the angle measurement method that could have resulted in measurement error but every effort was made to ensure that these were kept to a minimum. These limitations include poor camera placement, if the person did not fill the field of view then it was more difficult to align the onscreen goniometer along bony landmarks and if the frame of interest was not exactly perpendicular to the view of the camera this resulted in some distortion to the angle measured. Further discussion of data collection limitations is presented in chapter 5.17.

Figure 8 Measurement of hip displacement angle and its relationship to step length and leg length.



The method of aligning the onscreen goniometer over the lower limb to measure joint angles using the SiliconCoach software is demonstrated in Figure 9.

Figure 9 Data processing using SiliconCoach with on screen goniometer aligned over the lower limb to measure knee angle

All of the movement variables evaluated in the clinical movement analysis for each of the functional activities are listed in Table 14.

Table 13 Method used to obtain joint angle measurements

Joint angles	Goniometer alignment
Ankle angle	Centrally along the length of the lower leg and along the base of the foot. The intersection point was at the base of the foot.
Knee angle	Centrally along the length of the injured femur and lower leg. Intersection point is at the centre of the knee joint.
Hip displacement angle	Centrally along the length of both femurs, angle measured at intersection point on pelvis.

Table 14 Movement variables evaluated in the clinical movement analysis

Functional activity	Variables
Gait	Velocity, cadence, step length injured and non-injured, step length symmetry index Knee and ankle joint angle at initial contact
Jogging	Velocity, cadence, step length injured and non-injured
Distance Hop	Distance hopped (injured and non-injured) Knee and ankle range: The difference in knee and ankle angle between initial contact and maximum knee flexion
Run and Stop	Knee and ankle range: The difference in knee and ankle angle between initial contact and maximum knee flexion

The same approach to data processing was used in part 1 and part 2

3.4 Reliability of measuring tools

A previous study has analysed the reliability of the Sony camera, laptop and software to be used in this study for measuring gait velocity. Excellent reliability with ICC's of 0.98 were found for inter-rater reliability and reliability between assessors and an opto-electric timer of ICC=0.98 (van Deursen et al. 2001). The between day intra tester reliability of measuring the hop distance has been found to be excellent; ICC=0.99.

The between day intra tester reliability of using SiliconCoach to measure joint angles is excellent or good; ICC=0.87 for the HDA, ICC=0.75 for the knee angle and ICC=0.78 for the ankle angle. To establish this the assessor was required to play 15 individual AVI files and for each one find the frame of interest and then align the onscreen goniometer over the lower limb. This process was repeated once a day for 3 days. The angle measurements for each testing session were written on separate data collection sheets so the assessor was not aware of previous measurements.

3.5 Analysis

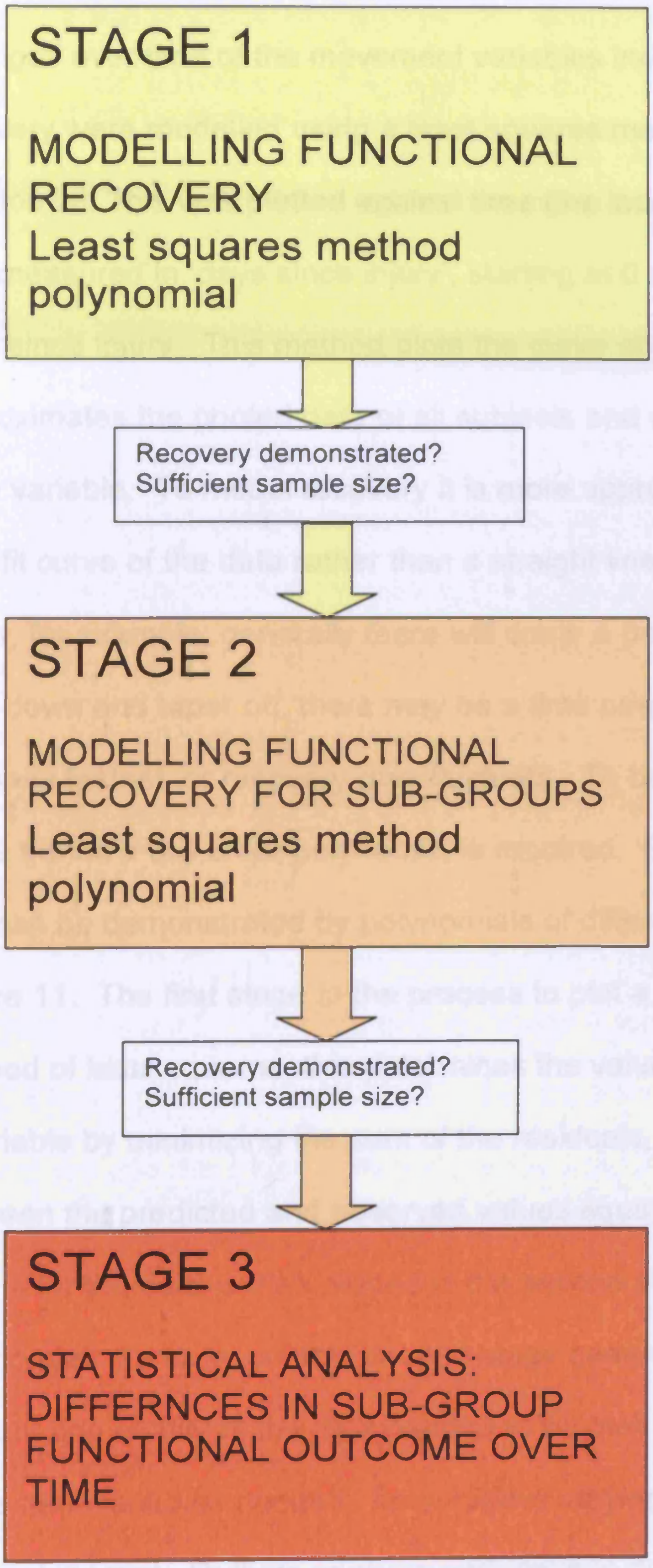
3.5.1 Modelling functional recovery

The aim of part 1 was to model functional recovery over time from acute rupture and compared to the mean and standard deviation of a healthy control group. This analysis was divided into 3 progressive stages with each stage evaluating this recovery in greater detail. The decision to progress the analysis between stages was based on 2 factors:

1. The functional activity had to demonstrate recovery over time on the previous stage to progress to the next stage of analysis.
2. There were sufficient subject numbers for the analysis.

This means that not all of the functional activities or variables were analysed to the same depth. The progressive stages of the analysis are depicted in Figure 10.

Figure 10 Stages of the analysis for function recovery

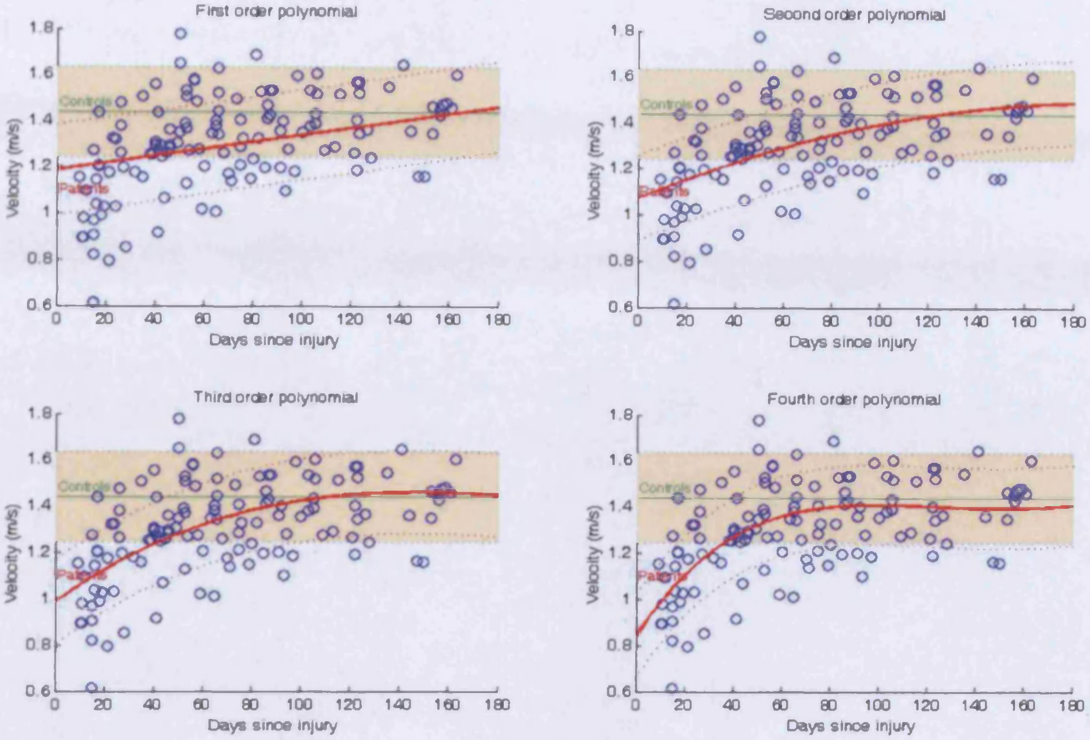


3.5.2 Least squares method 3rd order polynomial

Changes over time of the movement variables indicative of functional recovery were modelled using a least squares method for a 3rd order polynomial. This was plotted against time (the independent variable) which was measured in 'days since injury', starting at 0 up to a maximum of 150 days since injury. This method plots the curve of best fit which most closely approximates the pooled data of all subjects and can be applied separately to each variable. To model recovery it is more appropriate to plot a non-linear best fit curve of the data rather than a straight line because recovery is rarely linear, for example; generally there will come a point when ACLD recovery will slow down and taper off, there may be a time period when the recovery happens fastest; or recovery may fluctuate. To be able to demonstrate any of these trends a 3rd order polynomial is required. Examples of the curve detail that can be demonstrated by polynomials of different orders can be seen on Figure 11. The first stage in the process to plot a curve of best fit is to use the method of least squares; this determines the values of unknown quantities of a variable by minimizing the sum of the residuals, which is the difference between the predicted and observed values squared. The recovery curve of best fit for the data is then plotted in the second stage using a 3rd order polynomial. To carry out this second stage certain requirements regarding the amount and quality of the data needed to be met. Firstly, the data for the movement variables needs to be smoothly varying to be closely approximated by a polynomial. Outliers or sharp variations in data will distort the resulting polynomial curve and will be a less accurate representation of the data (NIST/ SEMATECH 2006). Secondly, to apply a polynomial of this order ideally a minimum of 4 measurements over time are required for each individual. The more data that is available the better because this will counteract the effects of the outliers and the distorting effect that these can have. Several steps can be taken to help evaluate the appropriateness and quality of the model. The first step is to identify the order of the polynomial used for fitting the data. If a polynomial of too high an order was applied then the curve would pick up noise and aspects of the curve would be inappropriate and not represent the actual data. If a polynomial of too low an order was applied then the recovery curve does not model any detail of the recovery, it just depicts it as a straight line. This is demonstrated visually in the first graph in Figure 11. The decision to use a third order polynomial was first of all based on theoretical grounds; recovery slows down and settles at the time of recovery. These details cannot be captured by a first or second order. The choice not to use a fourth order was made on the basis of preferring a model with most sparsity (3rd order) and the fact that the fourth order would require more data points per subjects. In Figure 11 the 1st, 2nd, 3rd, and 4th order fit for a representative data set are displayed. Mean and 1SD for healthy controls are also displayed. Note that the 3rd and 4th order plots both settle around the control mean.

The second step is to plot and inspect the polynomial curve and the 1SD of this curve. If there is sufficient data throughout the range of the data analysed the SD will run parallel to the mean curve. If the polynomial fit was used with insufficient data then there would be a divergence of the 1 SD curve from the polynomial curve. The third step is to visually inspect the data for outliers if present on a large scale then plotting a curve of best fit using a polynomial may not be appropriate for the reasons mentioned previously.

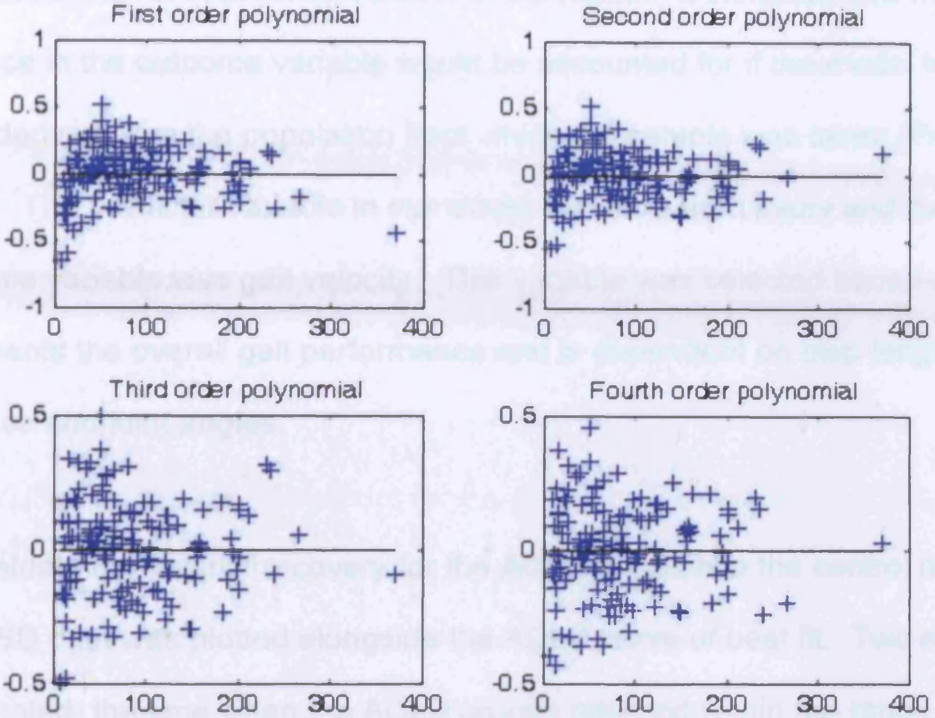
Figure 11 Examples of first to fourth order polynomials modelling functional recovery for gait velocity.



These plots of the different polynomials are based on the 36 subjects that had a minimum of 4 visits.

The fourth step is to plot the residuals of the data, which are the difference between the actual and predicted measurements. If the correct model has been applied then when these are plotted on a scatter graph there will appear to be no relationship between the variables. The residuals of the data in Figure 11 have been plotted in Figure 12. Based on these plots the first and second order polynomial can be ruled out as appropriate models; the third and fourth order polynomials are more appropriate as no apparent relationship is demonstrated for the residuals.

Figure 12 Residuals of the data for the 1st to 4th order polynomials



The advantage of this analysis is that it permits some flexibility in the timing of the patient measurement schedule. This was essential during this exploratory investigation, as the purpose of this study was to introduce research into this clinical setting and because longitudinally we could not guarantee that all patients would be measured at exactly the same time intervals during rehabilitation due to patient and clinic factors. Despite this flexibility the model was accurate because exact measurement times were used occurring at any time between 1 and 150 days rather than being at rigid times and the values in between having to be estimated (Matthews et al. 1990).

Finally for gait velocity the goodness of fit of the recovery curve was calculated in Matlab using the adjusted r^2 and its value for each of the different order polynomials that could have been applied. Adjusted r^2 indicates the level of predictive power of the model. It indicates how much variance in the outcome variable would be accounted for if the model had been derived from the population from which the sample was taken (Field 2005). The predictor variable in our model was time from injury and the outcome variable was gait velocity. This variable was selected because it represents the overall gait performance and is dependent on step length, cadence and joint angles.

To evaluate the level of recovery for the ACLD population the control mean and 1SD data was plotted alongside the ACLD curve of best fit. Two events were noted; the time when the ACLD groups returned within the range of values found in the control group (average ± 1 standard deviation) and when the ACLD groups returned to the average value of the control group. The ACLD groups were classified as having recovered to within a normal range when their values were within +/- 1SD of the control average (Kendall et al. 1999). The information on these recovery plots can guide decision making about; when is the best time during the recovery to deliver rehabilitation; about when is the most appropriate time to make a decision on long term management based on function and finally provide detailed information on the completeness of functional recovery for an individual or the group.

For stage 2 of the analysis functional recovery over time was modelled for the ACLD subjects sub-classified as functional copers, adapters and non-copers using a least squares method 3rd order polynomial for gait time-distance variables. The curve of best fit was plotted against days since injury and control reference data. This was explored descriptively with the aim to identify whether separate routes of recovery would be identifiable as an encouragement to use functional outcome measures to guide treatment for the individual sub-groups. For knee joint angle the copers and adapters needed to be combined because a limited volume of data was available for the copers.

A similar analysis was carried out for the hop distance. However, because there were fewer data points per subject it was doubtful whether the use of the 3rd order polynomial was valid. Therefore a 2nd order polynomial was used. In the time period analysed hop distance did not demonstrate a time of settled recovery so that the 2nd order could be used to fit that stage of recovery. Like gait kinematics the coper and adapter group had to be combined for the second stage of the analysis due to insufficient number of data points for the copers.

As a 3rd stage to the analysis a subset of gait data was analysed post-hoc using a mixed design repeated measures ANOVA to compare two factors; time (around 1 and around 4 months) and ACL sub-group (copers/adapters and non-copers) to evaluate for an interaction. One month was the first time point because this was when most patients had their initial data collection, 4 months was selected as the follow-up time because it was identified that gait would in most cases be recovered by this time point. Only a subset of ACLD subjects had data that corresponded to these time points. The groups of copers and adapters were pooled to maintain sufficient group sizes. From a rehabilitation standpoint within the NHS this is justified because these patients are able to function well at ADL and low demand sports whilst waiting for surgery. It is the non-copers who are at high risk of creating further long term damage to the knee due to the repeated episodes of giving way (Mafulli et al. 2003; von Eisenhart-Rothe et al. 2004).

3.6 Criteria of a Good Functional Outcome Measure

To measure recovery of function over time the activities evaluated needed to reflect the type of activities that the ACLD individuals may ultimately need to participate in. This means they need to include tasks that represent activities of daily living and sporting manoeuvres. They also need to be applicable over the course of rehabilitation and identify change in performance over time so that the detail of recovery can be identified to guide treatment content. Activities also need to be able to be performed by the majority of individuals. Their recovery also needs to correspond to performance of uninjured individuals, using 1SD of the control mean and control mean as the criterion, as described previously. Finally the movement variables that represent the functional tasks need to be measurable in the clinical setting, in a reliable manner.

3.7 PART 1: ACLD population demographics

ACLD subjects included in our investigation were compared to all those that attended the AKSS with an ACL rupture but did not participate in the investigation for age, gender and activity levels. This was done to check that our sample was representative of the larger population of all ACLD subjects. The ACLD group was also compared to the control group to check that they were matched for age, height, mass, gender and activity levels. Statistical test used to compare the groups were independent t-tests for the ratio level variables and chi square for the nominal level variables.

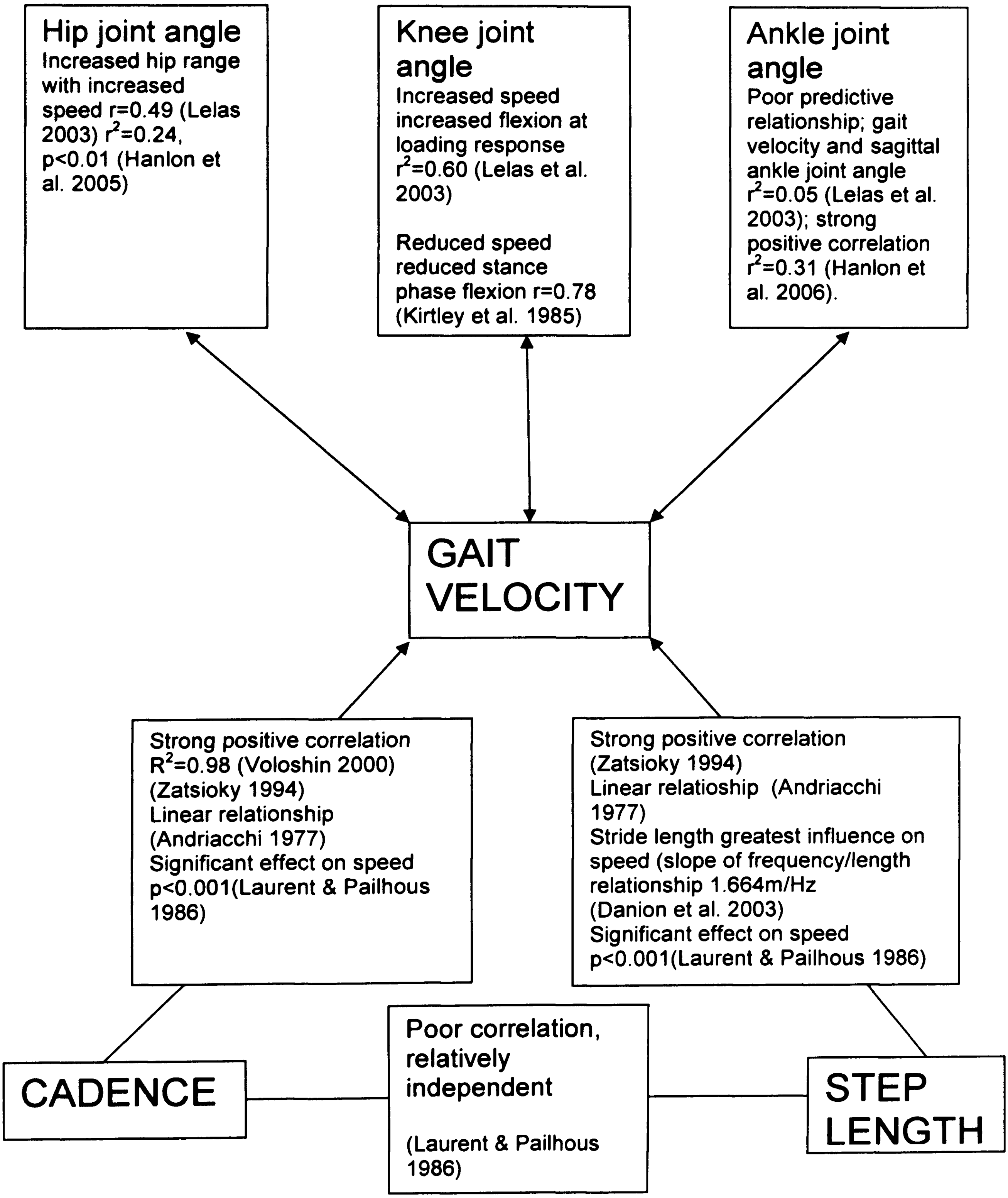
Pearsons' product moment correlations were used to evaluate the relationship between the time-distance variables for healthy subjects and ACLD subjects at 1 month post injury. The relationship between time-distance variables and selected kinematic variables in the ACLD sub-groups were analysed at 4 months post injury. Correlations were only performed on those variables that were found to be significantly different between the sub-groups at 4 months post injury, following the mixed design repeated measures ANOVA. A correlation was interpreted as significant when the alpha level was lower than 0.05. The strength of the correlation was classified according to the criteria of Landis & Koch (1977) these are given in Table 15.

Table 15 Criteria to evaluate the strength of correlations

STATISTIC	STRENGTH OF THE AGREEMENT
<0.000	Poor
0.00-0.20	Slight
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Substantial (high)
0.80-1.00	Almost perfect (very high)

A summary of the relationships between gait kinematic variables is depicted in Figure 13. These relationships between the variables based on previous studies are used as a basis to evaluate in the current study if the relationships between variables have recovered.

Figure 13 Summary of the relationships between gait time-distance variables and joint angles in healthy subjects based on the literature.



Increased hip range with increased speed $r=0.49$ (Lelas 2003) $r^2=0.24$, $p<0.01$ (Hanlon et al. 2005)

Increased speed increased flexion at loading response $r^2=0.60$ (Lelas et al. 2003)

Reduced speed reduced stance phase flexion $r=0.78$ (Kirtley et al. 1985)

Poor predictive relationship; gait velocity and sagittal ankle joint angle $r^2=0.05$ (Lelas et al. 2003); strong positive correlation $r^2=0.31$ (Hanlon et al. 2006).

Strong positive correlation $R^2=0.98$ (Voloshin 2000) (Zatsioky 1994) Linear relationship (Andriacchi 1977) Significant effect on speed $p<0.001$(Laurent & Pailhous 1986)

Strong positive correlation (Zatsioky 1994) Linear relatioship (Andriacchi 1977) Stride length greatest influence on speed (slope of frequency/length relationship 1.664m/Hz (Danion et al. 2003) Significant effect on speed $p<0.001$(Laurent & Pailhous 1986)

Poor correlation, relatively independent

(Laurent & Pailhous 1986)

3.8 PART 2: Movement Feedback Rehabilitation

3.8.1 Study design

A prospective cohort design was used to compare concurrent treatments of movement feedback (FB) and non-feedback (non-FB) rehabilitation, which were carried out in different physiotherapy departments. Individuals were randomised into their treatment group following their initial consultation at the AKSS by the physiotherapists in the clinic. Patients then received physiotherapy at one of the two locations depending on which treatment group they had been randomised to. Data collection occurred at 5 months post injury and individuals were telephoned at 12 months post injury so they could be sub-grouped into copers, adapters or non-copers. No movement analysis was performed at baseline but clinical information such as age, injury type, activity levels and gender was recorded. Two sets of semi structured interviews were conducted with the physiotherapists participating in this part of the investigation. The first set of interviews aimed to evaluate the value of providing physiotherapists with movement feedback and how this influenced rehabilitation; this was only carried out with the physiotherapists in the FB-group. The second set of interviews evaluated the content of rehabilitation and any differences between the FB and no-FB treatment so all the participating physiotherapists were interviewed.

3.8.2 Inclusion criteria

In general the same inclusion criteria were used as in part 1 and are given in section 3.1. In addition all patients that attended the AKSS had a clinical diagnosis of ACL rupture and lived within the Cardiff and Vale NHS trust were recruited onto the investigation. Patients were required to attend one of two departments depending on whether they were randomised into the FB or no-FB rehabilitation groups. If they were not willing to attend the allotted department then they were excluded from the study.

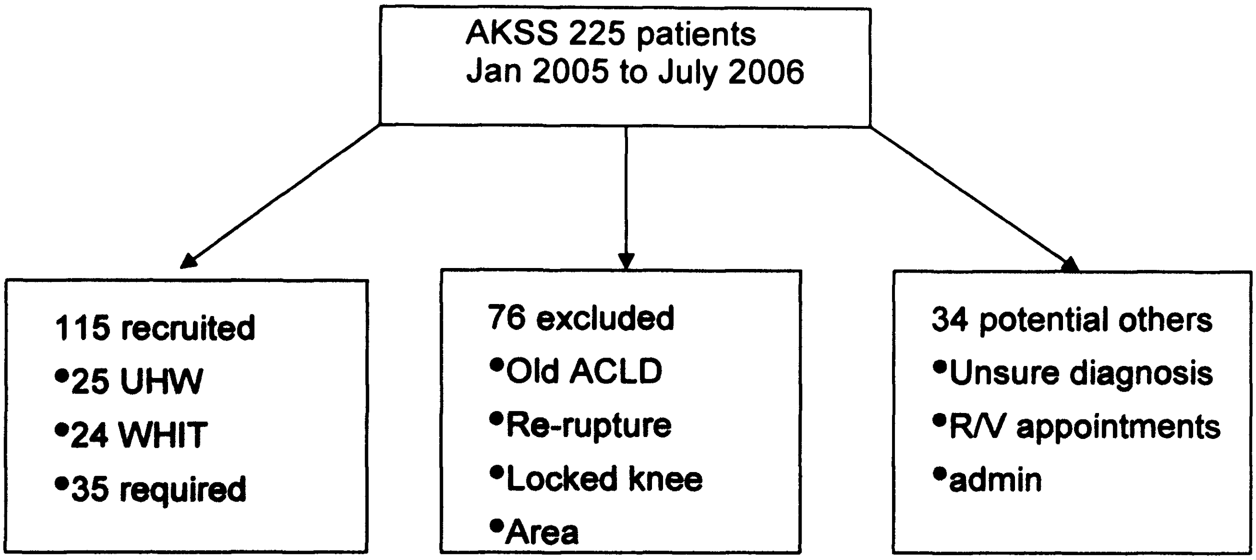
3.8.3 Sample size

The number of subjects required in this investigation to demonstrate a treatment effect was eighty subjects for two groups of forty. This is derived from a power calculation for t-tests using the work of Zatterstrom et al. (2000) and is based on requiring a power of 0.80, significance level of 0.05, a one-tailed test and standard difference of 0.6. A total of 40 subjects per group incorporate an extra 5 subjects allowing for some loss to follow-up at 5 months post injury. This is a feasible number to recruit based on an attendance rate to the AKSS of approximately eighty ACL deficient subjects a year. A total of 120 patients over an 18 month period were expected to attend the AKSS and based on part 1 it is anticipated that approximately 30% of patients will decline to participate, which would leave us with the required 80 participants.

3.8.4 Recruitment and randomisation

Over the recruitment period from January 2005 to June 2006 225 patients seen in the AKSS were given a clinical diagnosis of an ACL rupture by the extended scope physiotherapists working in that clinic. Out of 225, 110 subjects fulfilled the inclusion criteria and were recruited onto the investigation. The reasons why the 115 excluded subjects were not recruited were checked in the clinic electronic database and were used to evaluate if there had been any selection bias. This demonstrated that 76 of these subjects had not fulfilled the inclusion criteria but no definite reason could be found why the remaining 34 subject had not been recruited, this is summarized in Figure 14. Based on the clinical notes the main reason for this would appear to be due to a delay in making a clinical diagnosis of an ACL rupture and as a result of this uncertainty these individuals were not recruited onto the investigation. Another reason is that one of the exclusion criteria was written as 'significant previous surgery'. This can be interpreted in a number of different ways and resulted in some individuals being excluded that shouldn't have been, for example arthroscopy to the other knee for meniscal tears.

Figure 14 Summary of patients attending the AKSS with ACL rupture.



Once a clinical diagnosis of an ACL rupture had been made ACLD individuals were provisionally randomized into the FB or no-FB physiotherapy treatment groups by the extended scope physiotherapist working in the clinic, who was not blinded to differences in rehabilitation approach between treatment centres. This was done following a randomization list that was generated using the website: http://www.randomizer.org/form.htm (Urbaniak, G.C and Plous, S 1997). A set of 80 unsorted numbers ranging from 1 to 80 were provided by this program. A randomization list was then drawn up following this order of numbers, with the even numbers representing a subject for the feedback group and odd numbers for the non-feedback group. Subjects were asked if they would consider participating and were given the information sheet and consent form. A provisional physiotherapy appointment was made at either the FB or no-FB physiotherapy the appropriate department. It was explained that the consent form should be returned once they had considered in their own time whether they wanted to be part of the investigation. Data collection did not begin until a completed consent form had been returned.

At the five month follow-up there were 27 data sets for the feedback group and 25 for the non-feedback group. Reasons for the loss of subjects by the 5 month follow-up will be discussed in more depth in chapter 4.13.

3.8.5 Training the treating physiotherapists

Three physiotherapists at each of the two treatment sites were allocated to the rehabilitation of ACLD patients in this study. Across the sites these therapists were matched for number of years qualified, grade, relevant post graduate training and experience with managing knee injuries. The least experienced physiotherapists from both the FB and no-FB group withdrew from the study, one to move to a job elsewhere and the other due to maternity leave.

Prior to the study beginning the treating physiotherapists from both sites were given basic training about the research and treatment of ACLD knees. This was done as a power point presentation with a discussion session at the end. Both groups were trained separately because the FB group needed additional information about the movement analysis, timing of feedback, feedback content and research follow-up. The content of the power point presentation is given in Table 16.

Table 16 Content of the training participating physiotherapists were given prior to the research starting.

Study aim
Study design
Effects on physiotherapy treatment
Movement feedback: content, structure, scheduling (FB group only)
Subjects: numbers and process
Rehabilitation framework: goal setting, progression indicators, activity types, progression of activities, patient education, managing combined injuries.
Long term management
Patient information – commonly asked questions
Summary

The point in bold was given to the FB group only

Physiotherapists in the FB group were informed on the criteria the researcher would be using for grading each movement variable of an individual ACLD subject and how this would be documented on the movement feedback form for the physiotherapist. Key points that were emphasized:

- Individual ACLD performance would be compared to healthy subjects.
- That if the magnitude of the movement variables retuned to within 1SD of control mean then individuals were considered to have recovered to uninjured levels and these variables would be categorized as 'no treatment priority'. If the magnitude of the variable fell outside this range it would be highlighted as a 'treatment priority' on the feedback form. If the magnitude of the variable fell outside the control min/max value then this would be documented as a 'high treatment priority'.

No further training was given on how to interpret these findings, implications for rehabilitation or how this information could be incorporated into treatment.

It was anticipated that the physiotherapists would have sufficient knowledge base to interpret the movement variables due to their training and clinical experience and so that the clinicians designed the treatment themselves and were not guided by the researcher.

3.8.6 Physiotherapy rehabilitation in the FB and no-FB groups

The only treatment stipulation made to the physiotherapists in both groups was that subjects had to be treated on an individual basis, there was to be no class work. There was no enforced treatment program that had to be applied to all subjects and treatment did not have to continue for a set amount of time, patients could be discharged when the patient and physiotherapist felt it was appropriate.

An enforced rehabilitation program was not given for 2 reasons:

- Physiotherapists in the feedback group were receiving information about individual patient performance so it was anticipated that they would tailor individual rehabilitation accordingly. This would not happen if physiotherapists were required to use a prescribed rehabilitation program.
- An enforced rehabilitation program would not reflect true clinical practice where rehabilitation is multifaceted and individual. To maintain this within the research no restraint was placed on the number and scheduling of physiotherapy appointments or the content of rehabilitation.

This meant that rehabilitation was based around addressing deficits such as reduced ROM, strength, controlling knee instability and improving function using treatment approaches described previously. In addition it was anticipated that the physiotherapist in the feedback group would base their treatment around the presence or absence of any movement compensation strategies identified during the functional activities. Therefore it was anticipated that the content of the movement feedback and achievement of functional goals would have directed the content of treatment; making this a more functional approach to rehabilitation.

3.8.7 Design of movement feedback

3.8.7.1 Movement feedback content:

The selection of functional activities to be included in the movement feedback was based on the results of our preliminary study. In part 1, we found distinct difference in gait and distance hop performance between ACLD subjects and controls over time. In addition we were able to discriminate functional non-copers from copers and control subjects. Therefore we proposed that this information could be incorporated into clinical movement analysis to evaluate individual ACLD performance during rehabilitation compared to the healthy subjects. This would provide the treating physiotherapist with information about individual recovery, which could also be incorporated into treatment. Run and stop was included because like distance hopping this challenges knee stability with the large impact forces, shear forces and muscular activity required. It is considered essential that individuals can safely perform this activity before returning to sport. One legged squat was a new activity and was chosen as a substitute for jogging. It is commonly used in clinical practice to evaluate muscle strength and control and is seen as a precursor to jumping and hopping. Jogging was not included in the movement analysis because in part 1 no recovery of the jogging variables was demonstrated; once patients could jog they could jog. Cutting was not included because we found that we were not able to analyse it with a 2D system as the movement frequently doesn't occur perpendicular to the camera, causing a distortion of the true kinematics that the patient used. A copy of the feedback sheet used in the investigation is in Appendix 3.

3.8.7.2 Feedback scheduling:

Patients were videoed for feedback at 1, 3 and 4 months post injury. This was based on the results of part 1 of the PhD:

- By 1 month all individuals should have started their rehabilitation and would have given them time to consent. Feedback would be on gait and one legged squat.
- At 3 and 4 months it was anticipated that subjects would have been able to take part in all activities; acute symptoms would have settled. This would mean that movement feedback would provide more meaningful information for guiding the physiotherapist and patients towards return to sport.

Movement analysis was processed by the researcher as soon as possible and returned to the treating physiotherapist for their interpretation before the patient's next appointment.

Final data collection was at 5 months post injury. This time was chosen based on anticipated time to return to full activity stated in the literature (Kvist 2004a) and because it corresponded to the results of our study regarding recovery time. Results of part 1 demonstrated that patient recovery reached a plateau and returned to within 1SD of the control mean by 5 months post injury.

3.9 Treatment sites

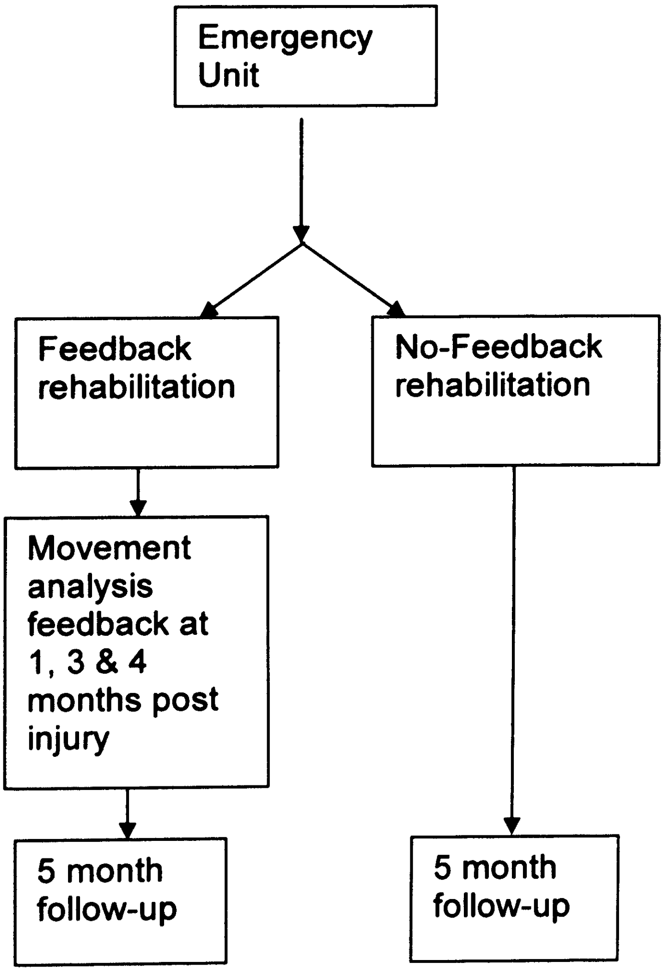
The two treatment sites (FB and no-FB) were based in different localities within the Cardiff and Vale NHS Trust. The physiotherapists treating patients referred to the feedback group received movement feedback about patient performance and those rehabilitating patients at the non-feedback site did not receive any feedback over the duration of treatment. Separate treatment localities were used to prevent the physiotherapists and patients in the no-FB group observing and discussing the content and structure of the movement feedback, which could have changed how the physiotherapists rehabilitated the ACL rupture. Patients and physiotherapists could not be blinded to which feedback group they belonged to but this structure aimed to significantly reduce their awareness of differences in treatment.

Using different treatment sites should not have influenced the research outcome through because both departments had the same rehabilitation facilities, out-patient physiotherapy manager and were in a similar locality within Cardiff so access was similar.

3.10 Visits

The research process and visits made by the patients in the FB and no-FB rehabilitation are given in Figure 15. In addition to the research visits, as part of the normal clinical practice patients were still followed up with the result of their MRI scan at approximately 3 months post injury and a decision made about their long term management.

Figure 15 The research visits made by each of the patients recruited onto the investigation



3.11 Follow-up

All patients were followed up at 5 months post injury for a final movement analysis. No feedback was given to the treating physiotherapist at this time as the data collected was just for research purposes. All subjects in the FB and no-FB groups were contacted for follow-up even if they hadn't completed a full course of rehabilitation. The data collection process for the ACLD patient at the 5 month follow-up visit included a brief clinical examination, completing questionnaires, demographic measurements and 2D video movement analysis of functional activities that an individual was able to perform. Greater detail of the measurements taken at this visit are summarised in Table 17.

Table 17 Measurements taken at the 5 month follow-up visit

5 month data collection visit	
Clinical examination	Swelling, ROM Knee stability
Questionnaires	Cincinnati knee rating system SF-36 General questionnaire
Demographics	Height Mass Age Gender Activity levels
Movement analysis	Gait 1 legged squat Distance hop Run and Stop

At 12 months post injury all patients were contacted by telephone and a questionnaire completed. This evaluated their final functional outcome as they were asked about current activities they participated in and episodes of knee giving way with ADL and sports. They could then be sub-classified into functional copers, adapters and non-copers by comparing their pre-injury activity level to 12 months post injury activity level and knee stability.

3.12 Questionnaires

Subjects were then asked to complete the SF36 (Ware & Sherbourne 1992), which is a quality of life questionnaire with eight sub-scales relating to patient participation and the Cincinnati knee rating scale (Barber-Westin et al.1999) which evaluates function at the 'structure', 'activity' and 'participation' levels. The validity of the SF-36 has been evaluated in patients with knee osteoarthritis and knee arthroplasty (Brazier et al. 1999; Bombardier et al. 1995). Validity has not been established in patients with ACL rupture although it has been used in studies evaluating these patients (Nyland et al. 2002; Thomee et al. 2006). The Cincinnati knee rating system is divided into sections that deal with patient symptoms, a global rating of how satisfied the patient is with the knee, a sports activity scale, activity of daily living function scale, sports function scale and occupational rating scale. The validity, reliability and responsiveness of this scale to change have been demonstrated for the scale as a whole and its individual components (Barber-Westin et al. 1999). Copies of these questionnaires are in Appendix 4.

3.13 PART 2 Analysis: Movement Feedback Rehabilitation

All data for analysis was entered into SPSS to check for normality and equal variances. Differences in patient demographics between the FB and no-FB group were analysed using independent t-tests for height, mass, age and number of physiotherapy sessions. Differences on categorical variables were analysed using chi square. The differences in functional outcome for the movement variables during gait, distance hop and run and stop between the two treatments at 5 months were evaluated using independent t-tests. An alpha level of equal or less than 0.05 was used to evaluate if the differences were statistically significant.

3.13.1 Modelling functional recovery

Functional recovery from time since injury was modelled for the FB group gait time-distance variables using a least squares method 3rd order polynomial; the same approach as used in part 1. This recovery curve for the FB group was then plotted alongside the best fit curves from the same analysis used in part 1, so that the curves could be compared. This could not be done for the no-FB group because we did not have repeated measures data for this group. The mean value and SD for both the FB and no-FB treatments were included in the model output as a singular point at 5 months post injury. The FB group would be expected to recover back to the control mean value in a faster time compared to the no-FB group.

To explore whether the treatment group had made sufficiently complete functional recovery at 5 months a further analysis was carried out in which both the ACLD treatment groups were pooled into one large group of 50 subjects. This pooling was possible because there were no significant differences between the 2 treatment groups for any of the 20 movement variables (see Results chapter). Although there was no difference in the level of recovery between the two treatment groups we were not able to exclude that the reason for this was because all ACLD subjects regardless of treatment group had made a full recovery for the functional variables at 5 months post injury. This combined ACLD group was compared to the control group from part 1; differences between groups were analysed using independent t-tests.

The relationship between movement variables and clinical signs such as pain, swelling and giving way were analysed using Pearson's correlation coefficient and Spearman rho. For both the correlations and independent t-tests an alpha level of less than 0.05 was considered statistically significant. This aimed to evaluate if movement performance was influenced by clinical symptoms. If there is no significant relationship this would indicate that they measure different aspects of recovery and are both required to evaluate outcome.

3.14 Semi-structured interviews

Two sets of semi structured interviews were conducted. The first set was with the 2 remaining physiotherapists that carried out the treatment in the FB-group. The aim of this interview was to establish if the physiotherapists had used the feedback, how useful they had found it and if they had incorporated it into rehabilitation of the FB group ACLD patients.

The second set of interviews was with the physiotherapists in both the FB and no-FB groups and aimed to establish how the physiotherapists in both groups rehabilitated ACLD individuals. This also provided the opportunity to evaluate if the physiotherapists who received the movement feedback changed their treatment approach accordingly and adopted a more functional approach to the rehabilitation. If the physiotherapists were identifying ways in which they were using the movement feedback in interview 1 then it was anticipated that this would have been reflected in their answers to interview 2.

The second set of interviews evaluating rehabilitation approaches was piloted on another physiotherapist who has treated and been involved in research with ACL individuals. This evaluated if the wording of the questions was correct and appropriate answers were obtained. The first set of interviews could not be piloted because they were very specific to receiving movement feedback as part of the study and could not have been answered by anyone who didn't have insight into this. All interviews were conducted in a quiet room away from the clinical treatment area; they were recorded on tape and were carried out and transcribed by the researcher. Each question was read out in turn; if an individual was unable to answer the question or further clarification was required then prompts were given by the researcher. At the end the interview interviewees were given time to make any other comments. The first stage of processing the data was to transcribe the tapes and then the interviews were then analysed by establishing themes. Copies of the interview questions are given in Figures 16 and 17.

Figure 16 The questions asked in the semi-structured interview 1 about the movement feedback

Semi-structured interview 1

1. Which components of the feedback did you find useful in evaluating patient recovery?
2. Why these components, what did they tell you?
3. Which components of the feedback did you use in patient treatment?
4. Why were these components useful?
5. Can you identify any components of the feedback that were not useful and why?
6. Can you indicate how the feedback information changed the way you treated patients?
7. How could the feedback be improved to make it more useful in patient management?
8. Is there any other information that you would have liked?
9. Did participating in this research alter the way you treat ACLD patients? If yes how? (duration of treatment, number of sessions, information provided)
10. How do you normally measure ACLD patient recovery during a course of treatment?

Figure 17 The questions asked in the semi-structured interview 2 about the ACL rehabilitation

Semi-structured interview 2

1. When designing a rehabilitation program what factors do you take into consideration?

2. What treatment goals would you set?

3. In terms of treatment goals how would you structure the rehabilitation?

4. How would you progress the treatment goals?

5. How would the rehabilitation differ between patients who are progressing well and those that are not?

6. Do you give a home exercise program? What form does it take?

7. What factors would lead you to discharge a patient?

8. Do you give advice/educate a patient on their condition and treatment?

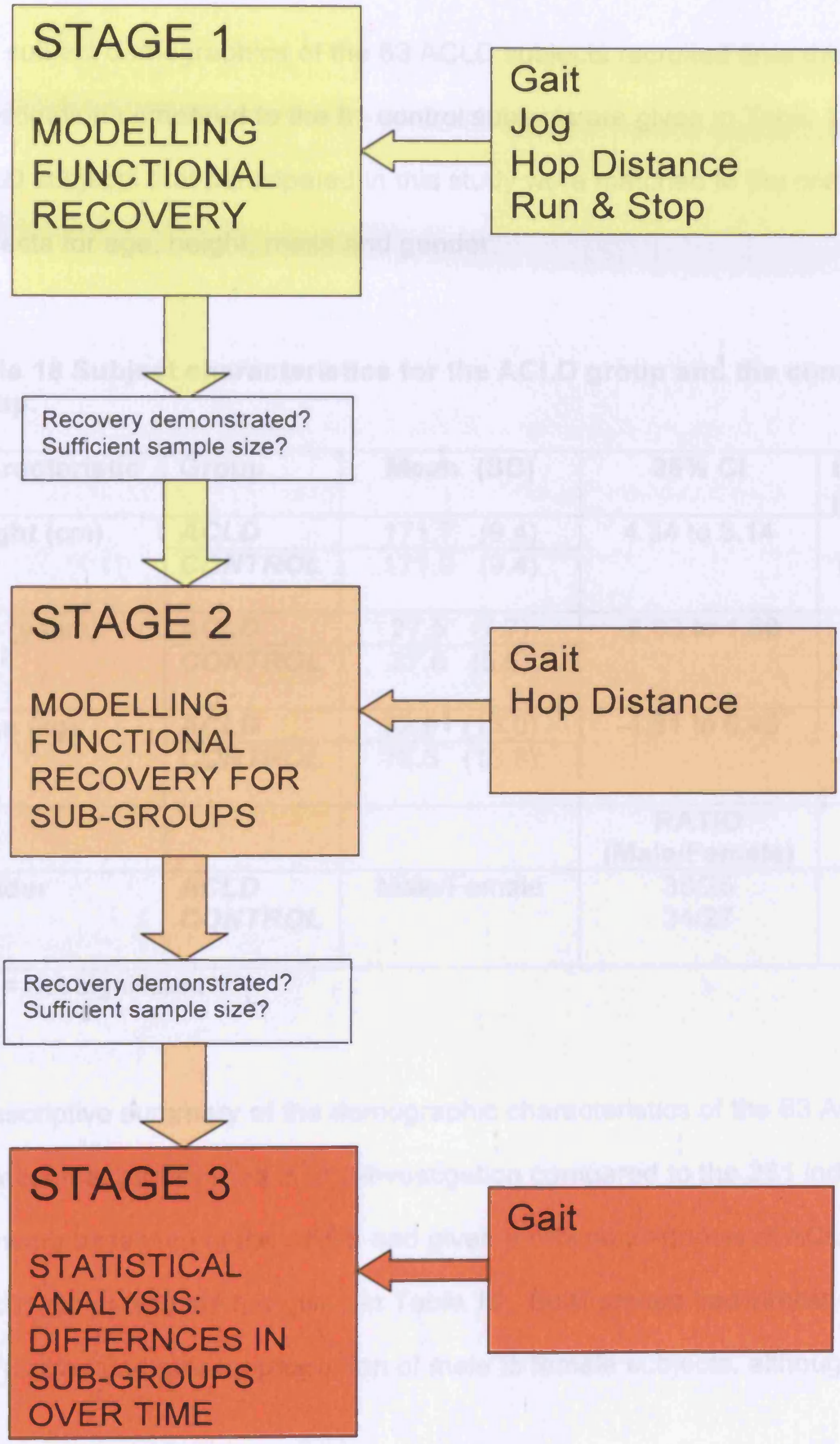
9. What form does this take and topics included?

10. What do you see as being your main role with these patients?

4.0 Results

This chapter is divided into two parts, the first part presents the results of part 1 of the study which aimed to measure and model changes of function over time starting from the time of acute rupture, generating information that could be used to guide rehabilitation. There were 3 progressive stages to the analysis but not all activities underwent all stages for the reasons detailed in chapter. The level of analysis for each activity is depicted in Figure 18. The second part of this results chapter presents the findings from part 2 of the study which aimed to evaluate the effectiveness on rehabilitation outcome of providing physiotherapists with movement feedback on patient performance.

Figure 18 Stages of the analysis evaluating functional recovery.



4.1 PART 1: Recovery of Function

4.2 Subjects

The subject demographics of the 63 ACLD subjects recruited onto this investigation compared to the 61 control subjects are given in Table 18. The ACLD subjects that participated in this study were matched to the control subjects for age, height, mass and gender.

Table 18 Subject characteristics for the ACLD group and the control group.

Characteristic	**Group**	**Mean (SD)**	**95% CI**	**t- value p-value**
Height (cm)	*ACLD*	171.7 (9.4)	4.34 to 3.14	-0.111 p=0.912 n.s.
	CONTROL	171.9 (9.4)		
Age (years)	*ACLD*	27.5 (7.7)	-2.83 to 1.88	-0.50 p=0.961 n.s.
	CONTROL	27.6 (5.6)		
Mass (kg)	*ACLD*	72.9 (13.0)	-4.81 to 6.45	0.128 p=0.899 n.s.
	CONTROL	72.5 (13.8)		
			RATIO (Male/Female)	
Gender	*ACLD* *CONTROL*	Male/Female	38/25 34/27	0.775 n.s.

n.s. = not significant

A descriptive summary of the demographic characteristics of the 63 ACLD subjects that participated in this investigation compared to the 281 individuals that were assessed in the AKSS and given a clinical diagnosis of ACL rupture but did not participate are given in Table 19. Both groups had similar ages, age ranges and greater proportion of male to female subjects, although the ratio of females to males was higher on the ACLD sample used in our investigation.

Table 19 Summary of patient characteristics for the ACLD sample (1) recruited and all ACLD subjects that attended the AKSS (2).

Characteristic	Group	Mean (SD)	Range	Ratio (Male/Female)
Age (years)	1 2	27.5 (7.7) 29.6 (9.2)	18 to 53 15 to 58	
Gender	1 2			38/25 170/44

At 12 months post injury the ACLD subjects were sub-grouped into functional copers, adapters and non-copers. The demographics of each sub-group are given in Table 20. There was no statistical difference between the sub-groups for age, height and mass. The coper group contained a relatively greater proportion of female subjects and individuals that participated in lower demand activities pre-injury. From the 42 subjects that were followed up at 12 months post injury, 17% were classified as copers, 45% as adapters and 38% as non copers. Overall only 5% of individual who participated in high demand activities pre-injury returned to them.

Table 20 Subject demographics for each of the ACLD sub-groups.

	Copers	**Adapters**	**Non-copers**	**F-value** **P value**
Age mean (yrs) (SD)	28.7 (8.0)	29.8 (8.5)	27.31 (6.74)	0.455 p=0.638 n.s.
Height mean (cm) (SD)	169.17 (12.73)	173.57 (7.2)	170.56 (10.29)	0.327 p=0.725 n.s.
Mass mean (kg) (SD)	71.33 (14.18)	72 (11.24)	71.78 (10.09)	0.05 p=0.995 n.s.
Gender	F(5) M(2)	F(6) M(13)	F(6) M(10)	
Number of subjects participating at each activity level pre-injury	Level 1= 2 Level 2= 1 Level 3= 4	Level 1= 17 Level 2= 0 Level 3= 3	Level 1= 12 Level 2= 2 Level 3= 2	
Total number of subjects	7	19	16	

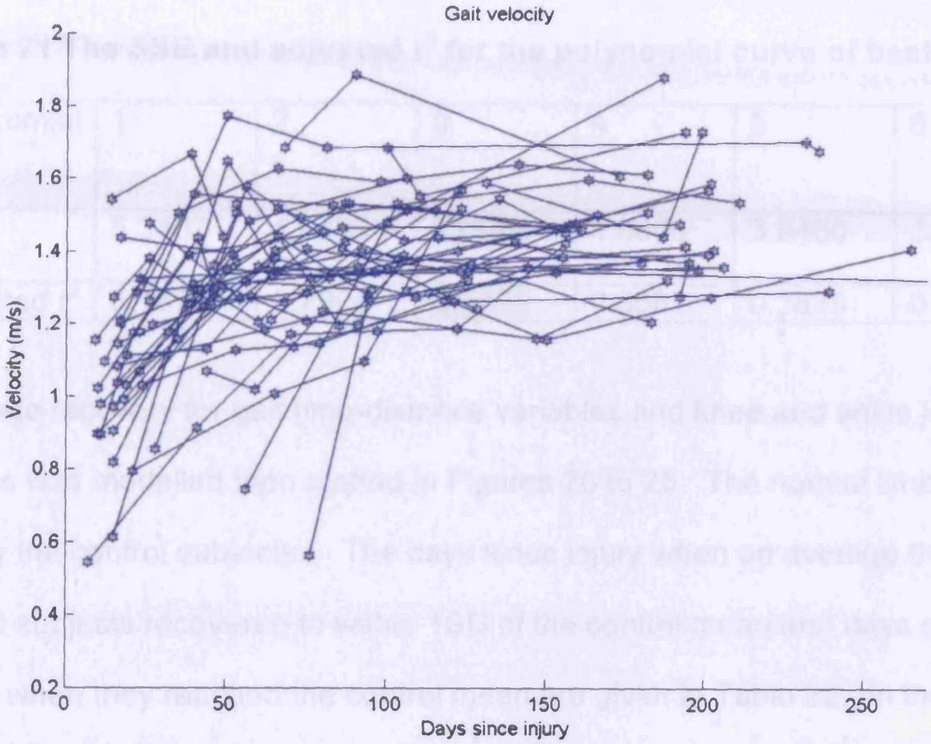
Pre-injury activity levels:

LEVEL 1= Contact sports with a high pivoting and jumping demand
LEVEL 2= Non contact sport with moderate pivoting and jumping demands
LEVEL 3= Non contact sport with low/no pivoting or jumping
n.s. = not significant

4.3 Recovery of gait: Stage 1

As an example to illustrate the large amount of data that was consistently collected over time to model functional recovery the gait velocity for each individual subject at each visit has been plotted in Figure 19, prior to fitting the curve of best fit. This figure demonstrates that although a general trend for recovery can be seen the volume of data obscures this relationship and supports the application of methods that can model this recovery into a curve of best fit.

Figure 19 Recovery over time of gait velocity for each individual ACLD patient.



Each data collection visit is represented as a star with a line joining individual visits.

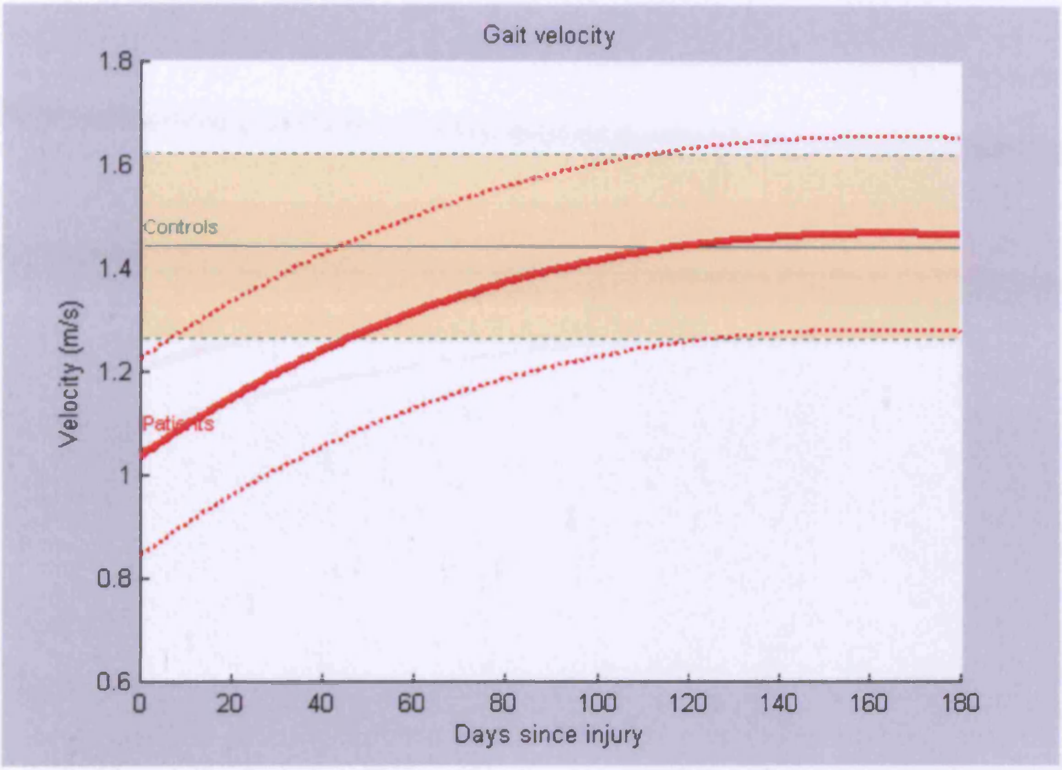
Goodness of fit for the curve was calculated using the SSE (sum of squares of the error) and adjusted r^2 for gait velocity. These are summarized in Table 21 for the different order of polynomials that could have been applied. The third order polynomial highlighted in yellow is the one that was finally used to model recovery. The biggest jump in r^2 was between the 1st and 2nd order polynomials, thereafter there was only small increases between the polynomials. Overall, this result indicates that the ability of time since injury to predict gait recovery is limited to about 32% indicating that more factors would have to be considered if a stepwise regression approach was used. This study did not set out to determine the relevant factors.

Table 21 The SSE and adjusted r^2 for the polynomial curve of best fit

Polynomial order	1	2	3	4	5	6
SSE	5.3407	4.6362	4.4075	4.0666	3.9460	3.9236
Adjusted r^2	0.1879	0.2900	0.3202	0.3682	0.3825	0.3815

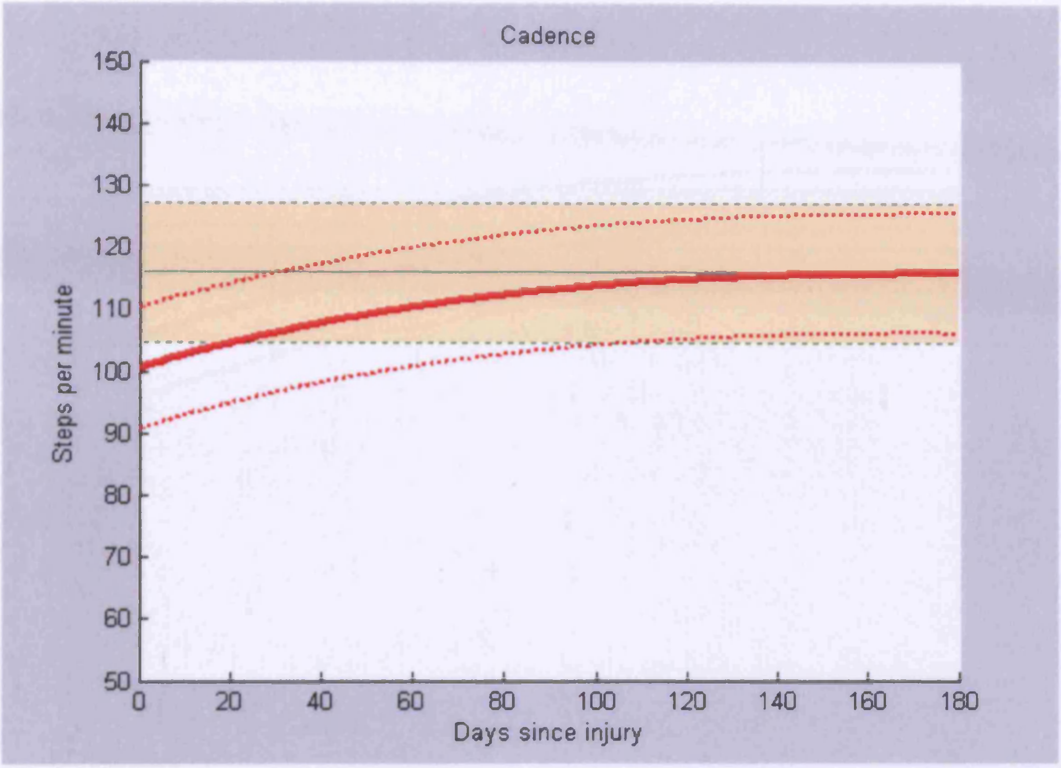
Average recovery for gait time-distance variables and knee and ankle joint angles was modelled then plotted in Figures 20 to 25. The normal limits are set by the control subjects. The days since injury when on average the ACLD subjects recovered to within 1SD of the control mean and days since injury when they reached the control mean are given in Table 22. In the early stage post injury ACLD subjects demonstrated greatest compensation strategies for the gait time-distance variables. Initially they walked with a slower velocity, lower cadence, shorter step lengths and increased step length asymmetry. Knee and ankle joint angles demonstrated less adaptation following ACL rupture and early recovery to within control limits but subjects tended to walk with increased knee flexion and the ankle less dorsi-flexed. For all the gait variables recovery was quickest early post injury and slowed over time. All of the variables recovered and reached a plateau at the control mean but not until between 60 to 145 days post injury.

Figure 20 Recovery over time of gait velocity.



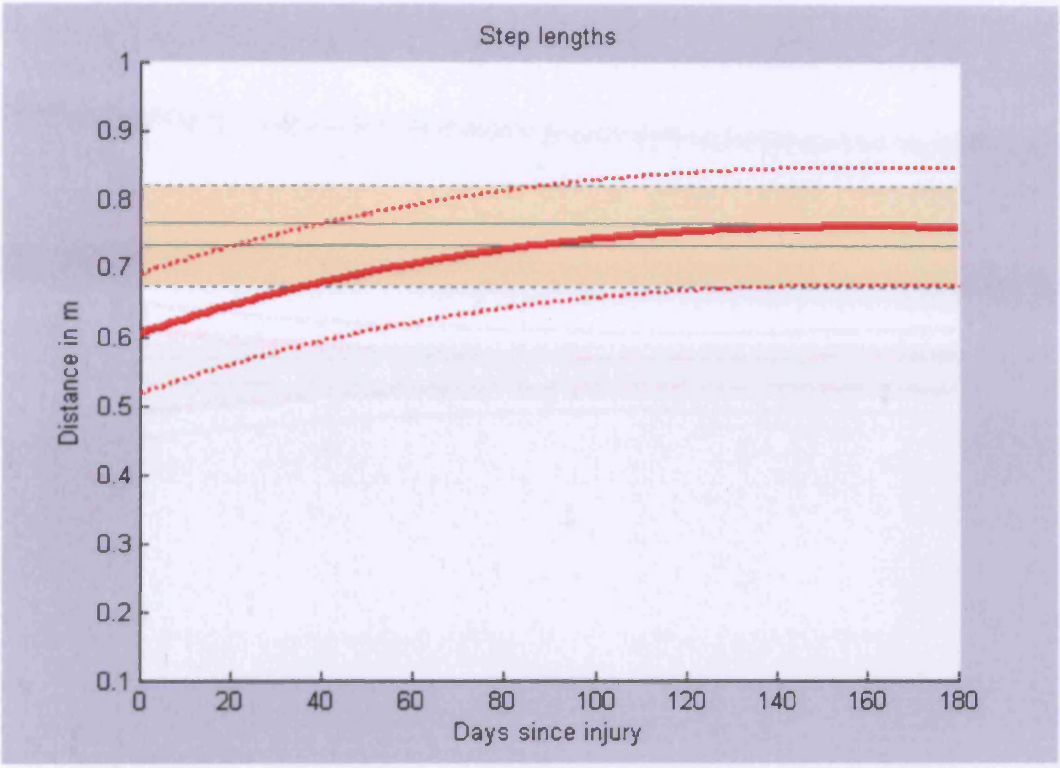
The ACLD group is indicated by the solid curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 21 Recovery over time of gait cadence.



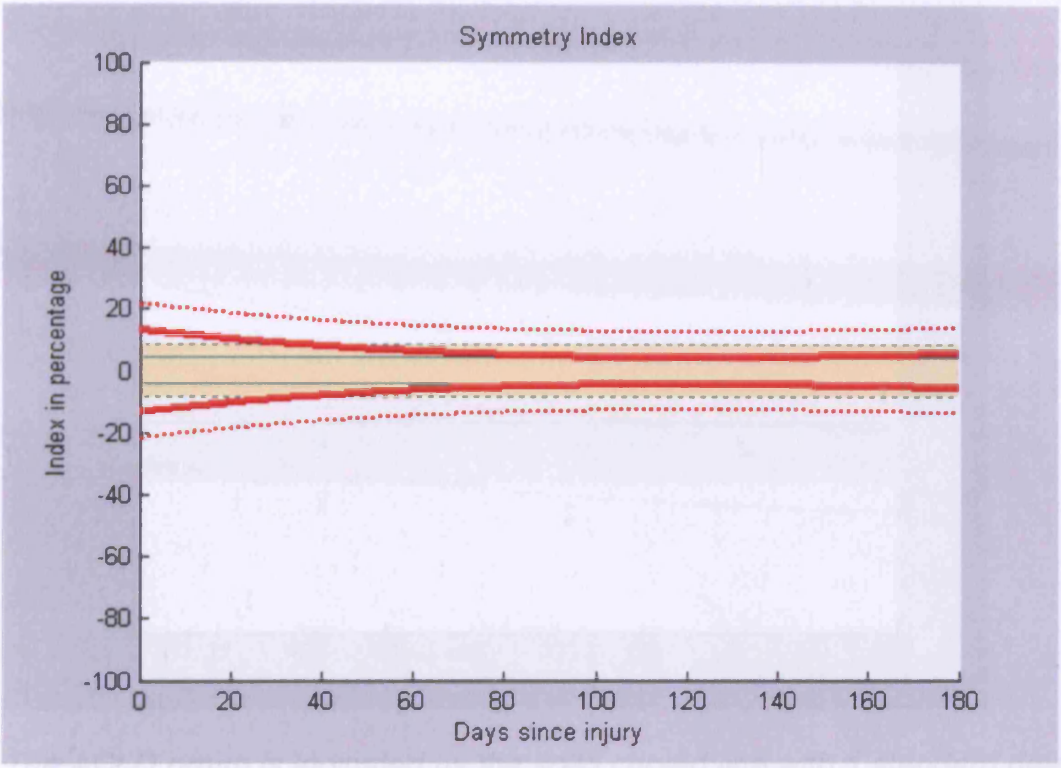
The ACLD group is indicated by the solid curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 22 Recovery over time of gait step lengths.



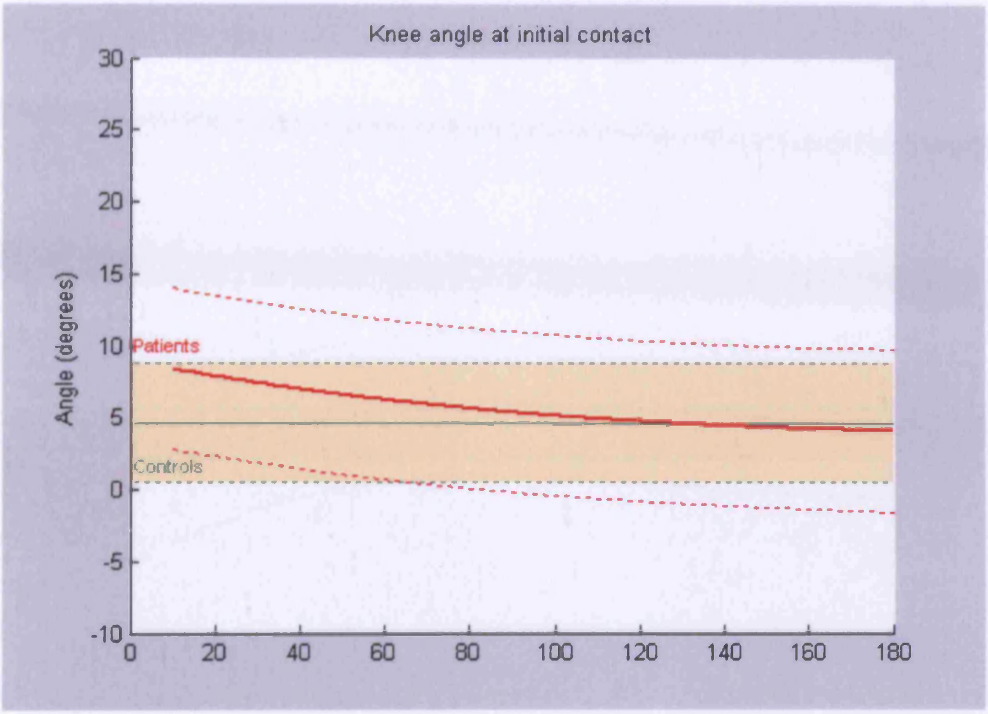
The ACLD group is indicated by the solid curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 23 Recovery over time of gait step length symmetry.



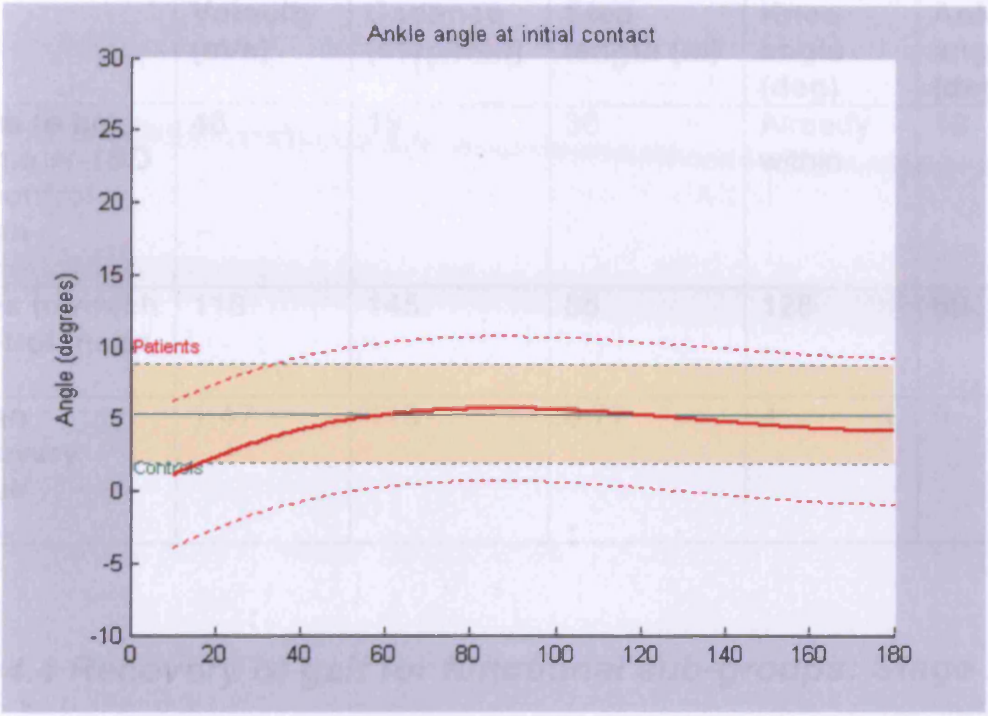
The ACLD group is indicated by the solid curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 24 Recovery over time of gait knee angle at heel strike.



The ACLD group is indicated by the solid curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 25 Recovery over time of gait ankle angle at heel strike.



The ACLD group is indicated by the solid curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

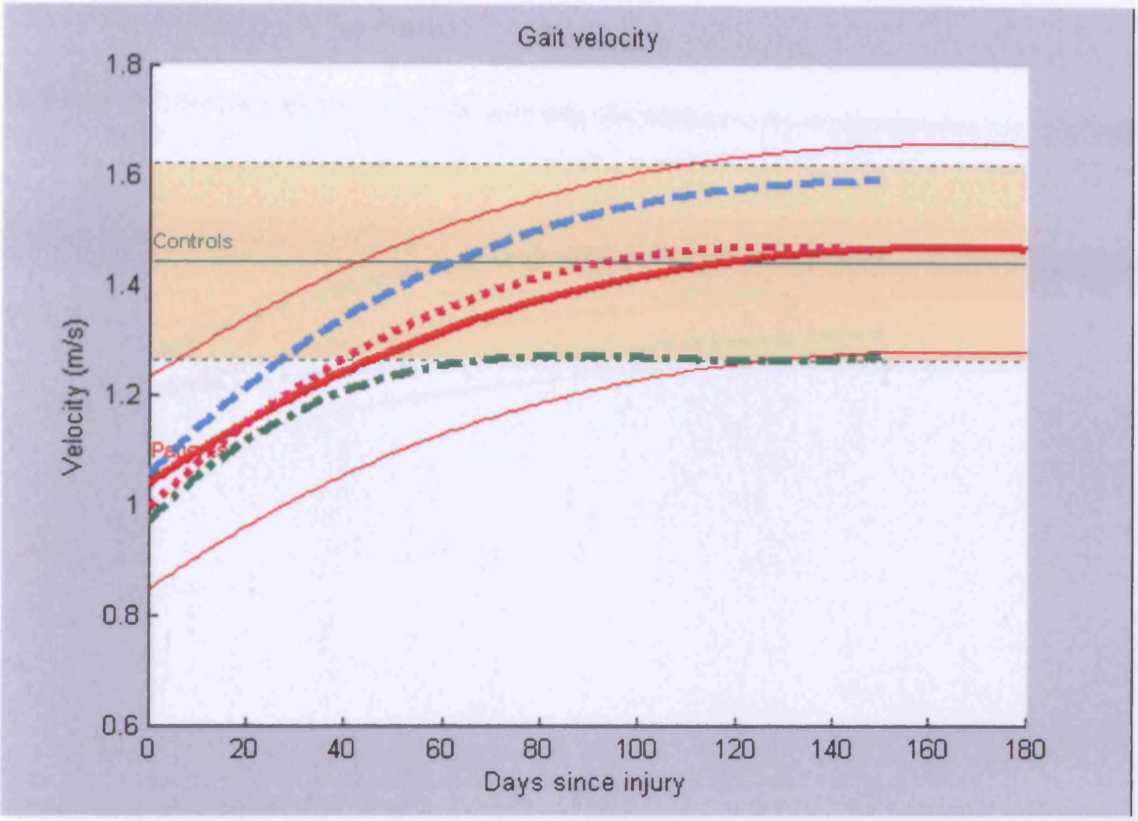
Table 22 A summary of average number of days for recovery and recovery values for ACLD subjects during gait.

	Velocity (m/s)	Cadence (step/min)	Step length (m)	Knee angle (deg)	Ankle angle (deg)	Step length symmetry (%)
Days to be within +/-1SD of control mean	46	19	36	Already within	18	30
Days to reach control mean	118	145	85	128	60	70
Mean recovery value	1.47	116	0.77	4	5	5

4.4 Recovery of gait for functional sub-groups: Stage 2

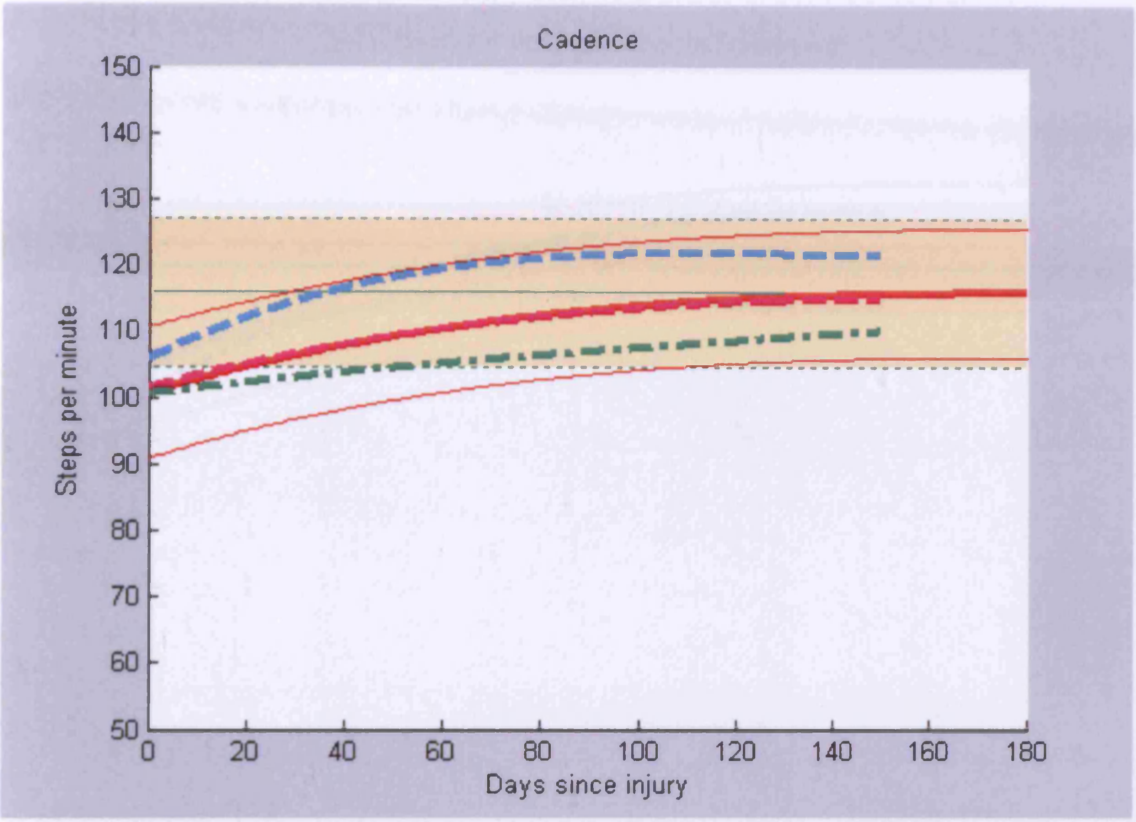
The recovery plots for gait velocity, cadence and step length with the curve of best fit for each of the sub-groups is given in Figures 26-29. Using descriptive interpretation of the graphs, for each of the gait variables the functional copers demonstrated the greatest rate and amount of recovery, reaching a plateau above the control mean but still within 1SD of the control mean. Functional adapters generally followed the recovery curve of all ACLD subjects before sub-classification and reached a plateau at the control mean. For velocity, cadence and step length copers and adapters had recovered to within 1SD of the control mean by 40 days post injury. Non-copers demonstrated a slower rate of recovery that did not reach the control mean for cadence. Even worse recovery was demonstrated for velocity and step length as their performance reached a plateau and finally fluctuated at the lower border of 1SD of the control mean. Non-copers did not return to the control mean for any of the gait variables and took 70 days before the 3 variables had returned to within 1SD control mean. The recovery in days and gait values for each of these variables is given in Table 23. The recovery curve for knee angle at heel strike is given in Figure 29. This is different to the other curves because the copers/adapters have been combined due to the amount of patient data available. Because of this these curves will need to be interpreted with a lot of caution. The non-copers appear to return within normal limits by 20 days post injury but did not demonstrate a recovery back to the control mean in these data. Copers/adapters initially seemed to performed worse, quickly recovered back to within 'normal limits' and reached the control mean by 95 days post injury. It appears they were unable to maintain this in the curve, as the knee angle deteriorated back to the same level as the non-copers but this effect could be due to the polynomial fit with limited data. Overall both groups appeared to walk with increased knee flexion at heel strike.

Figure 26 Recovery of gait velocity over time for the three functional subgroups and the average recovery of all the ACLD subjects.



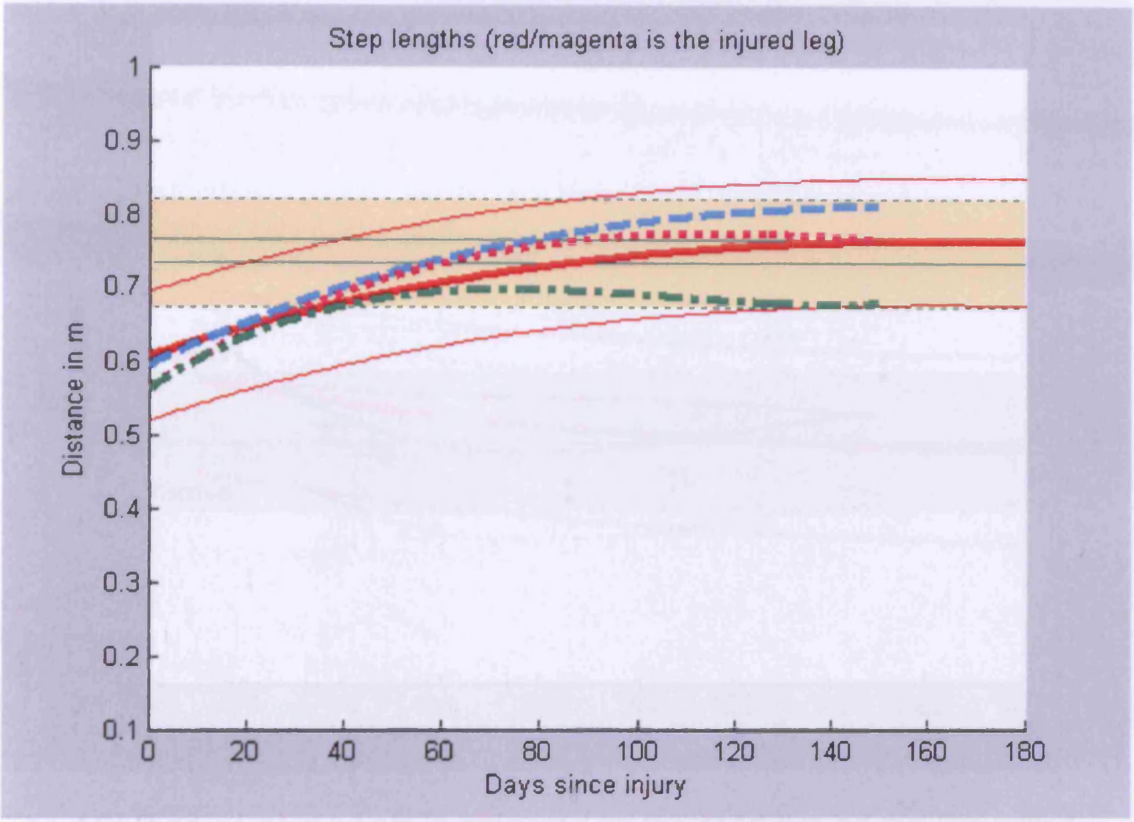
The ACLD group as a whole is indicated by the solid curved line with 1 standard deviation indicated by the thinner solid lines. ACL copers are indicated by the blue dashed line; adapters by the pink dotted line and non-copers by the green dot dashed line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 27 Recovery of gait cadence over time for the three functional subgroups and the average recovery of all the ACLD subjects.



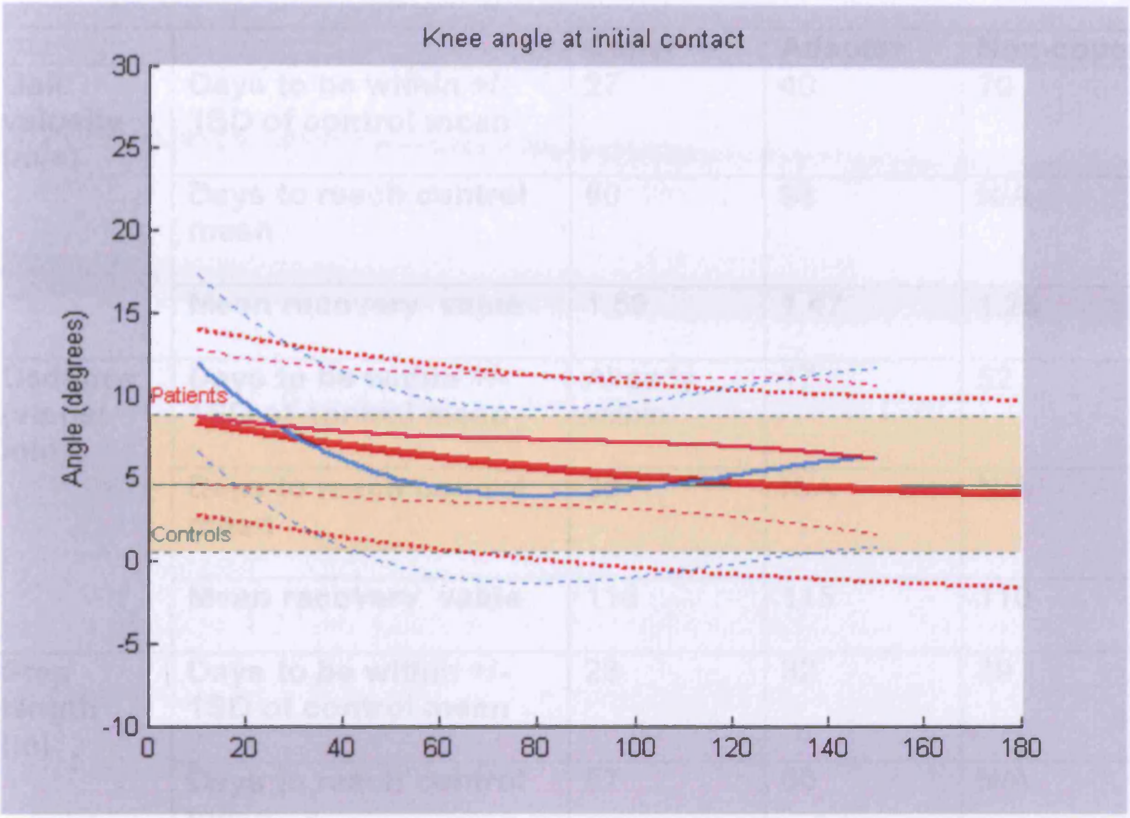
The ACLD group as a whole is indicated by the solid curved line with 1 standard deviation indicated by the thinner solid lines. ACL copers are indicated by the blue dashed line; adapters by the pink dotted line and non-copers by the green dot dashed line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 28 Recovery of gait step length over time for the three functional subgroups and the average recovery of all the ACLD subjects.



The ACLD group as a whole is indicated by the solid curved red line with 1 standard deviation indicated by the thinner solid red lines. ACL copers are indicated by the blue dashed line; adapters by the pink dotted line and non-copers by the green dot dashed line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 29 Recovery of knee angles for ACL sub-groups; copers /adapters (blue), non-copers (pink)



The ACLD group as a whole is indicated by the solid curved red line with 1 standard deviation indicated by the thin dotted red lines. ACL copers/adapters are indicated by the blue line and non-copers by the pink line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band. Note that there are reservations about the quality of the fitted lines because of limited data.

Table 23 A summary of number of days for recovery and maximum values for ACLD subgroups during gait.

		Coper	**Adapter**	**Non-coper**
Gait velocity (m/s)	**Days to be within +/- 1SD of control mean**	27	40	70
	Days to reach control mean	60	93	N/A
	Mean recovery value	1.59	1.47	1.25
Cadence (steps/ min)	**Days to be within +/- 1SD of control mean**	Already within	17	52
	Days to reach control mean	36	N/A	N/A
	Mean recovery value	116	115	110
Step length (m)	**Days to be within +/- 1SD of control mean**	28	32	39
	Days to reach control mean	57	60	N/A
	Mean recovery value	0.81	0.77	0.69
Knee angle at heel strike (degrees)	**Days to be within +/- 1SD of control mean**	36		Already within
	Days to reach control mean	95		N/A
	Mean recovery value	7		7

N/A = did not reach control mean

4.5 Recovery of gait for functional sub-groups: Stage 3

In this post-hoc analysis, a subset of the patients whose data had been used to plot the functional recovery of the sub-groups in part 2 were used to statistically compare differences in recovery between copers/adapters and non-copers over time. To be included in this stage of the analysis individuals had to have data collected at 1 and 4 months post injury. The demographic characteristics of the patients and controls are given in Table 24. There was no statistical difference between the groups for age, height, mass or gender. Descriptively both groups had a similar number of physiotherapy sessions, clinical symptoms recovered at a similar time and they had a similar mix of ACL ruptures combined with meniscal tears and collateral ligament sprains. The copers and adapters had to be pooled due to insufficient numbers in the coper group. From a rehabilitation standpoint within the National Health Service (NHS) this is justified because these patients are able to function well at ADL and low demand sports whilst waiting for surgery. It is the non-copers who are at high risk of creating further long term damage to the knee due to the repeated episodes of giving way. Therefore knowledge of their compensation strategies is most needed to guide rehabilitation and help them adapt in the short term.

Table 24 Demographic and clinical data for the ACL sub-groups.

Variable	Copers/ adapters	Non-copers	Controls	F value p-value
AGE (years) mean (SD)	30.6 (9.9)	27.5 (7.2)	27.6 (5.6)	0.628 p=0.543 n.s.
HEIGHT (cm) mean (SD)	170.02 (11.0)	171.96 (9.7)	171.91 (9.4)	0.109 p=0.897 n.s
MASS (kg) mean (SD)	73.5 (13)	70.7 (10.3)	72.3 (13.8)	0.082 p=0.921 n.s
				***x*2 value p-value**
GENDER	F=6 M=9	F=5 M=8	F=27 M=37	0.74 p=0.963 n.s
Injury type: ACL+/-MCL ACL+meniscus +/- MCL	 11 4	 9 4		
Days from injury to full range of motion and no swelling	88	86		
Number of physiotherapy sessions	10.5	9.2		
Pre-injury activities: Pivoting sports Non-pivoting sport	 11 4	 11 2		

Regardless of sub-group all ACLD subjects demonstrated a recovery of increased velocity, cadence and step length for the time-distance variables between 1 ad 4 months post injury. For the joint angles over time all ACLD subjects demonstrated significantly increased non-injured ankle dorsi-flexion and a trend for this in the injured ankle at heel strike. The injured knee became less flexed at heel strike and the injured and non-injured HDA increased by 4 months post injury. All of these results are summarized in Table 25.

Table 25 Gait differences over time (regardless of group).

Variable	Time 1 Mean (SD)	Time 2 Mean (SD)	F value	Significance value
Gait velocity (m/s)	1.07 (0.23)	1.42 (0.16)	74.74	p< 0.001**
Cadence (steps/min)	103 (8.77)	115 (10.72)	53.27	p< 0.001**
Step length injured leg (m)	0.62 (0.10)	0.73 (0.07)	29.70	p< 0.001**
Step length non-injured leg (m)	0.66 (0.16)	0.75 (0.07)	20.01	p<0.015*
Ankle angle injured leg (degrees)	0.98 (6.09)	5.11 (5.35)	4.14	p=0.052 n.s.
Ankle angle non-injured leg (degrees)	3.38 (4.40)	7.14 (4.03)	18.37	p< 0.001**
Injured knee angle (degrees)	10.52 (6.0)	4.27 (4.64)	25.32	p< 0.001**
Non-injured knee angle (degrees)	2.96 (2.64)	3.86 (3.77)	1.27	p=0.270 n.s.
Hip displacement angle injured leg (degrees)	42.57 (5.65)	46.70 (9.87)	4.46	p=0.045*
Hip displacement angle non-injured leg (degrees)	34.52 (7.11)	44.82 (7.16)	77.40	p< 0.001**

*significant (p<0.05); ** highly significant (p<0.01); n.s. = not significant

In the same analysis a comparison was also made between copers/adapters and non-copers over time (interaction). There were statistically significant differences in the gait pattern between ACLD copers/adapters and non-copers over time. Gait variables that demonstrated a slower rate of recovery in non-copers are summarised in Figures 30-34, Table 26. The gait of the non-copers was distinguishable from that of the copers/adapters over time due to a slower velocity, lower cadence and shorter step length (non-injured leg). For non-copers at HS the knee was significantly more flexed and the non-injured leg HDA was smaller.

Figure 30 Mean velocity and standard deviations for ACLD sub-groups at both visits. The interaction was significant ($F_{1,1}$ =10.89 p=0.003).

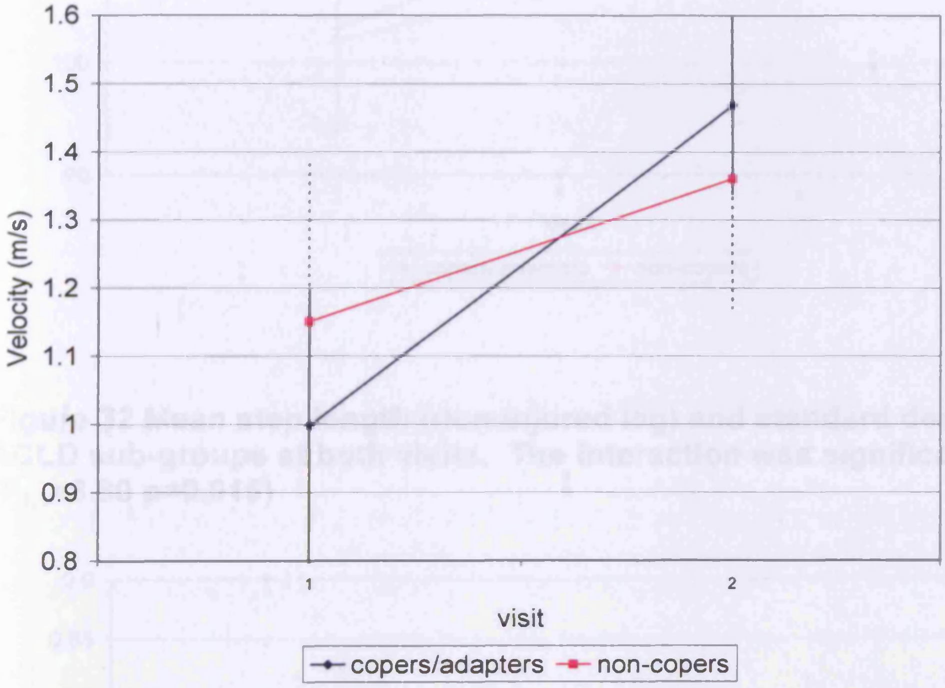


Figure 31 Mean cadence and standard deviations for ACLD sub-groups at both visits. The interaction was significant ($F_{1,1}$ =5.85 p=0.023).

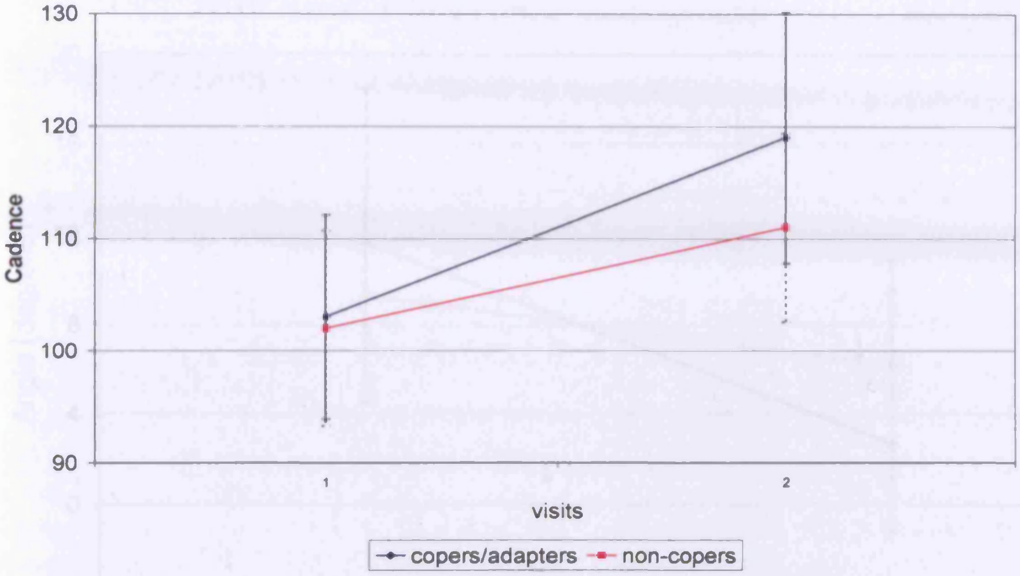


Figure 32 Mean step length (non-injured leg) and standard deviations for ACLD sub-groups at both visits. The interaction was significant ($F_{1,1}$=6.80 p=0.015)

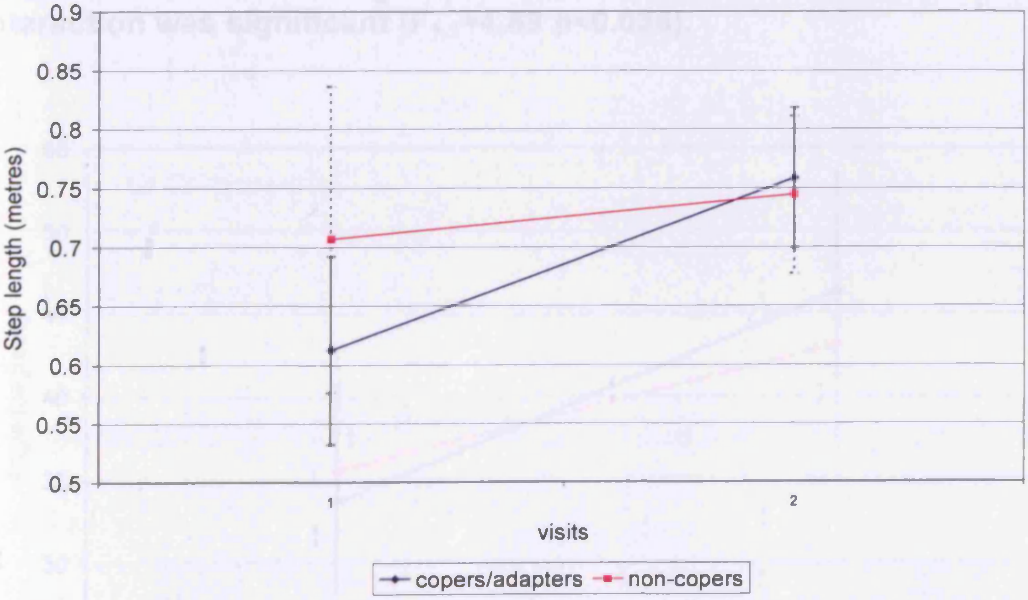


Figure 33 Mean injured knee angles and standard deviations for ACLD sub-groups at initial contact for both visits The interaction was significant ($F_{1,1}$=5.79 p<0.024).

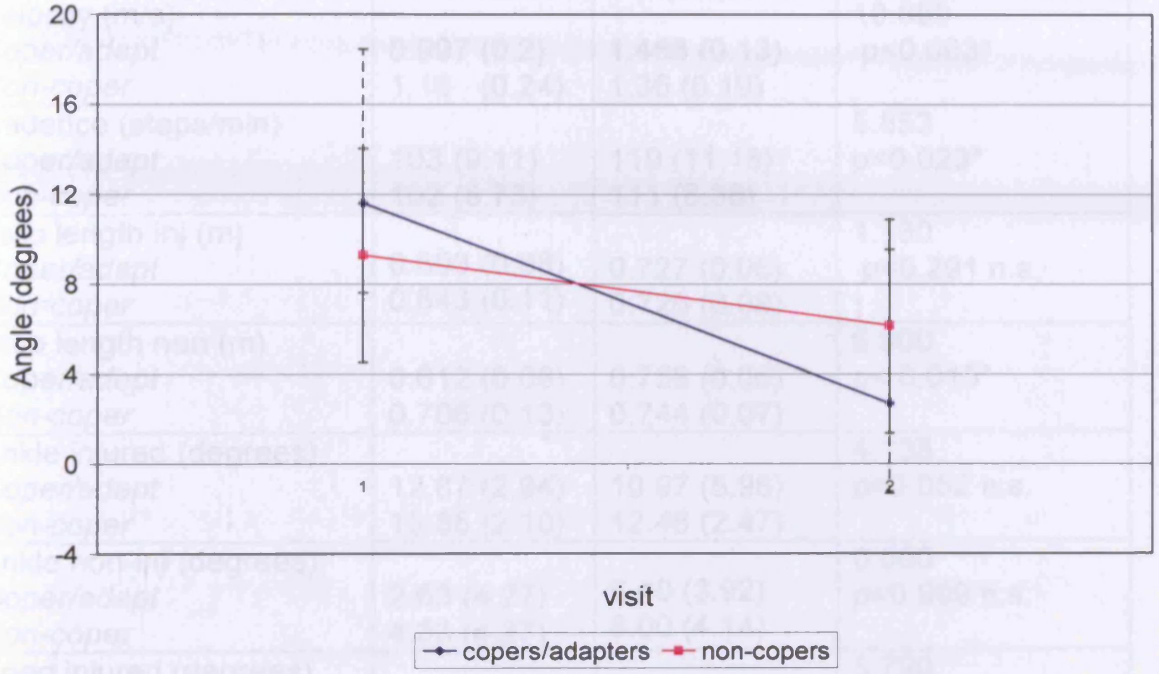


Figure 34 Mean non-injured hip displacement angles and standard deviations for ACLD sub-groups at initial contact for both visits. The interaction was significant ($F_{1,1}$=4.89 p<0.036).

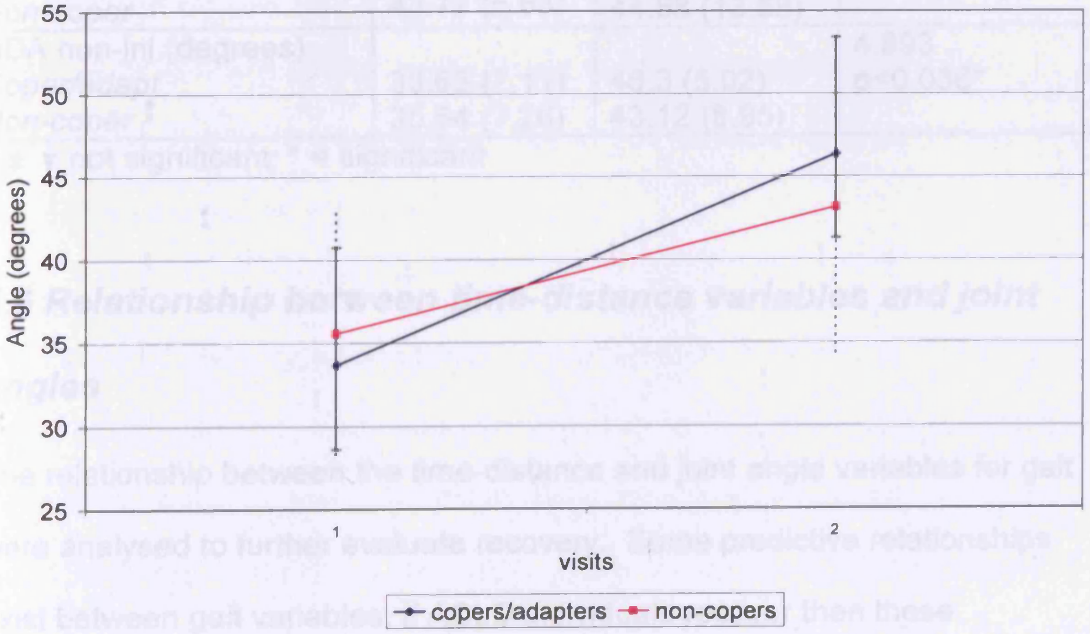


Table 26 Summary of gait variables for copers/adapters and non-copers over time.

Variable	Time 1 Mean (SD)	Time 2 Mean (SD)	F (significance)
Velocity (m/s)			10.889
Coper/adapt	0.997 (0.2)	1.468 (0.13)	p<0.003*
Non-coper	1.15 (0.24)	1.36 (0.19)	
Cadence (steps/min)			5.853
Coper/adapt	103 (9.11)	119 (11.18)	p<0.023*
Non-coper	102 (8.73)	111 (8.38)	
Step length inj (m)			1.160
Coper/adapt	0.603 (0.08)	0.727 (0.06)	p=0.291 n.s.
Non-coper	0.643 (0.11)	0.726 (0.08)	
Step length non (m)			6.800
Coper/adapt	0.612 (0.08)	0.758 (0.06)	p< 0.015*
Non-coper	0.706 (0.13)	0.744 (0.07)	
Ankle injured (degrees)			4.138
Coper/adapt	12.87 (2.94)	10.97 (5.96)	p=0.052 n.s.
Non-coper	13.85 (2.10)	12.46 (2.47)	
Ankle non-inj (degrees)			0.000
Coper/adapt	2.63 (4.27)	6.40 (3.92)	p=0.999 n.s.
Non-coper	4.33 (4.27)	8.00 (4.14)	
Knee injured (degrees)			5.790
Coper/adapt	11.6 (2.94)	2.67 (5.96)	p=0.024 n.s
Non-coper	9.27 (2.1)	6.12 (2.47)	
Knee non-inj (degrees)			0.058
Coper/adapt	2.47 (2.74)	3.53 (3.75)	p=0.812 n.s
Non-coper	3.54 (2.50)	4.23 (3.91)	
HDA injured (degrees)			2.284
Coper/adapt	41.53 (5.48)	48.27 (4.90)	p=0.143 n.s
Non-coper	43.77 (5.83)	44.88 (13.58)	
HDA non-inj (degrees)			4.893
Coper/adapt	33.63 (7.11)	46.3 (5.02)	p<0.036*
Non-coper	35.54 (7.26)	43.12 (8.95)	

n.s. = not significant; * = significant

4.6 Relationship between time-distance variables and joint angles

The relationship between the time-distance and joint angle variables for gait were analysed to further evaluate recovery. Some predictive relationships exist between gait variables, if ACLD individuals recover then these relationships should be re-established. The healthy control subjects demonstrated a very high correlation between gait velocity and cadence ($r=0.83$ $p<0.0001$). There was a high correlation between gait velocity and step length for the left and right leg ($r=0.67$ $p<0.0001$; $r=0.64$ $p<0.0001$).

In the first month post injury all ACLD subjects demonstrated that gait velocity was highly correlated to injured leg step length ($r=0.78$ $p<0.0001$), closely followed by non-injured step length ($r=0.76$ $p<0.0001$) and moderately correlated to cadence ($r=0.57$ $p<0.001$).

At 4 months post injury the ACLD non-copers continued to demonstrate a high significant correlation between gait velocity and injured leg step length ($r=0.88$ $p<0.0001$), non-injured leg step length ($r=0.83$ $p<0.0001$) and also cadence ($r=0.73$ $p=0.005$). A high correlation existed between non-injured leg HDA and gait velocity ($r=0.75$ $p=0.003$), a high correlation with step length (non-injured $r=0.681$ $p=0.010$ and injured $r=0.66$ $p=0.015$) and no relationship with cadence ($r=0.53$ $p=0.062$). Injured knee joint angle did not correlate significantly with any of the time-distance variables (cadence $r= -0.28$ $p=0.355$, velocity $r= -0.34$ $p=0.262$, step length non-injured $r= -0.33$ $p=0.265$, step length injured $r= -0.28$ $p=0.349$).

The ACLD coper/adapter sub-group demonstrated a significant moderate correlation between velocity and cadence ($r=0.59$ $p=0.020$). The correlations between step length and gait velocity were not significant (injured: $r=0.39$, $p=0.15$; non-injured: $r=0.38$, $p=0.167$). A high negative correlation existed between cadence and non-injured HDA (r=-0.67 p=0.006) and a moderate positive correlation between non-injured HDA and step length (injured r=0.52 p=0.046; non-injured r=0.58 p=0.023). There was no correlation between non-injured HDA and gait velocity (r=-0.17 p=0.550). Injured knee joint angle did not correlate significantly with any of the time-distance variables (cadence r=0.13 p=0.652, velocity r=0.19 p=0.507, step length non-injured r=0.14 p= 0.616, step length injured r=0.03 p=0.925). These correlations are summarised in Table 27.

In summary for the healthy controls there was a high correlation between gait velocity and cadence and velocity and step length. These same relationships were not found for the group of ACLD individuals at 1 month post injury or the non-copers and copers/adapters at 4 months post injury. At 1 month post injury ACLD subjects walked with a high correlation with step length and only a moderate correlation with cadence, indicating a greater dependence on step length to alter gait velocity. At 4 months the non-copers had re-established high correlations between the time-distance variables and HDA. Copers/adapters at 4 months demonstrated greatest disturbance in correlations between time-distance variables and joint angles and time-distance variables. They demonstrated a strategy of depending on cadence to alter gait velocity, this was also reflected in the lack of relationship between HDA and gait velocity. For both the non-copers and copers/adapters knee joint angle did not influence the resulting time-distance gait pattern.

Table 27 Correlations between time distance variables for controls and ACLD sub-groups at 4 months post injury and kinematics and time distance variables for the ACLD sub-groups

	Velocity	Cadence	step length injured side	step length non-injured side
Velocity				
Non-copers		r=0.73 p=0.005*	r=0.88 p<0.0001*	r=0.83 p<0.0001*
Copers/adapters		r=0.59 p=0.020*	r=0.39, p=0.15 n.s.	r=0.38, p=0.167 n.s.
Controls		r=0.83 p<0.0001*	r=0.67 p<0.0001*	r=0.64 p<0.0001*
Knee injured leg				
Non-copers	r= -0.34 p=0.262 n.s.	r= -0.28 p=0.355 n.s.	r= -0.28 p=0.349 n.s.	r=0.14 p= 0.616 n.s.
Copers/adapters	r=0.19 p=0.507 n.s.	r=0.13 p=0.652 n.s.	r=0.03 p=0.925 n.s.	r=0.14 p= 0.616 n.s.
HDA non-inj leg				
Non-copers	r=0.75 p=0.003*	r=0.53 p=0.062 n.s.	r=0.681 p=0.01*	r=0.66 p=0.015*
Copers/adapters	r=-0.17 p=0.550 n.s.	r=-0.67 p=0.006*	r=0.52 p=0.046*	r=0.58 p=0.023*

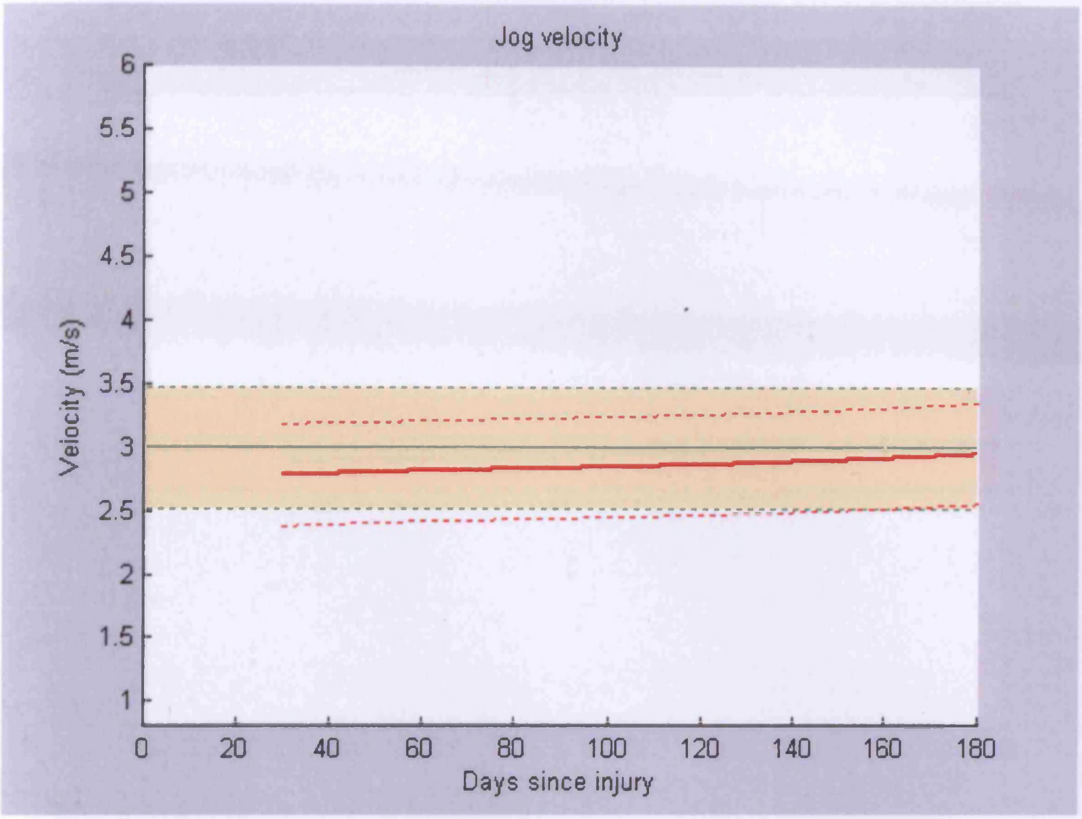
* = significant; n.s.= not significant

In summary gait demonstrated marked time-distance compensation strategies initially post injury that over time recovered back to the uninjured control mean. When individuals were sub-classified into copers, adapters and non-copers distinct differences in their recovery were modelled. For the time-distance variables the copers and adapters recovered back to within normal limits set by the control subject's by 40 days post injury and plateaued at or above the control mean. Non-copers demonstrated a borderline recovery only just reaching the lower boundary of the 1SD normal limits set by the uninjured controls. This was explored statistically on a sub-group of copers, adapters and non-copers that had gait data at 1 and 4 months post injury. This confirmed that non-copers continued to walk at 4 months with reduced velocity, lower cadence, shorter step lengths, reduced HDA and increased knee flexion. Altered correlations between gait variables at 4 months demonstrated that although coper/adapters demonstrated the greater gait recovery, they were not fully recovered because they still demonstrated altered relationships between these variables. Gait is ideally suited as an outcome measure during rehabilitation because it gives a lot of detail of change over time; it is possible to evaluate recovery based on ACLD performance criteria compared to controls (performing within 1SD of controls and recovery to control mean), it is an activity that is applicable to all individuals and can be performed and evaluated from very early post injury. In addition it also has the potential to distinguish between sub-groups of individuals with good and poor recovery.

4.7 Recovery of Jogging: Stage 1

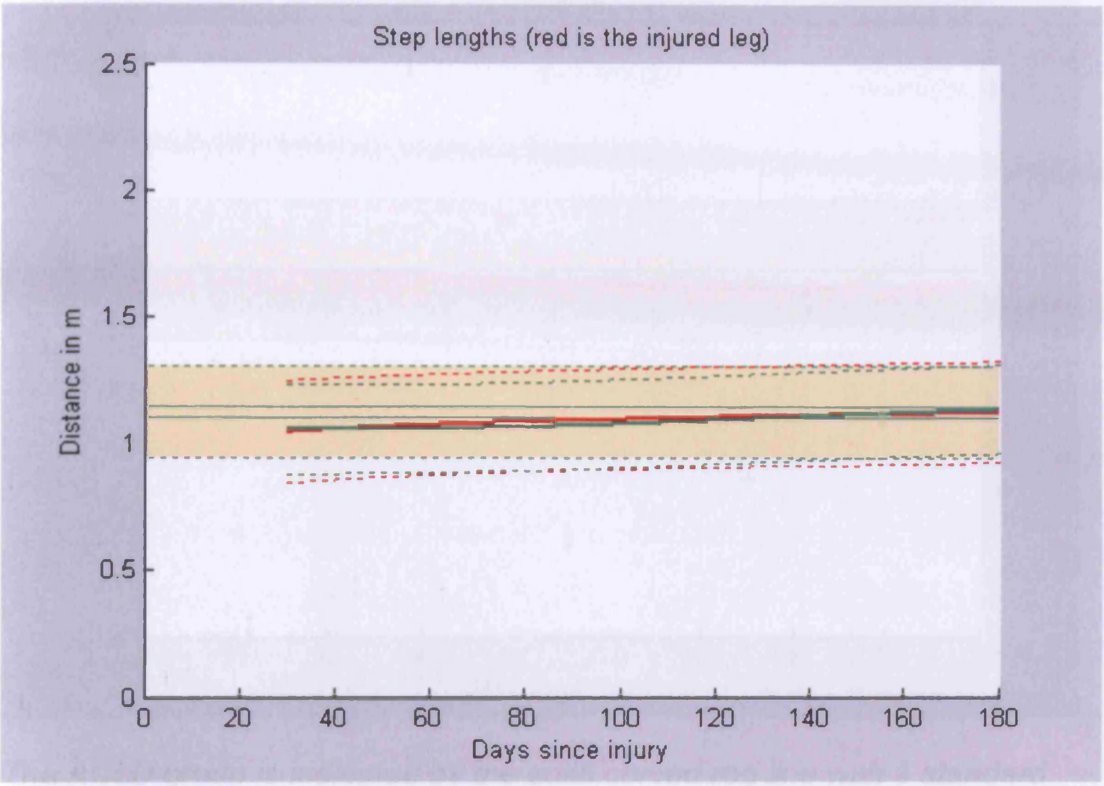
Initially post injury individuals were unable to jog due to pain, effusion and loss of ROM so measurement did not begin until 30 days post injury. The curve of best fit was applied to the pooled data of 43 individuals that had a minimum of 2 jog measurement over time. Very little recovery was demonstrated for the jogging variables. Once ACLD subjects started jogging at 30 days post injury they were already within 1SD of the control mean. Jogging velocity almost recovered to the control mean by 180 days post injury (see Figure 35). Recovery of step length demonstrated a similar pattern but recovered to the control mean earlier at 90 days post injury (see Figure 36). Jogging cadence demonstrated the most variable pattern; this started at the control mean but with time demonstrated some deterioration although it consistently remained within 1SD of the control mean (see Figure 37). No further analysis was undertaken for jogging because very little recovery of the variables was demonstrated over time; once individuals were considered safe to jog they were able to do so with minor adaptations for jogging time-distance variables.

Figure 35 Recovery curve for jogging velocity



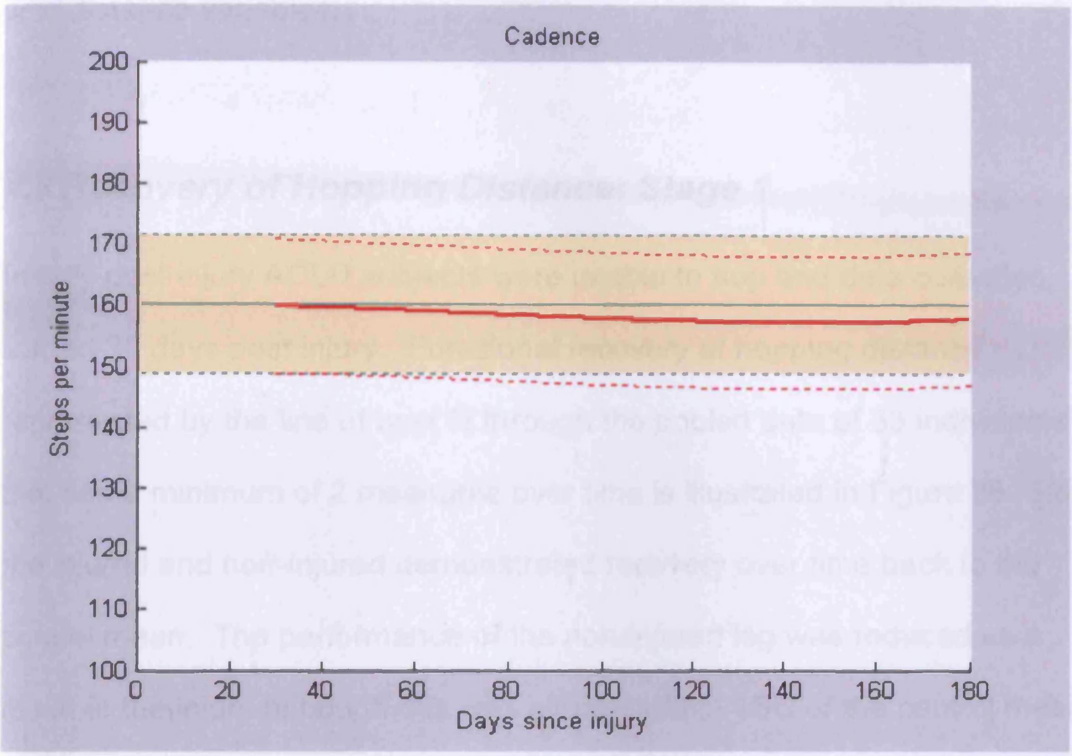
The ACLD group is indicated by the red solid curved line with 1 standard deviation indicated by the red dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 36 Recovery of jogging step length



The ACLD group injured leg is indicated by the solid red curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 37 Recovery of jogging cadence



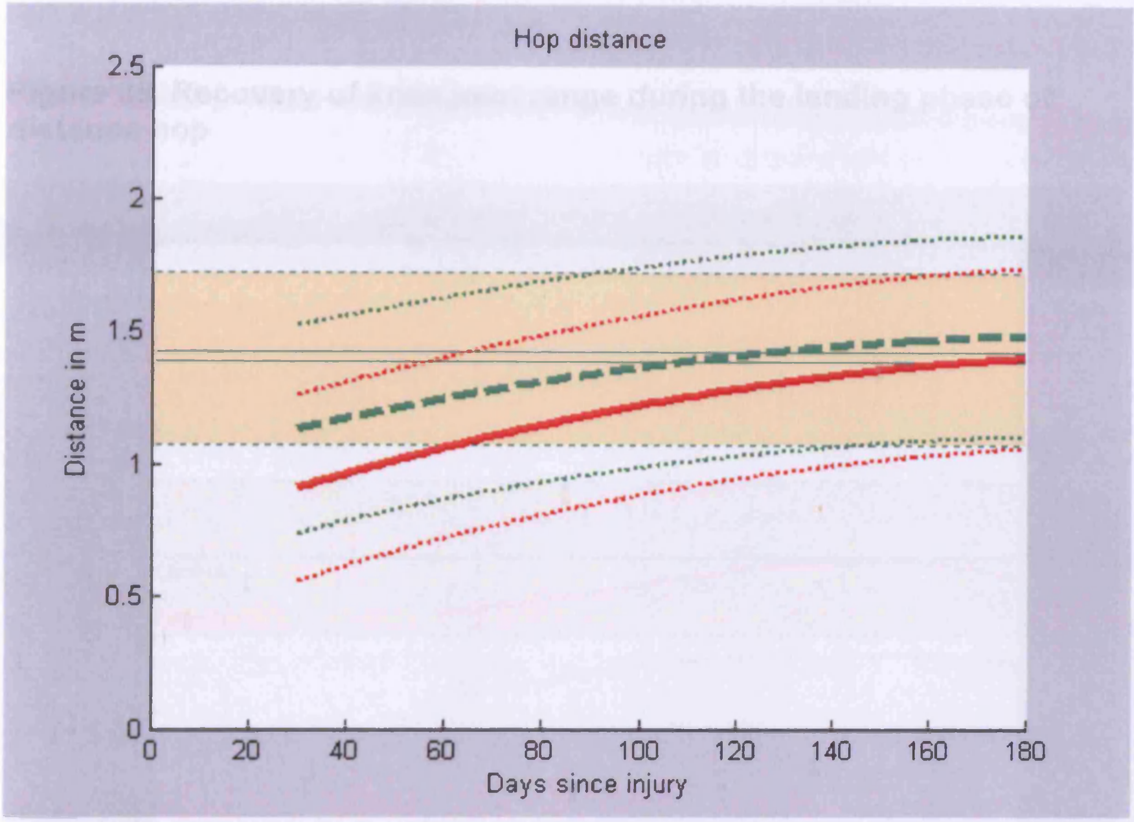
The ACLD group is indicated by the solid curved red line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

In summary for jogging time-distance variables ACLD subjects did recover to a similar level as uninjured controls. The strengths of this activity as a rehabilitation outcome measure are that it can be performed by the majority of ACLD individuals from early in rehabilitation but unlike gait it did not demonstrate any recovery detail so is not a useful guide to rehabilitation. Once ACLD subjects were considered safe to jog they were already within the normal limits of controls and performing very close to the control mean. This also suggests that the recovery criterion of 1SD does not apply to jogging time-distance variables.

4.8 Recovery of Hopping Distance: Stage 1

Initially post injury ACLD subjects were unable to hop and data collection started 30 days post injury. Functional recovery of hopping distance represented by the line of best fit through the pooled data of 33 individuals that had a minimum of 2 measures over time is illustrated in Figure 38. Both the injured and non-injured demonstrated recovery over time back to the control mean. The performance of the non-injured leg was reduced as a result of the injury although this was already within 1SD of the control mean at 30 days post injury and recovered more rapidly than the injured leg, recovering to the control mean by 100 days post injury. The injured leg recovered to within 1SD of the control mean by 62 days post injury and started to plateau at the control mean by 166 days post injury.

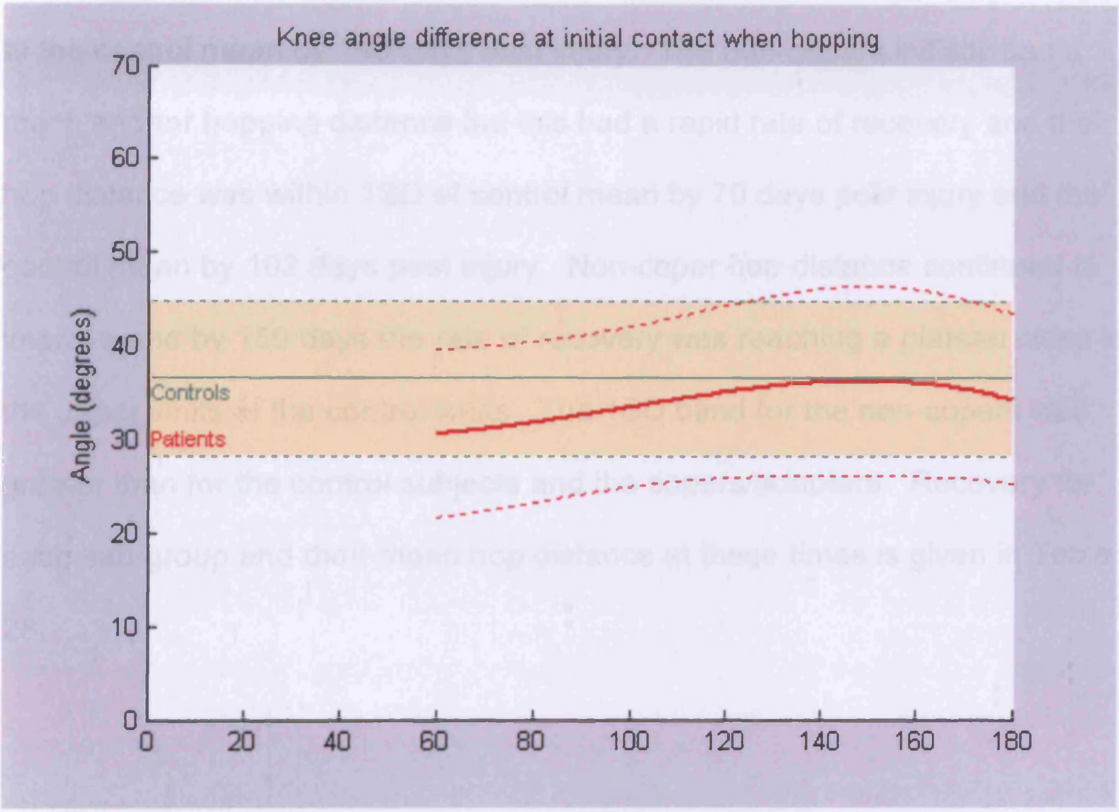
Figure 38 Recovery of hopping distance for the ACLD group injured and uninjured legs



The ACLD group injured leg is indicated by the solid red curved line and the uninjured leg by the green dashed line, with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

The recovery of knee range during the landing phase of distance hop is plotted in Figure 39. By 60 days post injury the knee angle has already recovered to within 1SD control mean and reaches the control mean at 135 days post injury but appears to start to decline again after this time. The analysis of distance hop was progressed to stage 2 because a sufficient number of subjects had been recorded performing this activity and the hop distance variable demonstrated a distinct recovery curve over time to inform rehabilitation.

Figure 39 Recovery of knee joint range during the landing phase of distance hop

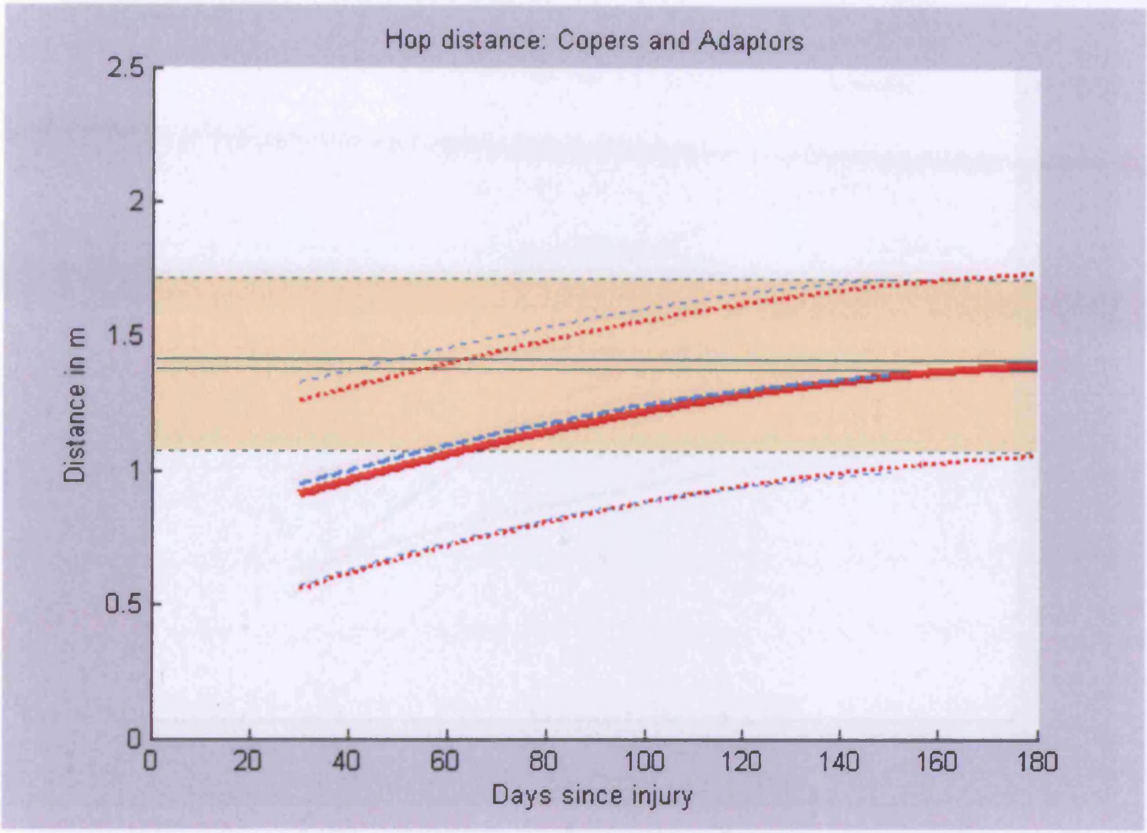


The ACLD group injured leg is indicated by the solid red curved line, with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

4.9 Sub-group recovery of distance hop: Stage 2

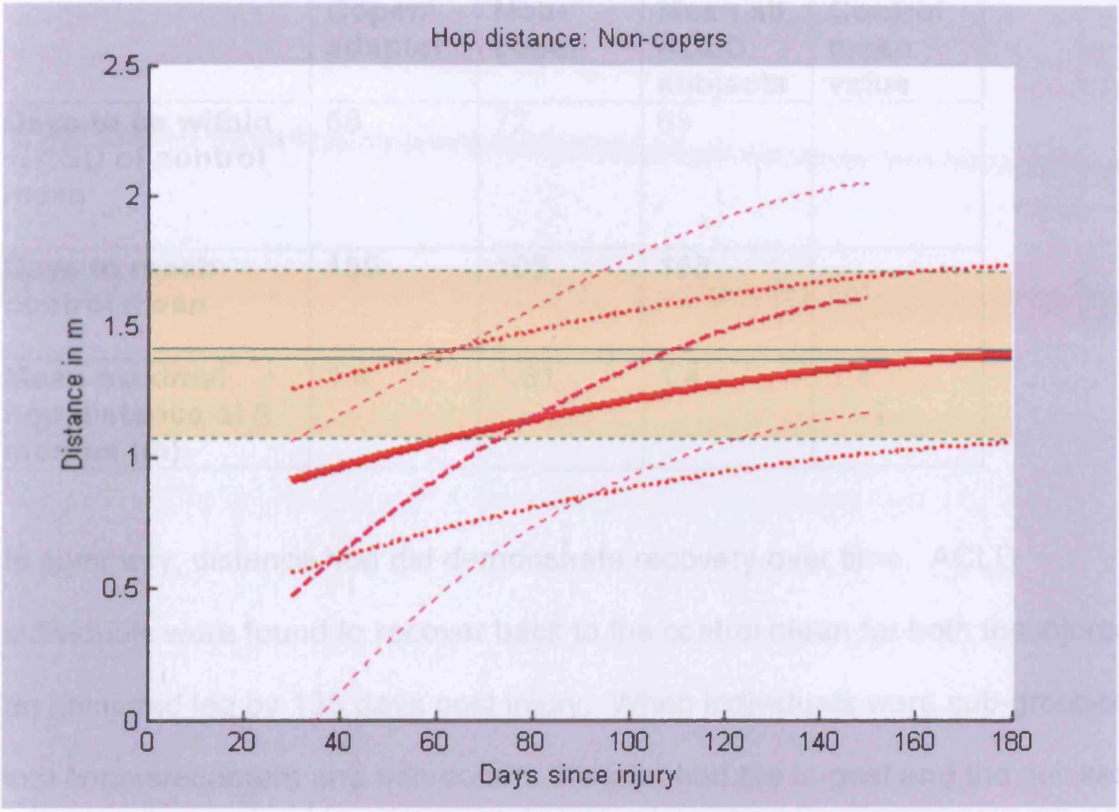
Functional recovery of hop distance for copers/adapters and non-copers are plotted in Figures 40 and 41. Copers and adapters needed to be combined due to insufficient numbers of copers for this analysis. When fitting a curve there needs to be sufficient data points available or else the accuracy of the curve will be reduced. The distance hop of copers/adapters followed the same rate of recovery as all the ACLD subjects before sub-grouping. At 30 days post injury they performed outside the control limits but recovered to within 1SD control mean by 58 days post injury and were reaching a plateau at the control mean by 145 days post injury. The non-copers initially had a much shorter hopping distance but this had a rapid rate of recovery and their hop distance was within 1SD of control mean by 70 days post injury and the control mean by 102 days post injury. Non-coper hop distance continued to improve and by 150 days the rate of recovery was reaching a plateau close to the upper limits of the control limits. The 1SD band for the non-copers was greater than for the control subjects and the copers/adapters. Recovery for each sub-group and their mean hop distance at these times is given in Table 28.

Figure 40 Recovery of hop distance for ACLD copers/adapters injured leg



The ACLD coper/adapter group is indicated by the dashed pale blue line the ACLD group as a whole is represented by the solid red curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 41 Recovery of hop distance for ACLD non-copers injured leg



The ACLD coper/adapter group is indicated by the dashed pink line the ACLD group as a whole is represented by the solid curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Table 28 A summary of the recovery of hopping distance for ACLD individuals

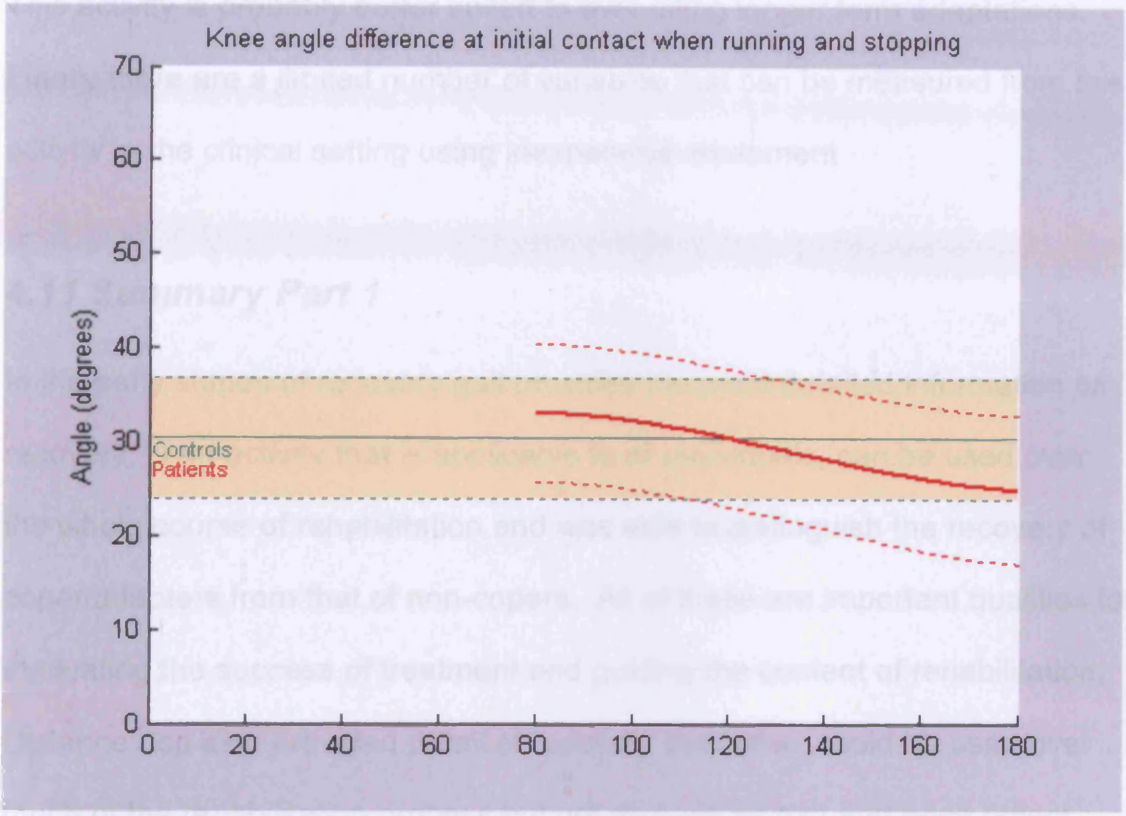
	Coper/ adapter	**Non-coper**	**Mean all ACLD subjects**	**Control mean value**
Days to be within +/-1SD of control mean	58	72	63	
Days to reach control mean	150	105	168	
Mean maximal hop distance at 5 months (m)	1.4	1.61	1.4	1.4

In summary, distance hop did demonstrate recovery over time. ACLD individuals were found to recover back to the control mean for both the injured an uninjured leg by 135 days post injury. When individuals were sub-grouped into copers/adapters and non-copers the later had the largest and the quickest recovery back to the control mean. The hopping curves were more prone to distortion because not all individuals could perform this activity; time from injury to when they were able to hop was more variable along with how many recording sessions each individual had for this activity. As a useful outcome measure to evaluate recovery in ACLD individuals it does fulfil the criteria of reflecting more challenging sporting manoeuvres, its recovery does demonstrate detail over time, it can be tested fairly early within the rehabilitation process (1-2 months post injury) and recovery for the copers/adapters corresponds to the recovery criteria of the healthy subjects (1SD and control mean) but this is not the case for the non-copers. This suggests that it is good for evaluating recovery but maybe not between the different functional sub-groups.

4.10 Recovery of Run and Stop: Stage 1

The recovery of the knee angle range of motion during the deceleration phase of run and stop has been modelled in Figure 42, 25 individuals had a minimum of 2 visits that included analysis of run and stop. By 80 days post injury the knee range was already greater than the control mean range but over time this demonstrated deterioration and ACLD subjects used a smaller range of knee motion during the deceleration phase. This reached a plateau just within the lower limits of the 1SD of the control mean. Fewer data points were available to plot this curve because fewer individuals were able to perform this activity and even fewer had multiple recordings, which will limit the accuracy of the curve. Due to the reduced amount of data the analysis was not progressed to stages 2 or 3.

Figure 42 Recovery of knee joint range during the deceleration phase of Run and Stop



The ACLD group is indicated by the solid red curved line with 1 standard deviation indicated by the dotted lines. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

In summary, for run and stop it does appear that ACLD individuals performed this activity with a stiffer landing phase. As an activity to evaluate recovery it does not fulfil all the criteria. Its strength is that it is a challenging activity for ACLD individuals so does reflect the types of activities that many individuals want to return to but it has a poor ability to measure change in performance over rehabilitation because it cannot be introduced until later in rehabilitation and many individuals are unable to perform it. It also appears that once individuals were safe to perform this activity they were already within the normal limits of healthy controls but demonstrated deterioration over time. This activity is probably better suited to evaluating longer term adaptations. Finally there are a limited number of variables that can be measured from this activity in the clinical setting using inexpensive equipment.

4.11 Summary Part 1

In the early stages of recovery gait provides the most detailed information on recovery, is an activity that is applicable to all individuals, can be used over the whole course of rehabilitation and was able to distinguish the recovery of coper/adapters from that of non-copers. All of these are important qualities for evaluating the success of treatment and guiding the content of rehabilitation. Distance hop also provided detail of recovery over time, could be used over much of the rehabilitation process but not as early as gait and does reflect more challenging activities that these individuals may wish to perform. This activity did distinguish the recovery of copers/adapters from non-copers but not in a way that generated useful information to guide rehabilitation. Jogging and run and stop were less useful activities for measuring functional outcome for different reasons. The main limitation for jogging was that it did not demonstrate detail of recovery over time. The application of run and stop is limited because it cannot be introduced until late in rehabilitation so is better suited to evaluating long term adaptation than guiding rehabilitation and evaluating outcome over the acute phase.

4.12 PART 2: FB versus No-FB Rehabilitation

4.13 Subjects

Based on the power equation a sample size of 35 subjects was required in each of the treatment groups. On conclusion of this investigation 27 data sets had been collected for the FB group and 25 for the no-FB group, which was considerably fewer than required based on our sample size calculations. From the 115 patients that were recruited into the investigation, 80 patients could not be followed up at 5 months post injury, resulting in an overall drop out rate of 60%. The numbers and reasons for this are summarised in Table 29, these are similar between the two groups and the main reason was because individuals did not end up having an ACL rupture based on their MRI scan. Only a small number of individuals withdrew consent, did not attend for the 5 month follow-up appointment or did not attend for their MRI scan and therefore their diagnosis could not be confirmed, excluding them from the investigation. These numbers and reasons are similar between the groups, making them comparable. If the not attending rate had been much higher in one group than the other this may have indicated that ACLD individuals were not able to comply with the rehabilitation or getting any benefit from it. This would have raised concerns about the appropriateness of the physiotherapy treatment.

Table 29 Reasons for the loss of subjects by the 5 month follow-up

Reason for loss	FB	No-FB
Early reconstruction	6	5
No ACL rupture	13	9
DNA/No MRI	5	7
moved	2	2
Withdrew consent	3	2
Exclusion criteria	1	1
Unable to trace	3	2
Treatment elsewhere	3	2

From the 27 subjects in the FB group that were followed up at 5 months post injury, 15 individuals received all 3 sessions of movement feedback, 5 individuals received 2 sessions of feedback and 7 individuals received less than 2 sessions of feedback before stopping physiotherapy but still attended the 5 month follow-up. Five other individuals attended two feedback sessions each but were not available for the final follow-up at 5 months.

It was not possible to blind the physiotherapists and patients of the differences between the FB and no-FB rehabilitation programs so to reduce the influence that this could have had on the treatment outcome the rehabilitation programs were carried out on 2 separate sites, as described in the methods. This was successful for the ACLD patients as none of them transferred rehabilitation between the FB and no-FB physiotherapy departments. Unfortunately one physiotherapist from each site did swap between the departments but this was not until 15 months (FB to no-FB) and at 19 months (no-FB to FB). The physiotherapist who transferred from the FB to no-FB site at 15 months did not treat any further ACLD patients as part of the study, so any increased knowledge that they had of movement analysis was not applied to patient rehabilitation whilst working at the no-FB location. The last transfer of another physiotherapist between the no-FB to FB site at 19 months, coupled with 3 of the physiotherapists leaving the trust, forced recruitment of ACLD subjects onto the study to stop. After this time point only one of the original physiotherapists remained. The effects of recruiting new physiotherapists onto the study and the interaction they would have with physiotherapists who had been part of the investigation but had swapped sites was considered too detrimental; potentially undermining the treatment effect of the feedback intervention. By finishing recruitment after 19 months the effects of the increased awareness between the physiotherapists involved in the research was kept to a minimum.

All the demographic characteristics and symptoms of the FB and no-FB treatment groups are summarised in Tables 30 and 31. Both groups were matched for age, height, mass, number of physiotherapy sessions, gender, pre-injury activity level, and injury type and activity level at 5 months post injury.

Table 30 Demographic characteristics of the FB and no-FB rehabilitation groups

Variable	Mean (SD)	t	p value	95% confidence intervals
Age (years)				
FB	28.67 (8.9)	-0.038	0.970	-5.0 to 4.813
No-FB	28.76 (8.7)		n.s.	
Height (cm)				
FB	176.28 (7.68)	0.018	0.985	-4.69 to 4.776
No-FB	176.24 (8.95)		n.s.	
Mass (kg)				
FB	83.85 (17.71)	0.125	0.901	-9.557 to 10.827
No-FB	83.22 (18.12)		n.s.	
Physiotherapy sessions				
FB	6 (4.0)	1.102	0.276	-1.049 to 3.588
No-FB	5 (4.0)		n.s.	

n.s. = not significant

Table 31 Summary of the categorical demographic variables for the FB and no-FB treatment groups tested by means of the χ^2 test for associations between the feedback groups

Variable			χ2	p value
Gender	Female	Male		
FB	8	19	0.642	0.423
No-FB	5	20		n.s.
Pre-injury activity level	High impact & pivot	Low impact & pivot		
FB	25	2	0.939	0.333
No-FB	21	4		n.s.
Injury type	ACL+/-MCL	ACL+/-MCL+/-meniscus	1.406	0.236
FB	13	14		n.s.
No-FB	8	17		
5mth activity level	High impact & pivot	Low impact & pivot		
FB	4	23		0.442
No-FB	2	23	0.591	n.s.

n.s. = not significant

Based on the clinical symptom scales within the Cincinnati knee rating system there was no difference between the FB and no-FB treatment groups at 5 months post injury for swelling, pain, full giving way, partial giving way, global assessment of knee symptoms or activity level, which is summarized in Table 32.

Table 32 Summary of FB and non-FB clinical symptoms based on the Cincinnati knee rating system tested by means of the Mann-Whitney U test for feedback group differences

	Median	U	p (exact)
Swelling			
FB	6	245.5	0.395
No-FB	6		n.s.
Pain			
FB	6	320	0.749
No-FB	6		n.s.
Full giving way			
FB	8	284.5	0.765
No-FB	8		n.s.
Partial giving way			
FB	6	300	0.843
No-FB	6		n.s.
Overall global			
FB	4	318	0.716
No-FB	5		n.s.
Activity level			
FB	75	257.5	0.915
No-FB	75		n.s.

n.s. = not significant

Descriptive results for the SF-36 are summarized in Table 33. These questionnaires have not been analysed statistically because no differences were found between the FB and no-FB groups for any of the other outcomes which have evaluated function at the structure, performance and participation levels. The movement variables which are the primary outcomes are presented in the following section. Based on the similarity of the treatment group means and SD's for the SF-36 domains it is not anticipated that there would have been any difference between the groups for these variables.

Table 33 Descriptive summary of the SF-36 for the FB and no-FB treatment groups

SF-36 domain	**Mean**	**SD**
Physical functioning		
FB	77	13
No-FB	75	23
Social functioning		
FB	89	24
No-FB	88	30
Role limitations- physical		
FB	58	42
No-FB	61	45
Bodily pain		
FB	64	24
No-FB	63	27
General medical health		
FB	72	22
No-FB	77	17
Mental health		
FB	75	14
No-FB	75	18
Role limitations emotional		
FB	85	30
No-FB	81	35
Vitality		
FB	61	22
No-FB	64	19

Finally, based on a descriptive analysis there does not appear to be any difference between the treatment groups for the number of copers, non-copers or adapters, this is detailed in Table 34. Compared to part 1 of the investigation there are a lower percentage of copers in part 2.

Table 34 Summary of the number of individuals in the functional sub-groups

	Copers (%)	Adapters (%)	Non-copers (%)
Treatment group			
FB	2 (7%)	13 (48%)	12 (44%)
No-FB	2 (8%)	13 (52%)	9 (36%)

4.14 Functional Task performance at 5 Months Post Injury

4.14.1 Gait

There were no significant differences between the FB and No-FB treatment groups for any of the gait time-distance variables or joint angles at 5 months post injury except for ankle angle at initial contact. The gait characteristics for all of the variables for both treatment groups are summarized in Table 35. The subjects in the FB group tended to be in a more dorsi-flexed position at initial contact. The clinical relevance of the FB subjects dorsi-flexing an additional two degrees is questionable and because there were no other statistically significant differences then it appears that there was no difference in gait, regardless of treatment group. All the time-distance gait parameters for the feedback groups were below the values found in part 1 of the study. Therefore the question whether full recovery was achieved at 5 months was explored in a further analysis in the following section.

Table 35 Gait differences between treatment groups at 5 months post injury

	Mean (SD)	T value	p value	95% confidence interval of the difference
Gait velocity (m/s) FB No-FB	 1.395 (0.17) 1.335 (0.18)	 1.217	 0.229 n.s.	 -0.039 to 0.158
Cadence (steps/s) FB No-FB	 111.9 (7.30) 111.2 (5.97)	 0.377	 0.708 n.s.	 -3.094 to 4.524
Step Length injured (m) FB No-FB	 0.740 (0.07) 0.707 (0.08)	 1.571	 0.123 n.s.	 -0.094 to 0.077
Step length non-injured FB No-FB	 0.750 (0.06) 0.728 (0.09)	 0.990	 0.327 n.s.	 -0.022 to 0.064
HDA injured FB No-FB	 43.63 (5.29) 44.03 (4.65)	 -0.271	 0.787 n.s.	 -3.342 to 2.548
HDA non-injured FB No-FB	 42.86 (5.02) 41.04 (4.34)	 1.337	 0.188 n.s.	 -0.919 to 4.552
Knee angle IC FB No-FB	 3.20 (3.66) 3.13 (3.67)	 0.072	 0.943 n.s.	 -2.032 to 2.183
Ankle angle IC FB No-FB	 6.94 (3.48) 4.54 (4.51)	 2.089	 0.042*	 0.089 to 4.708

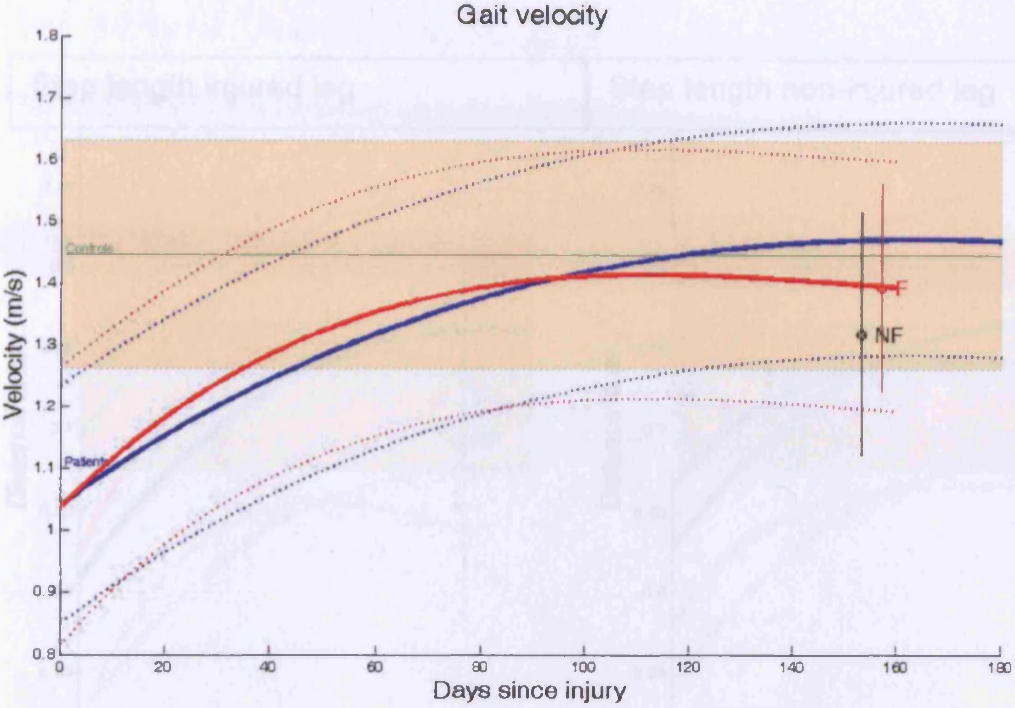
n.s. = not significant

* = significant $p<0.05$

4.14.2 Modelling Functional Recovery of Gait

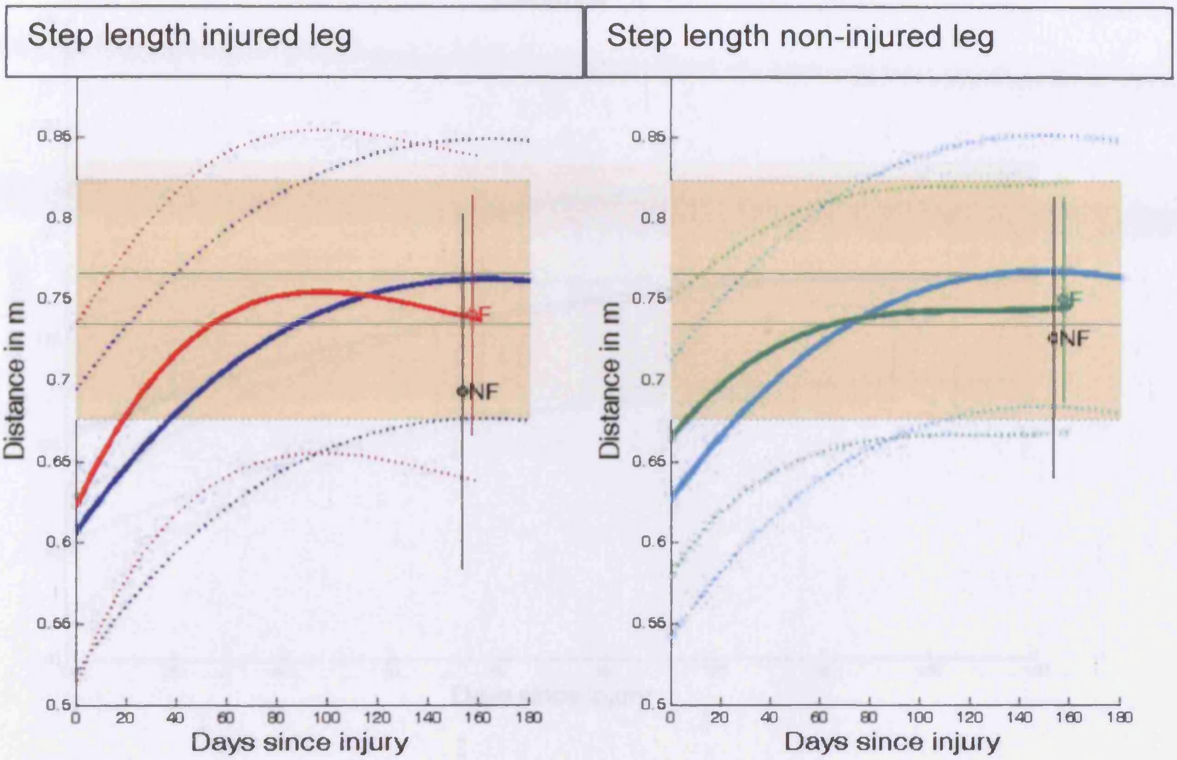
During the course of their rehabilitation ACLD patients in the feedback group underwent a total of 4 movement analysis sessions including the 5 month follow-up. Using the same approach as in part 1 a least squares method, 3rd order polynomial was used to plot a 'curve of best fit' through the data for gait velocity, step length and cadence. These curves most closely approximated the average recovery of all the ACLD subjects in the feedback group over time, these have been plotted alongside the FB and no-FB group mean values and SD at 5 months in Figures 43-45. For all 3 variables the recovery curve of the FB group does approximate the recovery curve from part 1. The main differences in the FB curve is that it does demonstrate an initial faster rate of recovery for velocity and step length but a slower rate for cadence than the curve of best fit from part 1. The variables also demonstrate a slightly inferior overall recovery (for both feedback groups), reaching a plateau just below the control mean and the original recovery curve but still within normal limits. By 5 months post injury velocity, cadence and step length for the FB group demonstrate some deterioration; particularly for gait velocity and cadence. The mean value for each variable for the FB group coincides with its curve of best fit. The mean values for both the FB and no-FB groups lay within the normal limits of the healthy controls but below the control mean. Although there was no statistical difference between these groups there is a trend for the no-FB group to have a slower velocity, shorter step length and lower cadence.

Figure 43 Recovery curve for gait velocity for the FB rehabilitation group and means and SD for the FB and no-FB groups



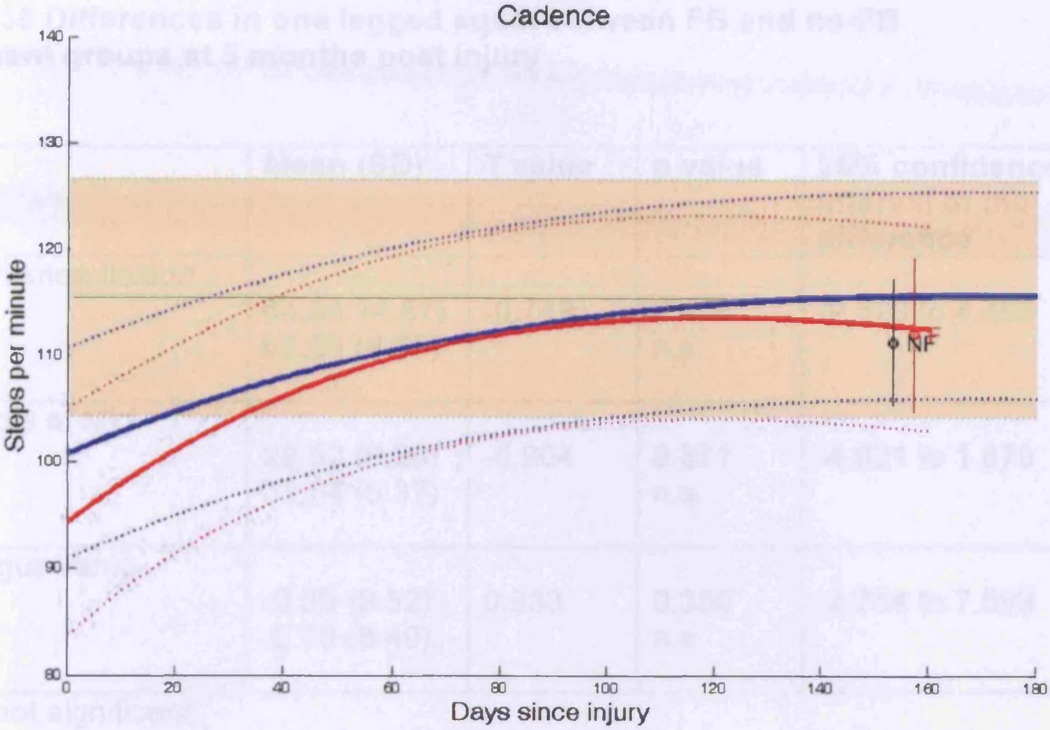
The solid blue curve is the average ACLD recovery curve from part 1 and the dashed line is the 1SD. The solid red recovery curve is the FB treatment group and dashed red curve is the 1SD. The average value and SD for the FB group at the 5 month follow is the red dot and vertical line. The average value and SD for the no-FB group is the black dot and vertical line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 44 Recovery curve for injured (red) and non-injured (green) step lengths for the FB rehabilitation group and means and SD for the FB and no-FB groups



The solid blue curve is the average ACLD recovery curve from part 1 and the dashed line is the 1SD. The solid red recovery curve is the FB treatment group and dashed red curve is the 1SD. The average value and SD for the FB group at the 5 month follow is the red dot and vertical line. The average value and SD for the no-FB group is the black dot and vertical line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band. For the non-injured leg the green line and dot are the FB group.

Figure 45 Recovery curve for cadence of the FB rehabilitation group (red) and means and SD for the FB and no-FB groups



The solid blue curve is the average ACLD recovery curve from part 1 and the dashed line is the 1SD. The solid red recovery curve is the FB treatment group and dashed red curve is the 1SD. The average value and SD for the FB group at the 5 month follow is the red dot and vertical line. The average value and SD for the no-FB group is the black dot and vertical line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

4.14.3 One legged squat

There were no significant differences between either of the treatment groups for the one legged squat variables; maximum knee flexion angle, ankle angle at maximum knee flexion (mkf) and knee valgus/varus angle at maximum knee flexion. These variables are summarized in Table 36.

Table 36 Differences in one legged squat between FB and no-FB treatment groups at 5 months post injury

	Mean (SD)	**T value**	**p value**	**95% confidence interval of the difference**
Maximum knee flexion FB No-FB	64.64 14.57) 67.59 (9.75)	-0.748	0.458 n.s.	-9.826 to 4.499
ankle angle at Mkf FB No-FB	29.52 (6.38) 31.04 (5.37)	-0.904	0.371 n.s.	-4.921 to 1.870
Knee valgus/varus FB No-FB	-0.30 (9.52) -2.70 (8.49)	0.933	0.356 n.s.	-2.784 to 7.599

n.s. = not significant

4.14.4 Distance hop

No statistically significant difference in distance hop performance was found between the two treatment groups for the distance in the injured and non-injured leg or kinematic variables. The hopping characteristics are summarized in Table 37.

Table 37 Differences in distance hop between feedback and no-FB treatment groups at 5 months post injury

	Mean (SD)	T value	p value	95% confidence interval of the difference
Hop Distance injured FB No-FB	1.230 (0.31) 1.150 (0.29)	0.827	0.413 n.s.	-0.115 to 0.273
Hop Distance non-injured FB No-FB	1.353 (0.33) 1.357 (0.24)	-0.039	0.969 n.s.	-0.201 to 0.193
Max knee flex take off FB No-FB	55.26 (7.27) 54.25 (7.97)	0.407	0.687 n.s.	-4.015 to 6.029
Max ankle DF FB No-FB	25.93 (4.91) 27.71 (4.78)	-1.122	0.269 n.s.	-4.989 to 1.434
Hop knee range landing FB No-FB	22.65 (8.80) 20.41 (7.21)	0.843	0.405 n.s.	-3.145 to 7.620
Hop ankle range landing FB No-FB	14.10 (6.11) 14.04 (6.97)	0.026	0.979 n.s.	-4.248 to 4.361

n.s. = not significant

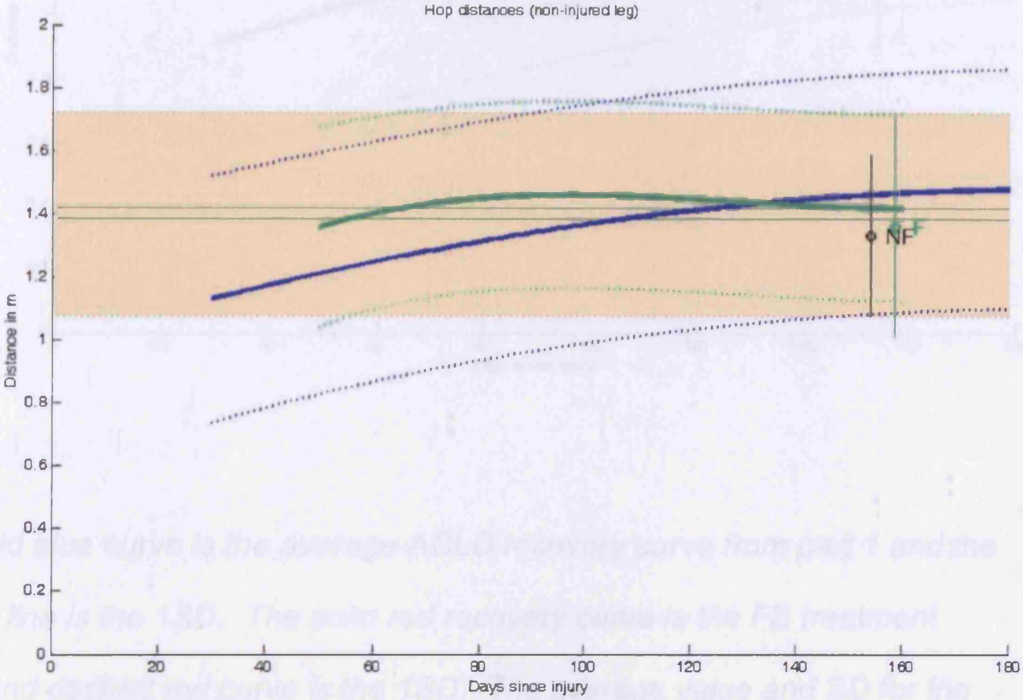
4.14.5 Modelling recovery of hop distance

A curve of best fit was plotted for the pooled data of all the ACLD subjects in the feedback group who hopped, using a method of least squares 3rd order polynomial. Unlike the recovery curve for the non-injured leg in part 1 the recovery curve for the non-injured leg in part 2 for the feedback group, fluctuated around the control mean from the commencement of recording at 45 days post injury, no altered performance was noted over time. For the injured leg the hopping distance increased with time and had a faster rate of recovery than for part 1 but it never quite reached the control mean, overall the injured leg hop distance in part 2 demonstrated an inferior recovery. The curve demonstrated some deterioration in distance hopped by 5 months post injury. The average hop distance for the non-feedback group was shorter at 5 months demonstrating that they had less recovery in this functional activity. The recovery curves of the injured and non-injured legs are plotted in Figures 46 and 47. The mean hop distance at 5 months post injury for the FB group (represented as the dot with NF) doesn't quite coincide with the recovery curve for the FB group. The reason for this is that the dot demonstrates the average recovery of all individual in both the FB and No-FB groups that had 5 month data collection. The polynomial curve is made up of all individuals that had multiple data collected but this did not have to include the 5 month visit. This means that 2 different samples were used in the calculations and this would explain why the average recovery point for the FB group and the polynomial are not aligned together.

The current recovery curve for hopping distance in part 2 demonstrates a steeper recovery curve that that modelled in part 1. It is important to point out that there are less data points that were collected up to 80 days post injury and therefore incorporated in the model. Less data points were collected because in the proposal data was to be collected at 1, 3 and 4 months post injury instead of monthly like in part 1.

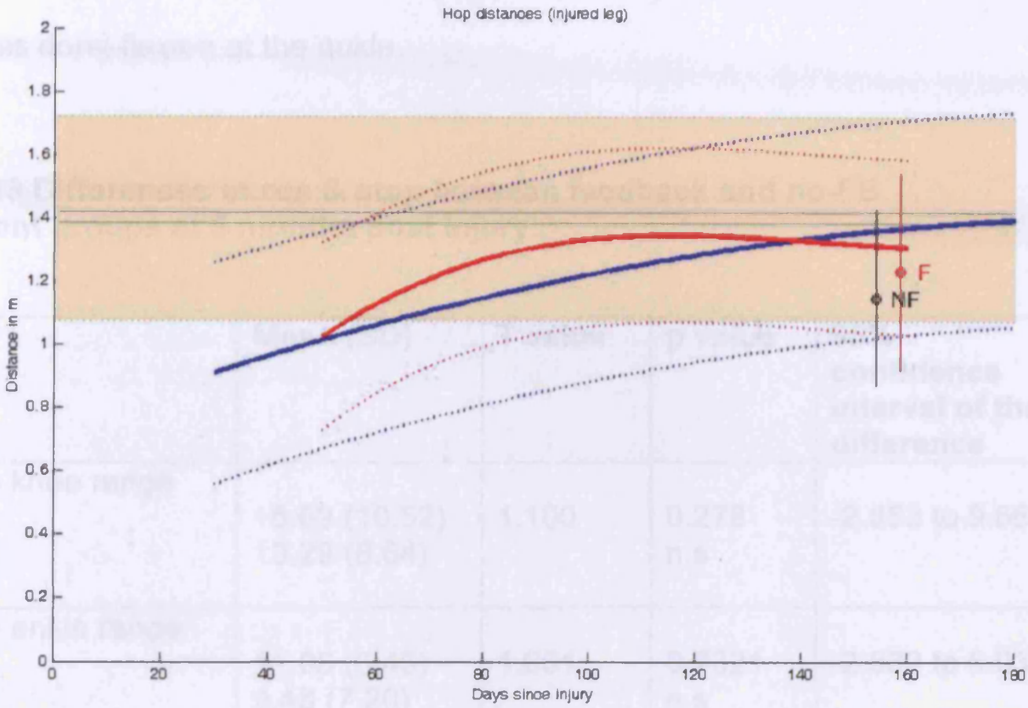
The start and stop point for the polynomial is based on the time range that data was collected in. This explains why the curve starts at a later date for part 2 results. If the curve is used to predict performance outside data time range then there can be less certainty in the accuracy.

Figure 46 The recovery curve and mean value for non-injured leg hop distance for the FB and no-FB rehabilitation groups.



The solid blue curve is the average ACLD recovery curve from part 1 and the dashed line is the 1SD. The solid green recovery curve is the FB treatment group and dashed green curve is the 1SD. The average value and SD for the FB group at the 5 month follow is the green dot and vertical line. The average value and SD for the no-FB group is the black dot and vertical line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

Figure 47 The recovery curve and mean value for injured leg hop distance for the FB and no-FB rehabilitation groups.



The solid blue curve is the average ACLD recovery curve from part 1 and the dashed line is the 1SD. The solid red recovery curve is the FB treatment group and dashed red curve is the 1SD. The average value and SD for the FB group at the 5 month follow is the red dot and vertical line. The average value and SD for the no-FB group is the black dot and vertical line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with tan band.

4.14.6 Run and stop

No significant differences between treatment groups were found for run and stop ankle and knee joint angle at 5 months post injury; this is summarized in

Table 38. The slight mean increase in knee flexion of the FB group is related to the simultaneous increased dorsi-flexion at ankle of the FB group during this deceleration phase. The no-FB group is in less knee flexion and therefore uses less dorsi-flexion at the ankle.

Table 38 Differences in run & stop between feedback and no-FB treatment groups at 5 months post injury

	Mean (SD)	T value	p value	95% confidence interval of the difference
Run&stop knee range FB No-FB	16.69 (10.52) 13.29 (8.64)	1.100	0.278 n.s	-2.863 to 9.664
Run&stop ankle range FB No-FB	11.08 (6.46) 9.48 (7.20)	1.601	0.7321 n.s	-2.832 to 6.033

n.s. = not significant

4.15 ACLD Subjects Compared to Controls at 5 Months Post Injury

No statistical difference in functional performance was found between the two treatment groups but the descriptive assessment of their recovery seemed to indicate that both treatment groups had less recovery and performed differently to controls and the ACLD subjects in part 1. Therefore it was considered important to perform one final stage to the analysis post hoc. This stage evaluated if at 5 months post injury there were differences between the combined feedback groups and the controls for selected gait, distance hop and run and stop time-distance variables and joint angles, for key variables that did not recover in part 1.

The hypotheses for this post-hoc analysis were:

H1 The combined ACLD feedback groups will perform worse for the selected time-distance variables in Table 39 compared to uninjured controls.

Ho1 There are no differences in gait time-distance variables between the combined feedback group and uninjured controls.

Table 39 Hypothesis 1: expected outcomes for gait time-distance variables for combined ACLD feedback group

Gait time-distance outcome variables for combined ACLD group
slower gait velocity
shorter injured and non-injured and step length
lower cadence

H2 The combined ACLD feedback groups will perform worse for the selected gait joint angles in Table 40 compared to uninjured controls.

Ho2 There are no differences in gait joint angles between the combined feedback group and uninjured controls.

Table 40 Hypothesis 2: expected outcomes for gait kinematic variables for the combined ACLD feedback group

Gait joint angles outcome for the combined ACLD feedback group
reduced hip displacement angle of the non-injured leg
reduced knee extension at heel strike

H3 The combined ACLD feedback groups will perform worse for the selected hop variables in Table 41 compared to uninjured controls.

Ho3 There are no differences in hop performance between the combined feedback group and uninjured controls.

Table 41 Hypothesis 3: expected outcomes for distance hop variables for the combined ACLD rehabilitation groups

Hop variables for the combined ACLD feedback group
Reduced injured leg hop distance
Reduced knee range during the deceleration phase
Reduced ankle range during the deceleration phase

H4 The combined ACLD feedback groups will perform worse for the selected run and stop kinematic variables in Table 42 compared to uninjured controls

Ho4 There are no differences in run and stop joint angles between the combined feedback group and uninjured controls.

Table 42 Hypothesis 5: expected outcomes for R&S joint angles for the combined ACLD feedback groups

R&S outcome variables for FB rehabilitation
Decreased knee range during the deceleration phase
Decreased ankle range during the deceleration phase

4.15.1 Subjects

There was no statistical difference between the combined ACL group and the healthy controls from part 1 for height, age, gender and activity levels. The

ACLD subjects did weigh more and this was reflected in their larger BMI. These results are summarised in Table 43. The groups are therefore considered matched on most parameters except mass.

Table 43 Demographic variables for the combined ACLD group and healthy controls

variable	Mean(SD)	t	p value	95% confidence interval of the difference
Height ACLD Controls	176.26 (8.23) 174.65 (8.13)	0.972	0.334 n.s.	-1.685 to 4.915
Mass ACLD Controls	83.55 (17.73) 76.60 (12.27)	2.283	0.0257 n.s.	0.912 to 13.201
BMI ACLD Controls	26.74 (4.78) 24.98 (2.94)	2.208	0.030*	0.175 to 3.358
Age ACLD Controls	28.61 (8.77) 27.26 (4.87)	0.958	0.341 n.s.	-1.454 to 4.150
		×	p	
Gender ACLD Controls	13:38 16:35	0.434	0.661 n.s.	
Activity level ACLD Control	45:6 19:8	3.826	0.066 n.s.	

n.s. = not significant; * = significant $p<0.05$

4.15.2 Gait performance

The ACLD subjects walked with a slower velocity, lower cadence and shorter injured leg step length compared to healthy controls. The only gait adaptation for the joint angles was a reduced non-injured leg HDA; there was no difference between the ACLD subjects and controls for knee joint angle. All the time-distance variables and joint angles evaluated are summarized in Table 44.

Table 44 Gait time-distance variables and joint angles for the combined ACLD groups and the controls.

Variable	**Mean(SD)**	**t**	**p value**	**95% confidence interval of the difference**
Gait velocity ACLD Controls	1.366 (0.17) 1.474 (0.14)	-3.497	0.001*	-0.170 to -0.047
Cadence ACLD Controls	111.58 (6.63) 116.04 (7.04)	-3.290	0.001*	-7.147 to -1.770
Step length (inj) ACLD Controls	0.724 (0.08) 0.752 (0.05)	-2.204	0.030*	-0.053 to -0.003
Step length (non-inj) ACLD Controls	0.739 (0.08) 0.752 (0.05)	-1.003	0.319 n.s.	-0.037 to 0.012
HDA non-inj ACLD Controls	41.99 (4.74) 45.13 (5.26)	-3.032	0.003*	-5.203 to -1.084
Knee angle IC ACLD Controls	3.16 (3.63) 4.56 (4.45)	-1.671	0.098 n.s.	-3.052 to 0.263

n.s. = not significant; * = significant P<0.05

4.15.3 Distance hop performance

Distance hop is a more challenging activity for ACLD subjects, they compensated by hopping a shorter distance with their injured leg. During the deceleration phase of the hop the knee joint went through a smaller range of motion, indicating a stiff landing strategy. There was a trend for the ankle to go through an increased range of dorsi-flexion during this phase but this did not reach statistical significance. These results are tabulated in Table 45.

Table 45 Summary of hopping variables for the ACLD and control groups

Variable	**Mean (SD)**	**t**	**p value**	**95% confidence interval of the difference**
Hop distance (injured leg) ACLD Control	1.194 (0.29) 1.454 (0.26)	-4.336	<0.001**	-0.380 to -0.141
Knee range during landing ACLD Control	21.65 (8.10) 36.08 (7.98)	-8.235	<0.001**	-17.919 to -10.947
Ankle range Landing ACLD Control	14.07 (6.42) 10.87 (10.22)	1.761	0.082 n.s.	-0.417 to 6.820

n.s. = not significant; ** = highly significant

4.15.4 Run and stop performance

Only joint angles were measured for the run & stop activity. The injured knee joint of the ACLD was found to go through a smaller range during the landing phase than the knee of the healthy controls. There was no difference between the groups for the ankle range utilized during the landing phase. These findings are summarized in Table 46.

Table 46 The knee and ankle joint angles of the ACLD and control subjects during Run & Stop

Variable	Mean (SD)	t	p	95% confidence interval of the difference
Knee range landing				
ACLD	15.03 (9.68)	-7.240	<0.001*	-19.675 to -11.175
Control	30.46 (7.93)			
Ankle range landing				
ACLD	10.30 (6.79)	-0.214	0.831 n.s.	-3.749 to 3.023
Control	10.67 (7.50)			

n.s. = not significant; * = significant

In summary, the combined group of ACLD subjects from both the FB and no-FB treatments did not demonstrate a full recover of functional tasks to perform like healthy subjects. For gait the ACLD subjects continued to walk with a slower gait velocity, shorter step length, reduced cadence and reduced hip displacement angle for the non-injured leg. The injured limb demonstrated a reduced hop distance. During the landing phase of distance hop and R&S the ACLD subjects used a reduced knee range of motion. This is the same strategy that was found descriptively in part 1 and thought to indicate an incomplete recovery. These results confirm that functional tasks can provide valuable information on outcome and guidance for treatment.

4.16 Correlations between performance and symptoms

Finally, correlations were carried out to evaluate if there was any relationship between the clinical symptoms experienced by the ACLD subjects, aspects of their treatment and their performance for gait velocity and hop distance.

Using Pearson's correlation and spearman rank no significant correlations were found between the symptom and treatment variables and gait velocity. These findings are summarized in Table 47. The relationship between these same clinical variables and injured leg distance hop was also explored. A significant low correlation was found between knee pain and hop distance and a significant moderate correlation between 5 month activity levels and hop distance, see Table 48. Overall there are few correlations between the clinical symptoms and aspects of their treatment and functional outcome. This indicates that the ACLD performance was not related to these factors and that they measure different aspects of recovery. Only pain during more challenging activities such as hopping may influence performance.

Table 47 Relationship between gait velocity and clinical variables

	Pearsons correlation coefficient	**significance**
Physiotherapy sessions	-0.016	0.917 n.s.
	Spearman rank	significance
Injury type	-0.025	0.862 n.s.
Swelling	0.122	0.421 n.s.
Pain	0.272	0.056 n.s.
Full giving way	0.068	0.652 n.s.
Partial giving way	0.206	0.160 n.s.
5mth activity level	0.120	0.436 n.s.
Overall knee rating	0.124	0.391 n.s.

n.s. = not significant

Table 48 Relationship between hop distance and clinical symptoms

	Pearsons correlation coefficient	**significance**
Physiotherapy sessions	-0.052	0.762 n.s.
	Spearman rank	significance
Injury type	-0.210	0.206 n.s.
Swelling	0.094	0.591 n.s.
Pain	0.547	<0.001**
Full giving way	0.184	0.282 n.s.
Partial giving way	0.295	0.081 n.s.
5mth activity level	0.436	0.01**
Overall knee rating	0.281	0.088 n.s.

n.s. = not significant; * = significant

4.17 Level of functional coping

Finally all the ACLD individuals from part 2 were sub-grouped into copers, adapters and non-copers based on their activity levels and number of episodes of knee giving way at 12 months post injury. The largest percentage of ACLD individuals were adapters (51%), followed by non-copers (41.2%) and the smallest group were copers (7.8%). No individuals with a low activity level pre-injury ended up being classified as a non-coper; this is summarized in Table 49.

Table 49 Summary of functional sub-groups for ACLD individuals in part 2

SUB-GROUP	number	%	Pre-injury activity level
Copers	4	7.8	High activity level 3 Low activity level 1
Adapters	26	51	High activity level 21 Low activity level 5
Non-copers	21	41.2	High activity level 21 Low activity level 0

4.18 Part 2: Summary

The objective of part 2 of this investigation was to evaluate if providing physiotherapists with movement feedback on ACLD patient functional performance over the course of rehabilitation results in an overall superior functional outcome. Based on the results obtained all of the null hypotheses were accepted for all of the functional activities. The variables are listed in Table 50.

4.18.1 Accepted null hypotheses

Ho1: There are no differences in the gait time-distance variables listed in Table between ACLD patients treated by physiotherapists in the feedback rehabilitation and no-feedback rehabilitation programs.

Ho2: There are no differences in gait joint angles between ACLD patients treated in the feedback rehabilitation and no-feedback rehabilitation programs.

Ho3: There are no differences in one legged squat joint angles between ACLD patients treated in the feedback rehabilitation and no-feedback rehabilitation programs.

Ho4: There are no differences in distance hop between ACLD patients treated in the feedback rehabilitation and no-feedback rehabilitation programs.

Ho5: There are no differences in run & stop between ACLD patients treated in the feedback rehabilitation and no-feedback rehabilitation programs.

Ho6: There are no differences in the Cincinnati knee rating system and SF-36 between ACLD patients treated in the feedback rehabilitation and no-feedback rehabilitation programs.

Table 50 Null hypotheses 1-5 accepted: there are no differences between the FB and no-FB groups for the movement variables.

Ho1: GAIT TIME-DISTANCE VARIABLES	**Ho3: ONE LEGGED SQUAT**	**Ho4: DISTANCE HOP**	**Ho5: RUN & STOP**
Velocity Cadence Step length injured and non-injured leg	maximum knee flexion (mkf) ankle angle at mkf knee valgus/varus at mkf	Hop distance injured and non-injured leg Knee range take-off phase Ankle range take-off phase Knee range deceleration phase Ankle range deceleration phase	Knee range deceleration phase Ankle range deceleration phase
Ho2: GAIT JOINT ANGLES			
Ankle angle HS Knee ankle HS HDA injured and non-injured			

4.18.2 Rejected Hypothesis

H1: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation have a better functional outcome for the gait time-distance variables in Table 51, than those patients whose physiotherapists do not receive movement feedback.

Table 51 Hypothesis 1: expected outcomes for gait time-distance variables for FB- rehabilitation group

Gait time-distance outcome variables for the FB-rehabilitation
Faster gait velocity
Longer injured and non-injured and step length
Higher cadence

H2: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation have a better functional outcome for gait joint angles in Table 52, than those patients whose physiotherapists do not receive movement feedback.

Table 52 Hypothesis 2: expected outcomes for gait joint angles for the FB-rehabilitation group

Gait kinematic outcome for FB-rehabilitation
Larger hip displacement angle of the non-injured leg
Increased knee extension at heel strike
Increased dorsi-flexion at heel strike

H3: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will have a better functional outcome for one legged squat variables in Table 53, than those patients whose physiotherapists did not receive movement feedback.

Table 53 Hypothesis 3: expected outcomes for one legged squat variables for FB rehabilitation group

One legged squat variables for FB rehabilitation
Larger maximum knee flexion angle
Increased range of ankle dorsi-flexion at maximum knee flexion
Increased knee valgus angle at maximum knee flexion

H4: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will have a better functional outcome for distance hop variables in Table 54, than those patients whose physiotherapists do not receive movement feedback.

Table 54 Hypothesis 4: expected outcomes for distance hop variables for FB rehabilitation group

Hop variables for FB rehabilitation
Increased injured and non-injured leg hop distance
Increased knee range during take-off phase
Increased knee range during the deceleration phase
Increased ankle range during the take-off phase
Increased ankle range during the deceleration phase

H5: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will have a better functional outcome for run & stop variables in Table 55, than those patients whose physiotherapists do not receive movement feedback.

Table 55 Hypothesis 5: expected outcomes for distance R&S for FB rehabilitation group

R&S outcome variables for FB rehabilitation
Increased knee range during take-off phase
Increased knee range during the deceleration phase
Increased ankle range during the take-off phase
Increased ankle range during the deceleration phase

H6: ACLD patients treated by physiotherapists that receive movement feedback on patient functional performance over the course of rehabilitation will achieve a significantly better functional outcome for the Cincinnati knee rating system and SF-36 than those patients whose physiotherapists do not receive movement feedback.

4.19 Post hoc analysis for ACLD subjects versus controls

The aim of this post-hoc analysis comparing the combined ACLD groups with all the subjects from the FB and no-FB treatment was to evaluate differences in performance compared to healthy healthy subjects. This analysis confirmed that in general the combined ACLD subjects did not made a full functional recovery for gait, distance hop or R&S. Accepted experimental hypothesis are detailed in the following section.

4.19.1 Accepted Hypotheses

H1 The combined ACLD feedback groups will perform worse for the selected time-distance variables in Table 56 compared to uninjured controls.

Table 56 Hypothesis 1: expected outcomes for gait time-distance variables for the combined ACLD feedback group

Gait time-distance outcome variables for combined ACLD group
slower gait velocity
shorter injured and non-injured and step length
lower cadence

H2 The combined ACLD feedback groups will perform worse for the selected gait joint angles in Table 57 compared to uninjured controls.

Table 57 Hypothesis 2: expected outcomes for gait joint angles for the combined ACLD feedback group

Gait kinematic outcome for the combined ACLD feedback group
reduced hip displacement angle of the non-injured leg
reduced knee extension at heel strike

H3 The combined ACLD feedback groups will perform worse for the hop variables in Table 58 compared to uninjured controls.

Table 58 Hypothesis 3: expected outcomes for distance hop variables for the combined ACLD rehabilitation groups

Hop variables for the combined ACLD FB and no-FB treatment group
Reduced injured leg hop distance
Reduced knee range during the deceleration phase
Reduced ankle range during the deceleration phase

H4 The combined ACLD feedback groups will perform worse for the selected run and stop joint angle variables in Table 59 compared to uninjured controls.

Table 59 Hypothesis 4: Expected outcomes for R&S joint angles for the combined ACLD feedback group.

R&S outcome variables for the combined ACLD feedback group
Decreased knee range during the deceleration phase
Decreased ankle range during the deceleration phase

4.19.2 Rejected null hypotheses:

Ho1 There are no differences in gait time-distance variables between the combined feedback group and uninjured controls for the variables listed in Table 60.

Ho2 There are no differences in lower limb gait joint angles between the combined feedback group and uninjured controls for the variables listed in Table 60.

Ho3 There are no differences in hop performance between the combined feedback group and uninjured controls for the variables listed in Table 60.

Ho4 There are no differences in run and stop performance between the combined feedback group and uninjured controls for the variables listed in Table 60.

Table 60 Summary of the variables for the null hypotheses that were rejected

Ho1 & Ho2	**Ho3**	**Ho4**
Velocity Cadence Step length, HDA non-injured leg knee angle	Injured leg hop distance, Knee range Ankle range (during the deceleration phase)	Knee range Ankle range (during the deceleration phase)

4.20 Semi-Structured Interviews

To explore possible reasons why no significant differences were found in part 2 of the study, two different semi-structured interviews were conducted. The first interview was carried out on the two physiotherapists who received the patient movement feedback. This aimed to evaluate if and how they used this feedback in the rehabilitation of ACLD patients and if the usage evolved over time impacting on the type of rehabilitation patients received. The second interview was conducted on all four physiotherapists who treated patient in both the FB and no-FB groups to gain insight into the rehabilitation that ACLD patients received and if there were any differences between the FB and no-FB physiotherapists. The emerging themes related to each of these interviews will now be described.

4.20.1 Semi-structured interview 1: Feedback usage

Five themes were identified

1. The clinical usage of movement feedback in ACLD patient management:
    a. To evaluate outcome/recovery
    b. To inform rehabilitation techniques
2. Barriers to clinical application:
    a. Clinicians ability to interpret
    b. Clinical relevance
    c. Time factors
    d. When given
    e. Who given to
3. Evolving rehabilitation over time:
    a. Did the rehabilitation patients received evolve over time in response to physiotherapists adopting a different approach to rehabilitation?
4. Recommendations:
    a. For clinical application in the future
    b. For future research into movement feedback

4.20.2 Theme 1: Incorporated of feedback into treatment.

Both physiotherapist 1 and physiotherapist 2 used the movement feedback in the management of ACLD patients to evaluate recovery and inform treatment. In addition physiotherapist 2 used this information to help decide on how to progress patients. Gait analysis, one legged squat and distance hop were identified as activities that were particularly informative. Run and stop movement data was considered to provide the least useful information by both physiotherapists. They felt that the clinical signs and symptom data was something they already evaluated themselves and didn't add anything extra to the feedback. Physiotherapist 2 found the observational compensations section useful whereas physiotherapist 1 didn't. Specific examples of how the physiotherapists incorporated the movement analysis into treatment are given in Table 61. The physiotherapists had to be pushed with the questioning to try and establish how they interpreted the information and incorporated it into treatment.

Both physiotherapists reported that being provided with the movement feedback made them look more closely at the patient's movement strategies themselves and made them more aware of the quality of the movement, compensations and variables that they would not normally have considered. They reported doing this independently to the specific feedback sessions that were part of the research. As a result of receiving this information they themselves tried more with observational analysis when they were with the patients.

Table 61 Responses of the individual physiotherapists of how they incorporated the movement feedback into treatment.

PHYSIOTHERAPIST 1	PHYSIOTHERAPIST 2
Gait: if they were slow make them increase their speed	Squatting and hop flexion range: getting them to go through a greater range.
Think about energy absorption and which joints they were absorbing at. Depending on the range were they compensating with the ankle and protecting the knee?	Gait variables: making them speed up and take longer strides.
If they weren't flexing during an activity I would push them to see if they could.	Look at their pelvis and how much flexion they have in their knee.
Varus and valgus: make me think about control around the hip.	1 legged squatting - think about the need to do gleuts work.

The way in which the two physiotherapists applied the movement feedback to treatment was markedly different. Physiotherapist 1 reported that the feedback was not used on every patient because of timing issues, because it was obvious how some patients were recovering due to their poor performance, based on the physiotherapists own experience and observational analysis. In addition physiotherapist 1 never shared the movement feedback information with the patient; they just used it for their own reference. In contrast, physiotherapist 2 shared the information with the patient to make them aware of movement compensations, to indicate if these were recovering and to explain treatment progressions and goals.

4.20.3 Theme 2: Barriers to clinical application

Several barriers to applying the movement feedback into treatment were identified in the interview with physiotherapist 1 and are listed in Table 62. Fewer barriers were identified in the interview with physiotherapist 2. The main issue with physiotherapist 2 was lack of understanding and ability to interpret some of the variables. For example, ankle joint angle was not considered to be of relevance in an ACLD knee unless they had previous injury to the ankle. This indicated a lack of appreciation of whole lower limb adaptation to injury. Conversely physiotherapist 1 had a much greater understanding of whole lower limb adaptations and made some attempt to relate this information back to underlying reasons as to why individuals were performing as they were. The only muscular control strategies that either physiotherapist discussed were related to core stability and gluteal activity. For physiotherapist 1 this was applied to hopping and 1 legged squat and for physiotherapist 2 just to one legged squat. Interestingly, neither physiotherapist related ACLD performance back to the quadriceps or hamstring muscles, which cross the knee and are therefore the most likely to be involved following ACL rupture. This is surprising considering the emphasis that physiotherapists place on neuromuscular control within rehabilitation.

Table 62 Barriers to applying clinical movement analysis to patient management

PHYSIOTHERAPIST 1
Lack of understanding and ability to interpret: Didn't appreciate lack of accuracy associated with observational analysis. Felt that the uninjured reference terms were difficult to understand and needed to be simplified. Lack of acceptance of the information given, didn't consider that the control data truly represented healthy subjects and needed to be broken down into sub-groups.
Time constraints: The feedback was given immediately after seeing a patient whereas the next appointment may not be for several weeks so the information no longer seemed relevant. Sessions taking longer because observing more. The pressure to see patients and accompanying administrative duties detracted from evaluating the movement feedback.
Own experience: This inhibited his use of the movement feedback; it was considered that observational analysis was sufficient e.g valgus and varus with one legged squat, distance hopped.

4.20.4 Theme 3: Evolving rehabilitation over time:

Both physiotherapists indicated that their understanding of movement analysis increased over time. Physiotherapist 1 reported that the information actually meant more by the end of the study and was able to form his own impression of what the information meant and stated;

> *When you are first given the information at the beginning of the study as much as you are trying to understand the information it means more to you by the end of the study. You are starting to form your own impressions of what the values mean.*

Physiotherapist 2 reported greater confidence in treating these patients as a result of participating in this study. This included pushing patients a bit further to test their knee stability during their recovery, something this physiotherapist reported being too nervous to do previously and being more specific in movement observations at each stage.

Both physiotherapists indicated that participating in the study made them more aware of movement analysis and variables to observe, to the extent that they performed observational movement analysis themselves in addition to the identified feedback sessions that were part of the study. Physiotherapist 2 reported continuing to use movement feedback beyond the duration of the project.

4.20.5 Theme 4: Recommendations to improve usage

To improve the use of movement feedback initial training needed to go into greater depth about how to interpret patient data against the uninjured subject reference data. More guidance was required on how to relate the patient data to movement compensation strategies, what the underlying causes of those strategies were and how this could be targeted in rehabilitation. This was not included in the original training because the aim was not to dictate treatment to the physiotherapists. A phasing in period of using the movement data was required so that the physiotherapists had some time to familiarize themselves with the information and how to apply it to rehabilitation. Finally, Physiotherapist 2 felt that movement feedback on additional sports specific activities would have been beneficial.

4.20.6 Summary

Overall it seems that the movement feedback was applied only to some extent to rehabilitation of ACLD patients by the physiotherapists in the FB treatment group. Reasons for this include limited understanding of this clinical movement analysis and its application, experience and time constraints. In addition both physiotherapists underwent a period of learning. Finally both physiotherapists used the movement feedback differently in treatment.

To evaluate if there were differences in the rehabilitation that patients in the FB and no-FB groups received a further set of semi-structured interviews were carried out on all the physiotherapists in the FB and no-FB groups. If the FB physiotherapists had used the movement feedback in the rehabilitation then it was anticipated that this would have resulted in a slightly different treatment approach based around individual patient movement adaptations. If there were no differences in the treatment approaches between groups then this may help account for the lack of statistical differences between the two rehabilitation approaches.

4.20.7 Semi-structured interview 2: Rehabilitation techniques

Four interviews were conducted, two on the treating physiotherapists in the FB group and two on the no-FB physiotherapists. These interviews aimed to provide an overview of how the ACLD patients were rehabilitated and more specifically to evaluate if the FB physiotherapists placed greater emphasis on movement analysis and function, resulting in a different approach to rehabilitation. Three themes were evaluated, firstly, what factors were considered when designing a rehabilitation program, secondly what was the content of rehabilitation and thirdly what emphasis was placed on functional recovery.

4.20.8 Theme 1: Factors considered in rehabilitation design

All the physiotherapists mentioned the patients clinical symptoms such as pain, swelling, ROM and giving way as factors considered when designing rehabilitation programs. A number of other factors were identified and are listed in Table 63 along with the number of physiotherapists that identified them. The most commonly identified factors are listed first.

Table 63 Factors considered when designing a rehabilitation program

FACTOR	FACTOR FREQUENCY AMONGST PHYSIOTHERAPISTS
Clinical signs and symptoms: pain, swell, ROM	**Factor identified by all the physiotherapists**
Stage in the disease process/ natural history of ACL rupture	**Factors identified by 3 physiotherapists**
Patients expectations, beliefs and understanding of injury	
Patient goals and pre-injury activity levels	
Level of function	**Factors identified by only one physiotherapist from each treatment group**
Muscle power, muscle activity	
Compensations and adaptations	
Age	
Rehabilitation facilities	
Other pathology	

4.20.9 Theme 2: Content of rehabilitation

The physiotherapists included ROM activities, strengthening, fitness training, proprioceptive/balance activities, core stability exercises, functional activities progressing from gait and ADL to sports specific activities, goal setting, home training program and advice. The content of rehabilitation was very similar between all of the physiotherapists and no obvious difference in the content could be identified. The rehabilitation content was similar to the activities described in published rehabilitation guidelines (Fitzgerald et al. 2000b; Manal Snyder-Mackler 1996; Brukner & Khan 1993) and took a deficit approach towards rehabilitation (Sugden 2007). All the physiotherapists described their progression of functional activities based on biomechanical principles such as direction of force, increasing loading, base of support. Providing advice features highly as a component of rehabilitation, a summary of advice topics given is in Table 64.

Table 64 Advice topics given by physiotherapists

ACL anatomy and function
Symptoms and outcome
Why rehabilitate
Surgery
Life style changes

Incorporating functional activities as exercises into rehabilitation featured strongly in all of the rehabilitation given by the physiotherapists but there was no mention by the FB physiotherapists of combining this with clinical movement analysis or movement feedback.

4.20.10 Theme 3: Incorporation of movement analysis

Neither of the physiotherapists from the feedback group mentioned identifying or addressing individual patient movement compensations and adaptations. In contrast one physiotherapist in the no-FB group did. Factors that influenced the decision to progress functional activities included; giving way symptoms, patient apprehension/confidence, and ability to perform or not able to perform the specified activity. Movement analysis data for time-distance variables and lower limb joint angles, which were given to the FB physiotherapists, were not given as a factor influencing progression.

4.20.11 Summary

Evidence from the semi-structured interviews would indicate that there was a similar approach in the rehabilitation given by the FB and no-FB physiotherapists. Both groups designed rehabilitation around deficits that would be expected in an ACLD knee and exercises to counteract this; strengthening, balance/proprioception and ROM. Functional activities were incorporated as exercises but there was no evidence that this was combined with any form of clinical movement analysis to try and improve functional performance or measure functional outcome.

5.0 Discussion

The aim of this study was twofold. In part 1 the aim was to measure functional recovery longitudinally from acute injury and over the course of rehabilitation for a range of functional activities using a 2D clinical movement analysis system. This aimed to establish which aspects of functional performance could be used to evaluate outcome over time and direct the content of rehabilitation. For part 2 of the research an exploratory trial was developed which incorporated feedback about movement performance variables from part 1 into rehabilitation. This part of the study therefore aimed to evaluate if providing physiotherapists with movement feedback on ACLD patient functional performance over the course of rehabilitation resulted in a better functional outcome.

5.1 Summary of findings for part 1

Sixty three ACLD subjects entered onto this study and had their functional recovery measured over the course of their rehabilitation from the time of acute injury up to 6 months post injury. At 12 months post injury individuals were sub-classified as functional copers, adapters and non-copers based on subjective performance. Individual performances for each of the sub-groups were then modelled and could be compared descriptively. Recovery was measured according to performance over a wide range of functional activities that are commonly used in rehabilitation and subject the ACLD knee to different challenges. Due to the exploratory nature of this investigation it was unknown before data collection started how many subjects would be able to participate in all of the activities over time and at what point in the recovery process they would be able to commence the more challenging functional activities. To accommodate for this the analysis of functional recovery for each activity was split into 3 stages, with each stage providing a greater depth of analysis. Not all of the activities were analysed through each of the stages.

Overall all variables with time demonstrated recovery to within the normal limits set by the healthy subjects, although time-distance gait variables and hop distance demonstrated the most distinctive recovery patterns. These variables tracked change in performance over time and compared to control data were able to measure clinically significant change and evaluate recovery based on performance criteria based around the control mean and 1SD. Once individuals were sub-grouped into copers, adapters and non-copers each group demonstrated different recovery responses. Functional copers and adapters did recover to within normal limits but the non-copers recovery remained border-line, at the lower edge of 1SD from the control mean. Both sub-groups demonstrated altered relationships between gait variables compared to healthy subjects. Even though the gait of copers/adapters demonstrated greater recovery of the gait variables, they were still using altered strategies to achieve this.

5.2 Subjects

Prior to evaluating recovery of function for ACLD subjects it was important to establish if the ACLD and control groups were similar for demographic variables and exclude these as the underlying cause of differences in movement performance. Our analysis confirmed that these groups were matched for age, height, mass and gender. Similarly the ACLD sub-groups that had their recovery evaluated in stages 2 and 3 of the analysis for part one were matched for age, height, mass and gender, so these factors cannot be considered responsible for the differences between the groups. There was one distinguishing feature between the sub-groups; the adapters and non-copers had a higher ratio of individuals that played sports requiring a high level of jumping and pivoting pre-injury, whereas the copers did not. This is supported by previous studies which have found that individuals who spend more hours per week participating in jumping and cutting sports pre-injury will have a poorer outcome (Daniel et al. 1994; Fithian et al. 2005).

Finally the whole population of ACLD patients that attended the AKSS were compared descriptively to the sample of ACLD subjects that were included in this study. Data was only available for a limited number of variables but this aimed to provide an overview as to whether the results for the movement data could be generalized to the total population of ACLD subjects. The whole ACLD population and the study sample had similar age means and ranges but the study sample of ACL subjects contained more female subjects and a greater proportion of individuals participating in sports requiring a high degree of pivoting. This was probably due to the presence of a sports college within the UHW catchments for physiotherapy. This makes it all the more surprising that despite the higher proportion of high level athletes in this sample, recovery of the functional variables still took a considerable time. Based on demographic variables that were recorded the sub sample of ACLD subjects appear sufficiently representative of the total patient population although some caution is appropriate when generalizing the results of the movement data to the total population of ACLD subjects.

5.3 Gait

5.3.1 Recovery of function

Initially following injury, gait is the only activity that patients can perform and an altered gait pattern should be anticipated as a number of factors related to an acute knee injury such as pain, swelling, restricted ROM and instability can have a direct effect on gait time-distance and kinematic variables (Robon et al. 2000; Shrader et al. 2004; Torry et al. 2000; Cerny et al. 1994). In healthy subjects simulated knee flexion contractures have been found to result in reduced stride length, cadence and velocity (Cerny et al. 1994). Inducing an effusion in the knee of healthy subjects can result in increased knee flexion throughout the stance phase of gait (Torry et al. 2000). Pain relief in knee OA and knee arthroplasty patients has been found to lead to significant improvements in gait time-distance variables (Kroll et al. 1989; Shrader et al. 2004) and kinetic performance (Shrader et al. 2004). In addition many direct relationships exist between the gait parameters so a deviation to one variable can cause disruption to gait elsewhere. Some of the relationships that have been demonstrated between gait variables that are most relevant to this investigation were summarized in Figure 13, in the methods. Although relationships between these variables are well supported, there is much less agreement as to whether these relationships are linear, quadratic or if they are predictive (Andriacchi et al. 1977; Danion et al. 2003; Hay 2002; Voloshin

2000; Zatsiorky et al. 1994; Lelas et al. 2003). The relationship between gait velocity and the other time-distance variables and joint angles is particularly noteworthy and it is important with ACLD individuals to establish if any deviations are related to altered gait velocity or due to the pathology.

Based on the recovery plots modelled in part 1 of the current investigation, gait variables took far longer to recover than was anticipated but no studies have been carried out measuring recovery of gait over time using sufficient methodology to serve as a useful comparison. The rate of recovery was quickest initially and then gradually slowed. All variables were within the control reference values by 46 days post injury but took between 60 and 145 days to reach the control mean and even longer to plateau. The most distinctive adaptations and recovery were demonstrated for the gait time-distance variables. These variables were able to track change in performance over time, they demonstrated clinically significant change based on uninjured subject performance, they distinguished between the different functional sub-groups, could be measured over the whole course of treatment from initial injury and are relevant to participation in activities of daily living. Adaptations for knee and ankle joint angle were less pronounced, from the early days post injury ACLD joint angles were already within the normal limits of healthy subjects, these variables did not demonstrate clinically meaningful change and were less useful for tracking recovery. The only other study to monitor functional recovery of ACLD subjects over time found that it took between 2.8 and 4 weeks to achieve independent, non-antalgic gait, using visual analysis (Johnson et al. 2000). The quickness of this recovery is possibly due to using unstructured observational analysis; a less sensitive and less reliable method of gait analysis (Brunnekreef et al. 2005; McGinley et al. 2006).

The initial compensation strategy for the ACLD subjects in this investigation was to walk with a shorter step length, increased step length asymmetry and lower cadence, which resulted in a distinctly slower walking speed. Cadence quickly recovered to within control limits, this meant that patients were compensating by walking with shorter steps, making this an important variable for evaluating recovery over time. This strategy may have been adopted during the acute phase to ensure knee stability in the presence of swelling and restricted knee range of motion. We found that for ACLD subjects (unlike controls) step length had the strongest positive correlation with gait velocity. In control subjects cadence was more highly, positively correlated with gait speed. This finding is not surprising because at slow speeds in healthy subjects, step length is proposed to be the primary factor related to changes in gait speed. At high gait speed cadence has been found to be the primary influence (Hay 2002). It has also been proposed that changes in gait speed during free walking result more from a change in length than in frequency (Danion et al. 2003). Because the ACLD subjects in the current study have a reduced velocity in the acute phase post injury step length would be expected to have the strongest relationship to velocity. The eventual recovery of step length coincided with the recovery of the step length symmetry index back to 5%, which was the mean value of the controls in this investigation and that reported in healthy individuals in the literature (Auvinet et al. 2002). This variable did not contribute any additional information to step length for directing rehabilitation in this group of ACLD patients and was therefore not included in the movement feedback in part 2 of this study.

Altered gait joint angles at the ankle, knee and hip were present at 1 month compared to 4 months post injury although some of these adaptations were not very distinctive on the recovery plots. The knee angle was never outside the control limits and the ankle ROM at HS recovered to within 1SD of the controls by 18 days post injury. Descriptive analysis of these plots would suggest that gait joint angles make an early recovery. Based on the statistical analysis early gait compensations for joint angles were found and could be explained by the underlying gait time-distance adaptations. Gait deviations at the ankle and the hip could be due to ACLD subjects walking at a slower speed initially post injury, rather than the knee injury. Both of these variables have been found to be strongly positively correlated to gait speed in healthy subjects (Hanlon & Anderson 2005; Lelas et al. 2003). Our ACLD subjects displayed the same ankle and hip kinematic patterns as healthy subjects walking with a slower gait velocity, with a trend for reduced dorsiflexion at HS and a reduced HDA. At the knee joint our ACLD subjects were found to walk with increased knee flexion at both phases. In contrast, healthy subjects have reduced knee flexion with slower velocity (Kirtley et al. 1985; Hanlon & Anderson 2005; Lelas et al. 2003). Therefore the knee kinematic adaptations in our patients are probably related to their acute symptoms of swelling and restricted ROM (Cerny et al. 1994; Torry et al. 2000). But this will require further research to evaluate this.

In modelling recovery of the functional activities, time since injury was used as the predictor variable and a third order polynomial was chosen as the non-linear approximation of the recovery process. The adjusted r^2 found for this model was only 0.32 and therefore the predictive value of time from injury for estimating gait recovery was found to be fairly low. This means that to predict recovery of individuals more predictor variables are required and therefore the findings of this study will have a limited ability to generalize to other ACLD populations in terms of predicting functional recovery. Possible other variables that could have contributed to predicting the outcome such as age and activity level injury or performance variables such as muscle strength (Roberts et al. 2007) were not evaluated in this study. No further evaluation of predictive variables was made in the current investigation because the study was not designed for this particular analysis and future research would have to provide further insight into this matter.

Overall ACLD individuals appeared to eventually make a good recovery of gait and this is in support of the literature that has found few time-distance gait adaptations (DeVita et al. 1997; Georgoullis et al. 2003; Roberts et al. 1999a; Snyder-Mackler et al. 1995; Patel et al. 2003; Ferber et al. 2004; Muneta et al. 1998). This finding is in contrast to the subjective outcome that patients report at 12 months post injury; at which time a high proportion of non-copers report instability and functional adaptations during walking, particularly on uneven terrain or in unexpected circumstances. To understand gait deviations in these sub-groups of ACLD individuals the analysis was repeated with individuals sub-divided into copers/adapters and non-copers.

5.3.2 Gait Sub-Group Analysis

Based on descriptive analysis of the recovery plots, initially post injury ACLD sub-groups compensated with a slower gait velocity and shorter step length. For cadence only non-copers and adapters initially performed outside the normal limits. For most gait parameters the non-copers struggled to return within normal limits set by the controls. Conversely, all gait parameters for the copers returned well within normal limits of within 1SD of the uninjured control mean by 40 days post injury. This meant that copers were identifiable from the non-copers at this time based on the simple gait variables; cadence, step length and velocity. The functional adapters had a recovery similar to the copers but it was not possible to identify a time post injury when these individuals could be distinguished from the copers. In a health service with long surgical waiting lists it would be beneficial to be able to prioritise cases with the greatest functional loss. If as suggested by the results of this study, non-copers are identifiable by 40 days post injury using gait parameters, then this fits in well with current practice and guidelines about when ideally to perform an ACL reconstruction (Francis et al. 2001; Karlsson et al. 1999).

Bases on a statistical analysis of a sub-population of the ACL non-copers and copers/adapters, the gait adaptations that were noted on the functional recovery plots were still present at 4 months post injury; the non-copers did not demonstrate the same amount of recovery as copers/adapters at 4 months. The copers and adapters were combined for the statistical analysis due to insufficient numbers of copers. Non-copers continued to walk with a slower gait velocity as a result of a lower cadence and shorter step length on the non-injured leg, which is consistent with other studies on healthy subjects (Andriaccchi et al. 1977; Hay 2002; Voloshin 2000; Zatsioky et al. 1994). Step length continued to have the strongest relationship with gait velocity followed by cadence. This was the same altered relationship that all ACLD subjects demonstrated at 1 month post injury.

Statistical analysis also confirmed that adaptation of the joint angles persisted in the non-coper gait at 4 months post injury. These individuals demonstrated increased knee flexion at HS of the injured leg despite full passive range of motion. Clinically this small increase in knee flexion is important because it is thought to reflect quadriceps weakness in ACLD individuals (Snyder-Mackler et al. 1995). Without using video analysis this adaptation is unlikely to be identifiable. Weakness of the hip extensors has also been proposed as a cause of increased knee flexion in uninjured individuals (Arnold et al. 2005). Additionally, apprehension of giving way could have resulted in increased knee flexion, which has been demonstrated in ACLD subjects (Ferber et al. 2003). Clinical factors were found to be similar between our groups, so the effects of swelling, ROM, amount of physiotherapy, activity levels and pathology are considered minimal, although differences have not been explored in this study nor tested statistically. The increased knee flexion did not result in a reduction of step length or gait velocity; no significant correlation was found between these variables. Increasing the knee flexion angle would potentially stabilise the knee by placing the hamstrings in a more favorable position to contribute to knee stability (Li et al. 1999; Roberts et al. 1999a), although there is debate about the ability of the hamstrings to achieve this at such low flexion angles (Markolf et al. 2004). The line of action of the quadriceps would also be altered placing them in a less favourable position to generate large unopposed forces that could result in an increased range of ATT and potential instability (Li et al. 1999). The increased knee flexion could be consistent with a proposed generalised hamstring/quadriceps co-activation pattern to stabilize the knee (Roberts et al. 1999a; Rudolph et al. 1998). In line with the increased knee flexion there was a trend for reduced ankle dorsi-flexion of the involved leg at HS. This is an ankle response that has been demonstrated in more pronounced knee fixed flexion deformities (Cerny et al. 1994). It is proposed that this reduction in dorsi-flexion although not significant in this study may help to maintain limb length and therefore step length and velocity.

The reduced HDA in the non-copers was found to be positively correlated to step length and gait velocity. Weak hip extensors and quadriceps of the injured leg could lead to reduced hip extension therefore a reduced HDA, step length and velocity (Arnold et al. 2005). Apprehension of giving way may also lead to gait adaptations. Reduced non-injured limb HDA would contribute to knee stability by reducing the single leg support time and biomechanical load on the injured leg. This explains why no HDA adaptations were found in the uninjured limb as it was not required to contribute to stability of this limb.

We have previously indicated that the time-distance gait variables of the coper/adapters recovered within 1SD of the control mean. Despite this our results indicate that the copers/adapters did not demonstrate a complete recovery. Some of the correlations were not re-established to the normal situation: step length and non-injured HDA did not correlate with gait velocity after a period of recovery. It is unknown if individuals were still undergoing recovery at 4 months so still re-establishing the relationship between the variables or if their recovery had reached a plateau and this compensation represented a strategy that generally allowed them to maintain stability of the knee. The implication of this incomplete return to normal is that during more demanding situations such as small perturbations or in response to unexpected events, when gait needs to be adaptable ACLD individuals would have a poor ability to utilise alterations in step length, which could increase their risk of instability (Stergiou et al. 2004). Reorganisation and co-ordination of joint angles in response to learning has been identified in non-injured individuals. When learning a new dynamic balance task stronger cross correlations between lower limb joint angles were noted with practice (Ko et al. 2003a). A response to practice whilst learning a ski simulator task was greater movement at lower limb joints; which has been termed 'an unfreezing of degrees of freedom' (Vereijken et al. 1992; Vereijken et al. 1997). Although joint angles were evaluated rather than time-distance variables this restricted utilization of joint angles could represent a similar strategy to that occurring in the ACLD patients for time-distance variables in the current investigation. When still recovering ACLD individuals are not utilizing all the strategies available to them to adapt performance.

Very few studies have been conducted analysing gait compensation strategies in the acute phase post ACL rupture or between ACL sub-groups over time, most of the work has been carried out on individuals with chronic rupture. Many of the compensation strategies that have been identified in the literature for time-distance variables and joint angles differ to those found in the current study (DeVita et al. 1997; Georgoulis et al. 2003; Lewek et al. 2002; Alkjaer et al. 2003; Hurd & Snyder-Mackler 2007). There is very little agreement between gait compensation strategies identified in the literature and those found in this study. These differences in gait compensations will now be identified and reasons for this discussed. Overall few gait time-distance adaptations have been identified for actute, chronic or sub-groups of ACLD individuals (DeVita et al. 1997; Georgoulis et al. 2003; Alkjaer et al. 2003; Rudolph et al. 1998; Rudolph et al. 2001), compared to our finding of reduced cadence, step length and velocity. The only adaptation that reflects the time-distance variables analysed in the current study is a reduced step length following acute rupture (Knoll et al. 2004). Overall there is a consensus in the literature for altered knee joint angle; during walking ACLD patients tend to walk with a reduced excursion range of knee flexion also known as a knee stiffening strategy (Snyder-Mackler et al. 1995; Muneta et al. 1998; Rudolph et al. 1998; Roberts et al. 1999a; Rudolph et al. 2001; Patel et al. 2003; Ferber et al. 2004; Hurd & Snyder-Mackler 2007). This may have been a strategy adopted by our ACLD patients as represented by the increased knee flexion at heel strike in non-copers but our analysis is limited to just the one phase of gait so no firm conclusion can be drawn based on our data. The presence of increased or reduced knee flexion at heel strike in the literature is less well established. Rudolph et al. (2001) found a reduced flexion excursion range despite individuals using increased extension at heel strike. Our subjects walked with a reduced hip displacement angle on the non-injured leg. In the literature the only hip compensation strategy was increased hip flexion during stance in chronic ACLD individuals (Ferber et al. 2004; Ferber et al. 2004). It is difficult to compare these findings because the two variables analyse different aspects of hip function. No adaptations in ankle joint angle have been identified in the literature for acute, chronic ACLD individuals or functional sub-groups. We found an early compensation strategy of reduced dorsi-flexion at heel strike that was just a non-significant trend at 4 months post injury.

One of the major reasons why the results of our study conflict with the results of previous studies is the population of ACLD individuals analysed. We have been more liberal in our inclusion criteria and included individuals with ACL ruptures combined with MCL and meniscal tears (not requiring urgent surgery). This has been done because ACL ruptures commonly present with these associated injuries and therefore represents the population that is seen within an Emergency Unit and referred for rehabilitation within the NHS in the UK. Another difference is that the population in the current study was made up of recreational athletes that participated in sport to varying levels and activities that placed varying demands on the knee. In contrast some of the studies have only analysed ACLD individuals that participate in high level activities (Rudolph et al. 2001). Other differences can be explained because there is no standardized time from injury to timing of movement analysis across studies, few studies have been conducted on acutely injured individuals (Hurd & Snyder-Mackler 2007) and others have used a combination of individuals with acute and chronic ruptures (Andriacchi & Dyrby 2005) which may have obscured some gait compensation strategies. Our patients were analysed at a shorter follow-up time from injury (0 to 6 months) as opposed to one or more years post injury in many other studies (Alkjaer et al. 2003; Rudolph et al. 1998; Rudolph et al. 2001). In these studies this delay has allowed additional time for further recovery and adaptation. This could also alter the population of non-copers analysed because non-copers that are functioning at a very low level may already have undergone a reconstruction and would therefore not be included in the analysis, which may result in an overall superior gait performance. Additional reasons for the contrasting results are that kinematic variables have been analysed at different time points in the gait cycle or the time-distance variables have been represented as a percentage of leg length (Rudolph et al. 1998; Rudolph et al. 2001), making comparison across studies challenging. In the current study gait deviations were most marked for the non-copers, these may have been masked if the ACLD subjects had not been sub-grouped and analysed altogether as one group (Torry et al. 2004). Sub-grouping individuals is probably an important consideration for any future studies with ACLD individuals to be able to evaluate their potential for recovering functional performance and ultimate level of participation. Clinical gait analysis was able to measure functional recovery of simple time-distance variables. Changes in performance over time for individual sub-groups were identified that suggest differences in outcome and could be used to influence rehabilitation content and long term management. Based on these findings non-copers cannot expect to make a complete recovery for gait.

Rehabilitation may need to be changed to address this or the goal lowered to just making these individuals safe with ADL.

5.4 Jogging

Our ACLD injured subjects started jogging at about 30 days post injury, once they had regained a full range of knee motion and their swelling had resolved. At this point in their recovery the time-distance variables were already within the control limits. Over time jogging velocity, cadence and step lengths demonstrated very little change. Cadence and step length did recover to the control mean but the jogging velocity for ACLD subjects consistently performed just below this but within the normal limits set by the control subjects. Failure of jogging to recover compared to controls has been found previously by Rudolph et al. (2001) and as a trend by Rudolph et al. (1998). In the current investigation the results were not tested statistically but it may have been that the ACLD subjects didn't recover a full jogging velocity but because it is within the normal limits it may not be clinically significant. In addition the analysis by Rudolph et al. (2001) and Rudolph et al. (1998) was performed on ACLD non-copers. Failure in the current study to sub-group the ACLD individuals may have concealed a failure of jogging velocity to recover for the non-copers. Overall jogging did not provide any additional information to gait on the recovery of function; with this activity we were able to identify incomplete borderline recovery for non-copers compared to controls. It would appear that once the acute symptoms recover then ACLD subjects are just able to jog, so rather than a recovery curve there is a threshold over which subjects can jog, indicating that this activity is best used as a milestone rather than a tracker of recovery. Being able to jog could be related to resolution of acute symptoms such as pain, swelling and regaining full range of motion. If this is the case then using it as a milestone would also indicate recovery of these clinical symptoms. Although there didn't appear to be any jogging compensation strategies for the current population of ACLD subjects, if other variables such as extensor moments were analysed then based on other results adaptations may have been identified (Berchuck et al. 1990; Lewek et al. 2002; Patel et al. 2003). It would not have been practical to measure kinetics in the clinical setting using a movement analysis system that is simple to use and interpret and relatively inexpensive. Although no recovery curve was demonstrated, jogging shouldn't be discarded, it is still an important functional activity because it is essential for the safe return to many sports but it is best used as a milestone. In the agility literature it has been concluded that there is a lack of correlation between straight line running performance and fast turning ability (Sheppard & Young 2006). Instead it might be advisable to include an analysis of run and rapid direction change in the clinical movement analysis, which challenges the rotational stability of the knee. It is often this type of movement that causes individuals knees to give way on return to high demand contact sports (Scavenius et al. 1999; Houck & Yack 2001). This would need to be included as a later milestone due to the challenging nature of this activity.

5.5 Distance Hop

Once ACLD individuals were able to hop they compensated by hopping shorter distances and appeared to use a reduced knee range during the landing phase (a stiffer landing). With time from injury the hop distance increased and stabilized at the control mean at 5 months post injury. The knee ROM during landing also increased back to the control mean but was not maintained and demonstrated some deterioration but was still within the control limits. By adopting these compensation strategies ACLD subjects would have been performing within the limits of their knee stability and preventing giving way. We did not measure pain to evaluate its influence but swelling and ROM had recovered by 88 days post injury, so should not have been influential. Both the reduced hop distance and the stiffer landing could have been related to quadriceps weakness (Roberts et al. 2007). Although compensations at the hip and ankle joint were not measured these could have been used as a strategy that resulted in force absorption being transferred away from the knee and directed at the hip or ankle (Orishimo & Kremenic 2006; Coventry et al. 2006).

The non-injured limb also hopped a shorter distance initially post injury but demonstrated recovery back to the control mean. This was at a faster rate than the injured leg. This initial reduction in non-injured leg hop distance was possibly due to over protection in the acute stage post injury. This would indicate that it is not sufficient to use the non-injured leg as the control to measure recovery in clinical practice or during research (O'Donnell et al. 2006). This casts doubt on the sensitivity of calculating the hop limb symmetry index (Barber et al. 1990; Gustavsson et al. 2006) to evaluate functional recovery and using the result to provide advice on sporting activities that is safe to participate in.

Hopping is recognized as a challenging activity for an ACLD knee, individuals need to be able to control large vertical and, in particular, knee joint shear forces, coupled with large extensor moments and rapid deceleration (Simpson & Pettit 1997; Colby et al. 2000; Rudolph et al. 2000). It is also considered to be representative of sporting manoeuvres. Therefore, due to the challenging nature of this activity it was anticipated that non-copers would compensate by hopping a shorter distance but this was not demonstrated in their recovery curve. Initially post injury they hopped the shortest distance and were slower to recover to within the control limits, but by 5 months post injury their overall mean hopping distance was surprisingly high and exceeded the control and copers/adapter means, reaching a plateau at the upper boundary of the control limits. In part, this may be explained by the fact that not all non-copers were able to hop for fear of knee giving way, potentially introducing a bias and as a consequence a small sample size. This problem was also encountered by Rudolph et al. (2000) and although it confirms that hopping is a more challenging task when assessing knee stability, it does mean that our results need to be interpreted with caution. There are two possible explanations that may have contributed to the coper sub-group hopping a shorter distance. The first is that pre-injury the majority of the coper group did not participate in activities requiring a high degree of jumping and pivoting so overall may never have had the ability to perform as well at the distance hop. The second explanation may be that a functionally stable knee involves knowledge of the limits of knee stability, achieved at the expense of distance hopped (Vereijken et al. 1997). The recovery curve for the copers/adapters had the same recovery as all the ACLD subjects before sub-grouping and recovered, reaching a plateau at the control mean. The 1SD boundary for these ACLD subjects also mirrored the control subjects but for the non-copers this SD band was larger indicating greater variability in hopping performance. Variability in performance is important and there needs to be a certain amount of variability to allow adaptation to different environments and task demands. It has been found that in pathology or when learning a new task this 'normal' amount of variability increases with the more challenging task demands and can decrease to normal limits as performance is improved (Ko et al. 2003a; Hong & Newell 2006; Ko et al. 2003b; Niechwiej-Szwedo et al. 2007).

The mean hopping distance for all the ACLD subjects and for the copers/ adapters in the current study falls into the range of 96cm to 155cm found in generalised populations of ACLD subjects (Gauffin et al. 1990; Neeb et al. 1997; Scavenius et al. 1999; Rudolph et al. 2000; Myklebust et al. 2003). The distance hopped by the non-copers exceeds this but no other studies have compared hopping distance between coper/adapters and non copers using an analysis comparable to that used in the current investigation. Another explanation for the long distance hopped by the non-copers is the population of ACLD subjects included in the sample. Because the subjects were on a waiting list, with little prioritization then there may have been more non-copers with varying ability at hopping. Many of the non-copers in other healthcare systems would already have been operated on. The reduced knee range during the deceleration phase of landing found in the current study has also been observed in non-copers (Rudolph et al. 2000). The limitation of their study is that it is based on a very small sample size of non-copers that were able to hop. In general populations of ACLD individuals no differences in knee flexion angles were noted (Gauffin et al. 1990; Muneta et al. 1998) but this variable is not comparable to range of knee motion variable used in this investigation and based on these studies it cannot be concluded that there is no adaptation in knee range of motion. ACLD subjects may have achieved full flexion during landing but this does not take into account their knee angle at initial contact. In addition, Muneta et al. (1998) used standardized hop distances at a maximum of 90cm, which based on the results presented and the literature this may not have been sufficiently challenging for the ACLD knee and therefore individuals would not have demonstrated any adaptations. Overall based on this investigation hop distance is a useful variable to measure recovery and track performance over time for ACLD individuals. Descriptively clinically significant change and recovery can be evaluated by comparing the ACLD to control data so hop distance can inform clinical practice on outcome and therefore direct rehabilitation. This variable was less valuable for distinguishing between functional sub-groups than the gait variables because so many non-copers were unable to perform, distorting the curve. Other variables related to hop distance such as variability in performance may be valuable variables to incorporate into the movement analysis in the future. Knee range was not a useful variable for tracking performance, like the jogging variables this is probably better used as a threshold value over which individuals need to perform to evaluate recovery.

5.6 Run and Stop

At 80 days post injury the knee range used by the ACLD subjects during the deceleration phase of R&S was already slightly greater than the control mean. This demonstrated deterioration over time and the ACLD individuals started using stiffer landings (reduced knee ROM), although this just fell within the lower boundary of normal limits set by the control subjects. Using stiffer landings could have been a strategy to stabilise the knee and prevent episodes of giving way due to reduced quadriceps strength (Patel et al. 2003). There are several reasons why this deterioration over time may have been noted:

1. As individuals experienced instability over time and became adapters and non-copers they may have changed their landing to compensate. This may have been accompanied with a change in landing style from a soft to a stiffer landing to stabilize the knee.
2. Fear of instability with more challenging activities may also have been a reason to use a stiffer landing.

It is also worth noting that the worst performing ACLD patients declined to perform this activity so there is less data available. This means that this relatively poor outcome is not due to the worst of the non-copers artificially reducing the recovery. This variable is potentially useful for combining with hop distance to evaluate if individuals can return to higher demand activities but not to track recovery over time but as a milestone, with a performance threshold over which they need to succeed. Based on our findings if knee range during run and stop is assessed too early it could give a false impression of run and stop ability for an individual; initial performance was good and deteriorated over time. A recovery phase early after injury would have been anticipated but there were insufficient numbers of ACLD individuals able to perform this activity before 80 days post injury, so modeling did not begin until after this time. An insufficient number of studies have been performed on run and stop to compare results of knee joint angle during the landing phase against but this is a variable that warrants further investigation if sufficient numbers of ACLD patients are available.

5.7 Part 2: Movement FB versus No-FB Rehabilitation

The aim of part 2 was to develop an exploratory trial to evaluate if providing physiotherapists with feedback on patient movement performance from the variables identified in part 1, would result in the ACLD patients achieving a better functional outcome. Feedback was provided in written format and its content was selected joint angles and time-distance variables for gait, one legged squat, run and stop and distance hop. The level of recovery a patient achieved was evaluated against performance of healthy control subjects from part 1 and set criteria to grade recovery. Based on the statistical analysis there were no differences in functional outcome between the FB and no-FB patient groups for any of the gait, one leg squat, distance hop or run and stop movement variables at 5 months post injury. Descriptively the recovery of gait for the FB group demonstrated a similar time course to that modelled for the ACLD patients in part 1. The overall mean recovery values for the FB and no-FB groups were not as good as those in part 1, indicating a lower functional recovery at 5 months but the FB group consistently performed better than the no-FB group although not statistically significant. Based on these results a secondary objective was developed, which aimed to evaluate if there was a difference in functional outcome for a combined ACLD group made up of the FB and no-FB subjects compared to uninjured control subjects. Statistically significant differences were found; the combined ACLD group demonstrated an incomplete recovery adopting adaptations during gait, distance hop and run and stop at 5 months post injury.

5.8 Functional performance: FB v no-FB rehabilitation

No difference in functional performance were found between the treatment groups at 5 months post injury for the selected joint angles and time-distance variables during gait, one legged squat, distance hop and run and stop. This would suggest that regardless of which treatment the ACLD subjects received both groups had the same level of functional recovery; the type of feedback given did not result in an improved functional outcome. The underlying explanations for these findings will be discussed and can be sub-categorised into; subject related factors, the feedback mode, content and implementation, the training given to the physiotherapists, and the rehabilitation patients received. The findings from the current investigation will also be discussed in relation to other published studies that have evaluated the effectiveness of external feedback on skill acquisition.

5.8.1 Subject characteristics and symptoms

Both treatment groups were matched for demographic characteristics of age, height, mass, gender, average number of physiotherapy sessions received, injury type and pre-injury activity levels. This indicates that these factors did not influence the overall result of no difference in treatment outcome between the FB and no-FB rehabilitation.

Knee symptoms such as pain and swelling are known to cause altered movement strategies. It was therefore important to check whether the symptoms experienced by the ACLD knee subjects were different between the treatment groups. This was evaluated using the symptom scales of the Cincinnati knee rating system. Both groups were matched for pain, giving way, swelling and global knee rating so these factors contributed to movement adaptations equally between the treatment groups. Activity levels at 5 months post injury and the level of functional coping, adapting and non-coping was also similar between groups. Other subject factors such as the reason for drop out and dropout rate were similar between the groups. Although the overall drop out rate of 60% was very high because it was similar between the groups it did not appear to contribute to any follow-up or selection bias.

At the conclusion of data collection for part 2 of the study, 27 data sets had been collected for the FB group and 25 for the no-FB group, which was considerably fewer than required based on our sample size calculations. Insufficient numbers of individuals being followed up will have weakened the treatment effect of the feedback rehabilitation and the power of the study, this is also known as a type 2 error. Based on our results for selected movement variables the study power and sample size has been re-calculated retrospectively. These results indicate that for gait velocity we had a power of 0.17 and a sample size of 188 individuals would have been required per group to demonstrate a treatment effect. Similar results were found for hop distance; a power of 0.16 and sample size of 207 per group. It can be concluded that based on the numbers attending the AKSS it would not be feasible to carry out a study requiring this number of subjects in a single centre. Because rehabilitation is a complex intervention trying to evaluate subtle treatment differences by manipulating one component of rehabilitation and thereby finding differences in treatment effect may be difficult. Using the research framework for complex interventions developed by Campbell et al. (2000) more time may need to be spent in the modelling phase, identifying rehabilitation components that will affect treatment outcome and thereby developing the rehabilitation intervention before progressing to an exploratory trial. Careful consideration is also required to decide on an appropriate comparison intervention for an exploratory trial. Because of small standard differences between treatments with subtle differences, this necessitates large sample sizes. It may be more appropriate to develop research questions that evaluate the effectiveness of rehabilitation or no rehabilitation or conservative versus early surgical management for individuals with ACL rupture than research questions evaluating subtle differences in rehabilitation technique.

5.8.2 Feedback

Providing movement feedback compared to no feedback was the rehabilitation component that was manipulated in this exploratory trial but this resulted in the same functional outcome, there was no difference between the treatment groups at 5 months post injury. There are several factors related to the feedback that could have influenced this outcome such as: interpretation and application of feedback into treatment, the feedback criteria used to evaluate recovery, the type and mode of feedback and the timing of the feedback. Each of these factors may have contributed to weakening the treatment effect of the feedback and contributing to the non-significant findings. Each of these factors will be discussed in turn and recommendations suggested.

5.8.2.1 The interpretation and application of movement feedback.

Evaluating the effectiveness of incorporating feedback into treatment was firstly dependant on the feedback being correctly interpreted by the treating physiotherapists and secondly, based on this interpretation tailoring the rehabilitation accordingly. To evaluate their success semi structured interviews were conducted with the FB physiotherapists. The principal findings were that the two physiotherapists interpreted the information differently and had different strategies for applying into treatment, these 2 strategies are summarised in Table 65. It is important to highlight that physiotherapist 1 did not always use the feedback; if it was not being used then this would have undermined its treatment effect. This factor is even more important because the study already had a small sample size as discussed previously. Both of the physiotherapists reported a learning effect over time, resulting in them having increased ability to interpret and apply the feedback and greater confidence treating these patients by the end of the study. This probably impacted on the rehabilitation given and resulted in the treatment changing over the course of the study. It is not known how long this learning took but it could imply that initially the treatment given by the FB physiotherapists did not differ from that of the no-FB physiotherapists. This would have weakened the treatment effect of the movement feedback on rehabilitation, making it more unlikely to find a treatment group difference, in a study design where the differences in rehabilitation programs was already subtle.

Table 65 Strategies of the two physiotherapists for applying feedback

PHYSIOTHERAPIST 1	PHYSIOTHERAPIST 2
Didn't use on all patients and never shared the information with patients.	Shared with patient to make aware of compensations, indicate recovery and explain progressions and goals.
Felt own observational analysis and experience adequate.	Acknowledged lack of understanding and ability to interpret some variables therefore not made best use of the feedback.

The physiotherapists did not relate the movement adaptations back to underlying muscle performance and co-ordination for the hamstrings and quadriceps. This would have been expected based on the literature concerning the importance of these muscles in knee stability (Markolf et al. 2004; Issac et al. 2005; Doorenbosch & Harlaar 2003) and the findings of increased knee flexion during gait and reduced knee range during distance hop and run and stop in the current investigation. This suggests an underlying lack of understanding of the movement feedback and therefore difficulty applying the findings to treatment. Conversely both physiotherapists placed emphasis on hip joint angles during challenging activities and the relationship between the resulting joint angles with gluteal muscle activity and core stability. This was something that they were observing for themselves and did not receive feedback on. This is interesting for two reasons, firstly their increased understanding of hip joint angle and muscle activity over that occurring at the ankle and in particular at the knee which is the anatomical region of injury. Secondly the physiotherapists indicated difficulty applying knee and ankle joint angle data to treatment but they felt able to do this for the hip joint.

Neither of the physiotherapists found the symptom information useful they thought that was something they were already evaluating themselves. One of the physiotherapists thought that their own experience and observational analysis was adequate for evaluating patient outcome, despite known limitations of observational movement analysis (Kawamura et al. 2007; Krosshaug et al. 2007). This will have further hindered use and application of the movement feedback into treatment, weakening its effect.

5.8.2.2 The feedback criteria used to evaluate recovery

Based on the clinicians' experiences of using the feedback reported in the semi-structures interviews and recent developments in the literature, the criteria used to grade treatment priority could undergo some refinement to improve usage of movement feedback. One issue is that the cut-off value used to evaluate treatment priority was possibly too lenient, reducing the impact of this information on the clinicians and therefore application to treatment. The cut-off criteria used in the feedback to classify the clinical priority of any movement adaptations was 1SD either side of the control mean (Kendal 1999). If the magnitude of a variable fell within the 1SD range then this variable was classified as recovered and had no clinical priority, if it fell outside of this then it was rated as having a moderate clinical priority. If the variable value was close to the cut off point then this was rated as a low clinical priority. Based on the results of part 1, ACLD non-copers were distinguishable by a recovery which was close to the lower border of the normal limits. This means that for some non-copers the magnitude of movement variables would have fallen into the normal limits but for others fallen outside. As a result 1SD may have been too lenient a cut off point for evaluating individual performances against and an ideal cut-off point would have classified ACLD non-copers outside the 'normal limits', therefore other cut off points such as 0.5SD should be investigated. This has recently been recommended by Cisler et al. (2005) when evaluating treatment of alcoholism. These authors explored cut off criterion ranging from 0.5 to 2.0SD but in their study performance was not evaluated against uninjured healthy controls but compared to the patient pre treatment 'dysfunctional' scores, a method developed by Jacobson and Traux (1991). 2SD in the direction of functionality was used as the cut-off score; this meant for an individual to be classified as functional the post treatment score had to fall outside the range for the dysfunctional pre-treatment scores. The alcoholism evaluated in this study was a chronic condition and a different set of criteria rules may apply to acutely injured patients. In a review of applying clinical significance to quality of life measures, Norman et al. (2003) identified that when normally healthy individuals suffer an episode of pain that they are expected to recover from, then there is only a narrow margin in which to detect clinically significant change, so the cut-off score may need to be lower such as +/-0.5, as opposed to +/-2.0SD for a pathology that individuals may not be expected to make a full recovery from. This means that the level of expected impairment, time of follow-up and pathology all need to be considered when defining cut-off points and will be specific to the population being evaluated (Norman et al. 2003; Beaton 2003).

In practical terms for the current study the consequence of having a 1SD cut off point means that for some patients a clinical priority may have been reduced too early, or the physiotherapists may have interpreted a variable that just falls within normal limits as being fully recovered and therefore not incorporated movement feedback into rehabilitation. Individuals that had scores close to the cut off point may or may not have been sufficiently recovered, as acknowledged by Jacobson et al. (1999). This was demonstrated in part 1 of the current investigation, it was found that even after individuals had recovered into within 1SD of the control mean, their performance continued to recover. This suggests that individuals are functional when they are within 1SD of the control mean but they are not recovered so treatment may still be required, especially if maximising participation is the ultimate goal. Therefore the rehabilitation target should be achievement of a performance at the level of the control mean. If these methods of evaluating clinically significant change are to be applied to patient management it is essential that training incorporates this information. Specifically when interpreting the cut-off score there needs to be some flexibility and recognition that patients may continue to improve even after reaching this score.

There is a second stage to analysing clinical significance, this evaluates if a change in an individual's score is a reliable change and not due to measurement error. This involves calculating a reliable change index (RCI) by dividing the magnitude of change between pre and post treatment by the standard error of the difference scores (Jacobson et al. 1999). If the RCI is greater or lesser than 1.96 an individual is categorised as either reliably improved or reliably deteriorated. Using the cut off score for clinical significance in combination with the RCI results in five different categories that an individual can be classified into (Cisler et al. 2005):

1. Recovered (functional, reliably improved),
2. Functional but not improved (functional, reliably unchanged)
3. Improved but not functional (dysfunctional, reliably improved),
4. No Change (dysfunctional, reliably unchanged),
5. Reliably Deteriorated (dysfunctional, reliably deteriorated).

This classification method is a useful tool for evaluating the clinical significance of treatment outcome but it was too recent a development to have been incorporated into the current investigation. Nevertheless it does provide clinicians with even more detail of recovery and treatment outcome that takes into consideration functional change based not only on performance but also accuracy of the measurement tool. It also provides more precise definitions of functional status without the need for terminology that the physiotherapists in the current investigation found confusing and had difficulties understanding and did not trust such as standard deviation.

5.8.2.3 Type of feedback

The current study focused on providing written feedback to the physiotherapist with the anticipation that this would result in them either changing the rehabilitation in some way or that the physiotherapist would share this information with the patient, resulting in an improved functional performance. No significant improvement was found in the group that received FB compared to the group that had no-FB which could have been because feedback is of no benefit in maximising recovery or just this mode of feedback and the way it was applied was of no further benefit. The findings of the current investigation are not unique, other studies have also found no advantage of providing external feedback of varying types to healthy subjects learning a complex ice skating task (Haguenauer et al. 2005) or in the rehabilitation of patients with patello-femoral pain (Dursun et al. 2001; Yip & Ng 2006). The findings of studies that have demonstrated improved performance in individual's receiving external feedback are limited by their methodology, in particularly because they have not included an adequate control group receiving no feedback to compare against (Sinkjaer & Arendt-Nielsen 1991; Tsoa and Hodges 2007; McGraw-Hunter et al. 2006; Tzetzis &

Votsis 2006; Yoo & Chung 2006; Cirstea et al. 2006; Lam & Dietz 2004; Sinkjaer & Arendt-Nielsen 1991) or have failed to evaluate if feedback resulted in improved level of participation in addition to improved task performance (Qi & Ng 2007). The majority of previous studies evaluating feedback have compared the effectiveness of different types of feedback, such as; verbal feedback on errors in combination with and without video feedback (Kernodle et al. 2001), verbal feedback in conjunction with information on errors and correction methods (Tzetzis & Votsis 2006); different combinations of visual and verbal feedback (Janelle et al. 2003); visual feedback with or without mental practice (Yoo & Chang 2006); auditory feedback and imagery (McNair et al. 2000). There is insufficient evidence to suggest that one method is superior to another. Using written feedback is unique and has not been evaluated previously in conjunction with movement variables and functional activities. Previous studies have demonstrated that a number of other components of feedback can be beneficial in skill acquisition, such as information on errors and corrections (McGraw-Hunter et al. 2006; Tzetzis & Votsis 2006), including feedback on KoR and KoP (Cirstea et al. 2006; Badets et al. 2006; Badets & Blandin 2005; Tzetsis & Votsis 2006; Janelle et al. 1997), taking into consideration the stage of learning (Haguenauer et al. 2005; Kernodle et al. 2001) and any cognitive impairments (Cirstea et al. 2006). Based on these findings the strength of the feedback in the current investigation is that it did use a combination of KoP and KoR and identified errors and correct performance but left the physiotherapist to interpret how this may impact treatment or recovery. A further strength of the current feedback was that it evaluated functional performance measures and not deficits at the structure level in accordance with the ICF. It also included variables that were known to be relevant to performance and recovery following ACL rupture from the results obtained in part 1 of the study. Based on these results it was determined that a progression of activities was required as performance ability would change with time from injury. Therefore it was designed to include gait analysis which provided most insight into early recovery, hopping and run and stop, which evaluated more sports specific function. Jogging was excluded because it demonstrated no recovery and instead one legged squat was included as an intermediate activity.

Most of the studies that have evaluated the effectiveness of feedback have been conducted on healthy subjects learning novel tasks. It should therefore be anticipated that the effectiveness of using movement feedback will potentially be different in ACLD patients, for two reasons. Firstly the influence of the pathology and the symptoms associated with this injury such as pain, swelling and muscle weakness, which can cause altered movement strategies. Secondly, in the studies with healthy subjects these individuals are learning a new skill or developing a skill to a new performance level that they have never achieved before. This is in contrast to the ACLD patients in the current study who were relearning activities and skills that they already had experience of or were skilled at performing before their injury. Prior experience has been found to influence motor learning so it would have been anticipated that this would have enhanced the movement performance of the ACLD individuals (Wenderoth et al. 2002; Kostrubiec & Zanone 2002) but this was not found to be the case.

Other aspects of how the feedback was applied could also have contributed to the non-significant results obtained, in particular the timing of the feedback. One of the physiotherapists felt that because the information was not available on the day but had to wait until the patient's next physiotherapy appointment then this delay made the feedback less relevant. It is assumed that this is one of the factors that resulted in the same physiotherapist reporting that they did not use the feedback on every patient. It was not possible to provide immediate feedback due to the number of activities and variables analysed for the feedback. This could have been addressed in the pre-trial training; the physiotherapists needed to be advised that their usual rehabilitation schedule would have to change to accommodate the feedback, so that after a session of movement feedback the next treatment would need to be in quick succession.

The movement analysis that was performed in SiliconCoach would allow immediate feedback but the trade off would be that the number of activities and variables analysed would have to be reduced to accommodate this and therefore would not result in such a complete analysis of functional performance. If reduction in the number of variables was required to facilitate the use of movement feedback into clinical practice then further studies to evaluate which are the most important variables for predicting performance would be required. Alternatively there needs to be a change in philosophy of how movement feedback is incorporated into treatment. Maybe the therapist needs to schedule rehabilitation so that within a 'feedback session' movement is analysed, feedback given and treatment adjusted accordingly at the expense of performing other activities within the rehabilitation session. The advantages of this are that the number of feedback activities/variables can be maintained and due to the feedback occurring within a treatment session both the clinician and patient are active participants in the process.

5.8.2.4 Training

Although physiotherapists reported finding the feedback information useful they directly and indirectly indicated difficulties interpreting the information, understanding terminology, incorporating it into practice and therefore adapting treatment. The implication therefore is that the pre-study training that the physiotherapists were given needed to be more specific and facilitate greater understanding of the terminology used, functional outcomes, movement adaptation, how this applies to functional performance and how this can be addressed in treatment. As mentioned above there also needs to be training on methods of incorporating feedback into the schedule of treatment sessions and that this may involve altering the way in which they normally practice. Part of this training would also involve providing time to allow physiotherapists to familiarise themselves with the feedback before beginning data collection. The aim of allowing this time is that it would increase the physiotherapist's usage of the feedback and allow their treatments to evolve before the study began, as has been mentioned previously as a factor that weakened the treatment effect of the feedback.

In summary no significant benefit was found with using this type of feedback to improve performance in patients with ACL rupture. By identifying all the factors related to the feedback that could have contributed to this outcome such as mode of feedback, timing of feedback, recovery cut off scores, training and evolving treatment over time it is evident that feedback itself is a complex intervention with several components that need to be considered to maximise its effectiveness in rehabilitation. It is evident that further training on functional outcomes, movement analysis, implications for rehabilitation and information on how incorporating into treatment may change practice are required to maximise the feedback usage and minimise the influence that these factors play on weakening the feedback treatment effect.

5.8.3 Treatment

To evaluate the effectiveness of a particular treatment it is essential to check that patients received the intended treatment. For the purpose of this investigation it was important to establish if the physiotherapists in the FB group used the feedback, what other treatment modalities were included and could the rehabilitation given by the FB physiotherapists be distinguished from that of the no-FB physiotherapists. To find a difference in the treatment outcome between the FB and no-FB groups it was anticipated that the treatments received by the two groups would be different. In the first set of semi-structured interviews the FB physiotherapists reported that their observational skills and awareness of performance increased through participating in this study but it was unknown if this was enough to result in a different type of treatment. All of the points above were evaluated in the second set of semi-structured interviews. Based on the findings of these interviews it is apparent that the FB physiotherapists had some difficulty incorporating the feedback into treatment and there were no distinguishable differences in the content of the rehabilitation between the two groups. The factor most commonly identified as being considered when planning rehabilitation was the patient's symptoms, followed by the patient's expectations, goals and pathology. Activities reported by all of the physiotherapists as being included in the rehabilitation were advice, ROM, strengthening, fitness training, balance/proprioception training, core stability and functional and sports specific activities, which is similar to published guidelines (Fitzgerald et al. 2000b; Manal & Snyder-Mackler 1996; Brukner and Khan 1993). Feedback was not mentioned and the decision to progress functional activities was not influenced by movement variables but by patient confidence, giving way and ability to/not to perform. The only physiotherapist to mention including movement feedback into rehabilitation was one of the physiotherapists from the no-FB treatment group. Overall it appears that the physiotherapists from both groups took the same approach to rehabilitation which that focused on deficits, particularly of clinical symptoms.

Finally not all of the patients in the FB group attended all 3 of the movement feedback sessions; some received 2 or fewer. The impact of this is unknown but it is anticipated that in combination with the lack of difference in the approach to rehabilitation between the FB and no-FB physiotherapists, that this will also have contributed to weakening the treatment effect of the feedback and reduced the likelihood of finding significant differences between the treatments.

5.8.4 Summary

The movement feedback used in this investigation was developed around the findings from part 1 of the study. Functional outcomes that were identified as being able to model change in performance over time, demonstrate clinically significant differences in recovery between the ACLD functional sub-groups and progressively challenged the ACLD knee stability were incorporated into the movement feedback. Cut off scores based around the performance of control subjects were identified so that the severity of movement adaptations could be graded. This was then given to the treating physiotherapist in written format with the assumption that they would use this information to evaluate outcome and direct treatment accordingly. No significant differences in functional outcome were found between ACLD patients treated with a FB compared to the no-FB rehabilitation program. Our findings are not unique; numerous other investigations evaluating movement feedback effectiveness have also found no difference in treatment outcome in healthy individuals or patients with neurological or musculo-skeletal pathology. Several factors have been identified that resulted in a weakening of the treatment effect of the feedback and contributed to the current findings. One of the major factors was that the physiotherapists had difficulty interpreting and applying the feedback, resulting in them implementing it in different ways, not at all or having a learning effect on their treatment over time. The timing of the feedback was also identified as a barrier to implementation. Overall there appeared to be no difference in the treatment given by the physiotherapists in FB and no-FB groups. The final factor identified as contributing to the outcome of the current study is the low study power. The main implications of these findings is the need for more specific training on movement adaptations, how this may alter treatment and how rehabilitation may need to change to allow this type of feedback to be utilised. There also needs to be further exploration of the value of providing immediate movement feedback on treatment outcome. Finally there needs to be careful consideration of the research question and if it is feasible if there are only to be subtle differences in the rehabilitation and therefore a low standard difference in treatment effect.

5.9 Modelling Functional Recovery

Using the same analysis as part 1, functional recovery was modelled using a least squares method 3rd order polynomial. This plotted the recovery of the FB group along with the FB and no-FB mean and SD, for selected gait and distance hop movement variables. This data was superimposed onto the recovery plots from part 1, to allow comparison. Based on the gait and distance hop recovery curves the FB group demonstrated a similar recovery curve as the ACLD subjects in part 1, with both groups recovering to within the 'normal limits' set as 1SD either side of the control mean for; gait velocity, cadence, step length, step length symmetry and injured and non-injured leg hop distance. The only variables to recover back to the control mean for the FB group were step length at 55 days post injury and non-injured leg hop distance. The speed of recovery appeared faster for the FB rehabilitation group than part 1 ACLD subjects but this improvement was not maintained and velocity, cadence, injured leg step length and injured leg hop distance all demonstrated some deterioration. The mean values for all the variables at 5 months post injury for the FB and no-FB groups were within normal limits, although the mean values for the no-FB group were consistently lower and located towards the lower boundary of the normal limits. Overall these results suggests that both the treatment groups in part 2 had less functional recovery compared to the ACLD subjects in part 1 and additionally the no-FB group performed more like the non-copers in part 1 than the FB group. Further analysis would have been required to clarify these results, such as checking if the subjects from part 1 and 2 were matched for demographic variables. One possible explanation for the slightly inferior rehabilitation outcome and worse performance overall for the subjects in part 2 is that there was a lower level of coping and a slightly higher level of non-coping than in part 1. The value of the cut-off point of 1SD either side of the control mean was possibly too lenient and not a suitable criteria to classify individuals as recovered, as discussed previously. Based on our method of evaluating recovery the ACLD population treated on both parts of this study had a poorer functional outcome compared to healthy controls. This is in contrast to other published studies that have evaluated statistical differences for gait joint angles and time-distance variables and hop distance and found no statistical difference compared to controls (DeVita et al. 1997; Lewek et al. 2002; Georgoullis et al. 2003; Snyder-Mackler et al. 1995; Muneta et al. 1998; Roberts et al. 1999a; Ferber et al. 2002; Torry et al. 2004; Gauffin et al. 1990). Many of the reasons for the contrasting outcomes between the current study and the literature have already been discussed. It is worth emphasising that one of the main reasons for this difference in recovery is probably related to the different healthcare systems that patients are managed in, which has resulted in different ACLD populations. Unlike other healthcare systems few ACLD individuals within the NHS are given an ACL reconstruction acutely. This means that more patients with concomitant injuries will undergo a phase of conservative management. There may also be a greater number of sedentary patients and individuals who infrequently participate in high demand activities (Frobell et al. 2007). The implication of this is that outcome will vary widely between studies that have been carried out in different health care services and study results may only apply in services with the same overall philosophy of care. This means that further research is required on ACLD patients managed within the NHS, in particular randomised controlled trials with long term follow-up, which evaluate the effectiveness and implications of conservative management versus surgical management.

5.10 Movement Performance ACLD Subjects versus Controls

A final stage to the analysis was added retrospectively. The justification for doing this was to evaluate if the lack of significant differences between the FB and no-FB rehabilitation groups was because the ACLD subjects in both groups had made an incomplete recovery for the movement variables. Based on the descriptive analysis of the recovery plots, which demonstrated less recovery for the movement variables compared to controls and the ACLD subjects in part 1, it appeared that our ACLD individuals had not fully recovered, but statistical analysis was used to confirm this. To perform this analysis all of the ACLD individuals were combined into one group and compared to the controls from part 1.

This statistical analysis confirmed that at five months post injury the ACLD subjects still adopted movement adaptations and performed differently to the controls. For gait they still walked with a slower velocity, lower cadence and reduced injured leg step length, no difference was found for knee or ankle joint angles. For hopping ACLD individuals had a shorter injured leg hop distance, reduced knee and ankle ROM during the take off and landing phase. So the ACLD subjects in general did not perform as well as the uninjured control subjects and could indicate a lack of recovery.

Retrospective analysis has demonstrated that the ACLD and the control group were matched for age, height and gender so these demographic variables do not explain the group differences in movement performance. The groups were not matched for mass with the ACLD subjects being slightly heavier (83.55kg versus 76.60kg). It is not clear the influence that this could have had; Bohannon et al. (1996) did not find any significant correlation between gait speed and mass in healthy adults. Conversely in older adults, mass has been found to exert some influence over functional performance (Buchner et al. 1996; Samson et al. 2000). Because the findings of the later two studies are confined to older adults, all the other demographic variables were matched and our population was active then it is unlikely that differences in mass alone account for the differences in movement performance. For gait there was no significant correlation between the clinical symptoms and gait velocity. For distance hop there was a significant correlation between injured leg hop distance and pain and pre-injury activity level. These indicate that with this more challenging activity if an individual is experiencing pain then they will hop a shorter distance. In addition if individuals had a higher activity demand pre-injury then their hopping distance will be further. This means that when interpreting recovery of an individuals hop distance these factors need to be taken into consideration.

The overall conclusions that can be drawn from this analysis are limited because the research design was not developed prospectively for this analysis. Compared to the literature our ACLD subjects in part 2 have a poorer gait performance then would be expected and support the findings of part 1. Many of the reasons for this poorer performance have already been discussed for the part 1 data but also apply to the ACLD subjects in this sub analysis. These factors include the relatively early timing of the follow-up so there were still a high proportion of poor functioning non-copers in the ACLD population. Performing an ACL reconstruction in the acute phase is not the gold standard within the NHS, unlike other healthcare systems (Hurd et al. 2008a), which will result in a different population of ACLD subjects. The combination of pathologies included alongside the ACL injury was more mixed than used in many other investigations (Rudolph et al. 2001). Finally, our population of ACLD subjects included individuals with high and low level sporting and functional demands and not just high level athletes (Rudolph et al. 2001).

Other limitations of this analysis are that the subject numbers are low and no assessment has been made to evaluate if the group analysed in this investigation is representative of all individuals with ACL rupture. Therefore the ability to generalise these results to other populations of ACLD subjects is low. The control and patient data were collected at two very different time phases; control data was collected alongside part 1, 12 months earlier than the ACLD data in part 2. Some improvements to data collection were made between these phases such as camera placement and increasing the size of the person in the field of view. This could have had some impact on the quality of the data and accuracy of the results.

5.11 Summary

There was no difference in functional performance at 5 months post injury between the FB and no-FB treatments. Both treatment groups did make some recovery over time but the feedback did not result in an enhanced recovery. Factors related to implementation and design of the feedback, pre-study training, lack of difference in rehabilitation between the treatment groups and lower study power are all factors that have been identified that could have contributed to this result. Although the ACLD individuals recovered a retrospective statistical analysis would indicate that this was not a complete recovery as expected at 5 months compared to uninjured control subjects. This study does indicate that movement deficits do exist in ACLD individuals during a range of functional activities and that ACLD individuals do not recover by five months. Movement analysis can identify these adaptations and therefore is a potential tool to improve rehabilitation and patient management but the most effective way of incorporating it into treatment requires further clarification.

5.12 Clinical Implications

Functional recovery following acute ACL rupture has been modelled and long term compensation strategies identified for a range of movement variables during a number of functional activities, that all subject the ACLD knee to different challenges. This information was then used to develop a system to provide treating physiotherapist with movement feedback to improve outcome. In the following section the implications of these findings for the management of these individuals will be discussed.

5.13 Functional coping

The overall rate of functional coping for part 1 and 2 respectively was; 17% and 8%, adapting 45% and 50% and non-coping 38% and 42%. For both parts of the study the level of coping was at a slightly lower level than has been documented in the literature, where coping has been found to vary between 14% and 97% (Engstrom et al. 1993; Roos et al. 1995; Seitz et al. 1996; Fitzgerald et al. 2000c). The high level of coping found by Fitzgerald et al. (2000c) was in individuals that had undergone a pre-screening examination to test their suitability for conservative management, so anyone that was unlikely to cope was screened out resulting in a different population to that evaluated in our investigation. Most of the studies that have evaluated outcome in ACLD individuals have been conducted in countries that have a different healthcare system to that in the UK. The implication of this is that if surgical waiting lists are not as long or private healthcare is more predominant then those that perform particularly badly with an ACLD knee are likely to have surgery early and not be included in the follow-up, resulting in a different population to that evaluated in the current study. The number of subjects that functionally coped in part 2 was considerably lower than in part 1. The reasons for this were related to two factors. Firstly in part 1 only the subjects that had undergone physiotherapy and the movement analysis were followed up. In part 2, everyone was followed up, including those that had not attended any or a full course of physiotherapy. Secondly in part 1 most of the patients were treated by the main researcher who also had more experience in treating ACLD patients and video analysis than the physiotherapists who treated the patients in part 2. In addition because the individual in part 1 was the researcher and clinician appointments were scheduled so that the movement analysis was relevant. Finally there was the potential for bias to be introduced into either the treatment or data processing because of the direct access to the functional evaluations and the patient. Overall this means that the 8% rate of coping found in part 2, may be a more accurate representation of coping for patients managed in the NHS in the UK.

In part 1 pre-injury activity level did appear to be related to the functional outcome with the rate of functional coping dropping to 5% for individuals that participated in high demand activities involving landing and pivoting pre-injury. This is consistent with the literature which suggests that individuals that have high sporting demands have a poorer outcome and should be offered an early reconstruction (Daniel et al. 1994; Fithian et al. 2005). This is a factor that warrants further evaluation in a study evaluating factors that predict outcome.

5.14 Value of movement analysis to guide clinical practice

When related back to the ICF model the information provided by the movement analysis is at a functional performance level which has direct relevance to the ultimate treatment goal of maximising participation. Therefore this information can be used to evaluate outcome and recovery over treatment and guide the content of rehabilitation. A variable such as strength evaluates function at the structure level. Gait is generally not recognised as a functional activity to evaluate performance following acute ACL rupture but it is a basic activity required for many activities of daily living and many of the subjects in this investigation were experiencing knee symptoms with ADL. It is ideally suited to monitoring functional recovery throughout treatment due to its distinctive recovery curve, it can also be evaluated in the early stages post injury before individuals can perform more challenging activities and potentially can distinguish between functional copers and non-copers based on their recovery compared to control subjects. In the current study it took 3 months for walking recovery to plateau, non-copers were identifiable at 40 days post injury due to poor recovery of their gait and at 4 months post injury 5 gait variables had still not recovered. Based on these results this makes it the most informative of all the activities evaluated and due to the high level of non-coping it was the only activity that many individuals could perform. The jogging and run and stop variables did not provide valuable information to evaluate recovery on a continuous basis and direct rehabilitation, they are better used as milestone. For jogging there appears to be a threshold over which ACLD individuals appear to be able to jog, which coincides with recovery of clinical symptoms such as pain, swelling, full ROM and no giving way. Run and stop was also recovered by the time this activity was analysed on the ACLD individuals but with time performance appeared to deteriorate and it is borderline if this activity does recover. It may have been the variables that were analysed for these activities and not because these activities are inappropriate to measure functional recovery with ACLD subjects. In general distance hop did demonstrate a distinctive recovery curve over time that reached a plateau at the control mean but it can only be introduced in the later stages of recovery as the acute symptoms are resolving. To use it to distinguish between the sub-groups would not be appropriate because it wasn't failure of the non-copers to recover that made them distinctive it was due to them out performing the coper/adapters for distance hopped. Other studies have highlighted limitations of analysing hopping distance; individuals with poor functional scores have still been found to achieve hop distance symmetry and distance within normal limits (Barber at al. 1990; Itoh et al. 1998; Eastlack et al. 1999; Fitzgerald et al. 2000c). One legged squat was only analysed as part of the movement feedback in part 2, its recovery was not modelled over time. Despite this, in comparison to the literature on healthy subjects it would appear that for maximal flexion angle during one leg squat our subjects had not recovered (Beutler et al. 2002; Zeller et al. 2003). This is an adaptation strategy identified in other ACLD subjects performing the same task (Kvist 2005) and a similar stepping task (Rudolph & Snyder-Mackler 2004). Therefore one legged squat is a functional activity that warrants further evaluation in ACLD subjects, to develop its use as a functional movement outcome measure. Now that recovery has been modeled for gait, jog, distance hop and run and stop direct feedback could be given to the patient by plotting their performance against these recovery curves and control performance.

The movement analysis system used in this study was made up of a battery of functional activities that can assist clinical decision making in two ways; firstly by providing outcome data on individual performance and secondly by identifying adaptations that can be addressed in rehabilitation. The combination of time-distance variables and joint angles gave a more complete picture of movement strategies and therefore direction to rehabilitation. The recovery plots modelled in this study could be used by clinicians to give an overall impression of how an individual patient is performing and indicate if a patient's function is following a typical path of recovery. It would be anticipated that if an individual is performing below the recovery curve or outside the control limits then they are not functionally coping and are unsafe to return to more challenging activities. An appropriate rehabilitation program can then be tailored. The current movement analysis system cannot be used to predict outcome from injury. In order to do this a predictive model would need to have been developed using regression analysis exploring more predictor variables related to final outcome. This has been done by Chu et al. (2007) who evaluated predictors of outcome using mixed effects modelling following traumatic brain injury. Biomechanical variables were not included in their model but the strengths of the analysis used is that it can accommodate missing data sets over time, allows for variable timing of data collection, making it particularly suitable for modelling recovery for individual patients.

Measuring functional recovery of ACLD patients from initial injury over time in the clinical setting using a 2D camera system is unique. The advantage of using video for data collection over other cheaper and simpler methods, such as a stop watch (to measure gait velocity as an example), is that joint angle data was also collected. This allows a more complete movement analysis and provides explanations for compensation strategies that can be addressed in rehabilitation. Three dimensional movement analyses is not practical for the clinical setting due to lengthy processes involved during the setting up and analysis, adequate space for its use, secure storage and potential difficulty for the clinician to interpret. The latter point would seem to be particularly important based on the difficulties reported by one of the FB physiotherapists in the current study. There are even limitations to the accuracy of 3D movement systems during high demand activity; soft tissue movement during impact can cause skin marker movement. Based on the results of the current study and the literature a 2D system is adequate for measuring 2D joint angles and time-distance variables. These are movement variables that clinicians can issue simple instructions about changing their performance; it is much more difficult to advise a non professional athlete on how to modify their joint moments. Gait velocity has also been found to exert a direct influence on gait joint angles, cadence and step length, so to understand resulting gait patterns it is essential to have monitored gait time-distance variables (Kirtley et al. 1985; Voloshin 2000; Lelas et al. 2003; Hanlon & Anderson 2005).

Finally the adequacy of a 2D compared to a 3D system has been recognised by McLean et al. (2005), for measuring frontal plane knee joint angle. They conclude that a 2D system would be a practical choice for evaluating training programs which aim to modify joint angles; like what has been done in the current study.

5.15 Rehabilitation

5.15.1 Treatment content

ACLD rupture has traditionally been associated with inability to return to high demand sports and in accordance with this the rehabilitation literature has focused on regimes to enhance coping and screening tools to identify copers (Fitzgerald et al. 2000a; Eastlack et al. 1999). Based on the results of our study the appropriateness of these rehabilitation recommendations is questionable for ACLD patients being managed in the NHS. We found a high level of non-coping so tools that help identify these individuals and methods that assist individuals to adapt to their injury whilst awaiting surgery are particularly important. The reason for this is that the non-copers experience repeated episodes of giving way and these episodes are associated with meniscal tears. The greater the amount of cartilage damage then there is an increased risk of OA in the future (Nelson et al. 2006). The rehabilitation emphasis for all of these patients is to maximise safe function (Kvist 2004a).

Published rehabilitation programs focus on resolution of acute symptoms, strengthening, range of motion and improving neuromuscular control, particularly of the hamstrings, quadriceps and hip extensors. There is evidence of weakness of the quadriceps and hip extensors which represents itself during gait as increased knee flexion, despite full passive extension (Snyder-Mackler et al. 1995; Arnold et al. 2005), which needs to be addressed in rehabilitation. Early neuromuscular control exercises tend to focus on closed chain squatting type activities (Kvist 2004a). Neuromuscular control activities with non sports specific manoeuvres such as gait re-education are not specifically emphasised but would be recommend that there needs to be more focus on this in rehabilitation programs (Chmielewski et al. 2005; Fitzgerald et al. 2000c). Individuals are not being encouraged to walk using a set strategy but there are normal limits within which they might be expected to perform.

For both distance hop and run and stop there was a tendency for individuals to use a stiffer landing during the deceleration phase, which means a reduced range of motion at the knee joint is utilised during the ground contact phase of landing. This can be the result of landing at initial contact with the knee in a more flexed position, achieving greater maximum knee flexion or using a combination of the two strategies. Within the hopping literature for ACLD individuals various adaptations to knee joint angle have been identified but conclusions are limited because studies have only looked at one part of the deceleration phase resulting in the analysis of different variables; different populations of ACLD individuals have been investigated making comparison between studies difficult (Gauffin et al. 1990 and Rudolph et al. 2000); hop distances have been controlled in some investigations (Muneta et al. 1998); drop hop landings have been studies rather than distance hop (McNair &

Marshall 1994) and sample sizes have been so small because a limited number of individuals have been able to hop that statistical analysis has not been possible (Gauffin et al. 1990 and Rudolph et al. 2000). No increase in knee flexion angle at initial contact or maximum knee flexion angle was found by Muneta et al. (1998) or McNair & Marshall (1994). In contrast Rudolph et al. (2000) reported reduced flexion throughout the deceleration phase in non-copers compared to copers and Gauffin et al. (1990) found a tendency for increased knee flexion at initial contact but neither of these findings was tested statistically. Overall the current observation of reduced knee flexion during landing from the hop is partially supported by the literature. The underlying cause of this could be related to quadriceps weakness and reduced hop distance. Quadriceps weakness has been found to be an underlying cause of shorter hop distances in ACLD individuals (Roberts et al. 2007). Rudolph et al. (2000) did find significantly reduced quadriceps indices in non-copers in addition to altered joint angles although the relationship between these variables was not explored. Based on the literature of healthy subjects it does not appear that there is a clear cut relationship between knee ROM during landing and impact forces because it seems that the activity being performed, individual experience and gender can all influence the kinematic strategy used (Yu et al. 2006; Zhang et al. 2000; Simpson & Pettit 1997; McNitt-Gray et al. 2001). It is evident though that whatever the landing condition the knee remains the most important contributor to force absorption (Zhang et al. 2000 and Augustsson et al. 2006) although performance at the ankle and hip can increase to help contribute to force absorption and stability. There is evidence of an increased contribution from the ankle or the hip in fatigued trials of healthy subjects (Coventry et al. 2006; Orishimo & Kremenic et al. 2006) and from the ankle in ACLD non-copers (Rudolph et al. 2000). Angular velocity may also influence impact forces at the knee more than the range of motion during an activity (Yu et al. 2006; Simpson & Pettit 1997). In summary the findings indicate that ACLD individuals adopt a stiff knee strategy during landing. This is an acceptable method of landing but it may be indicative of underlying quadriceps weakness or insecurity about knee stability that needs to be addressed. To successfully integrate back to sport it is important that there is not an over reliance on the stiff landing strategy because this may prevent adaptation to different conditions encountered and may result in instability (Ko et al. 2003b; Stergiou et al. 2004). Therefore when evaluating functional outcome it is recommended that the knee ROM over the whole landing phase is reported, as this is the most informative variable as opposed to the joint angle at a particular time point during landing. Angular velocity is an additional variable that is easy to measure using the 2D movement analysis system and with further clarification would be an informative variable. Based on our hopping data individuals should practice these manoeuvres to relearn the limits of their knee stability, this may also apply for other sports specific activities. Based on motor learning principles the practice conditions should then be developed to make this occur in more realistic sporting environments (Magill 2007). Only then will individuals be able to assess if they can truly return to sport without compensations or if they need to adapt to control knee stability in the short term.

There is no evidence to suggest that you can prevent an individual becoming a non-coper but ideally treatment needs to start early to avoid inappropriate compensation strategies. Once an individual becomes a non-coper it may be difficult to change this situation, due to secondary damage through repeated giving way (Nelson et al. 2006). If an individual is identified early as a non-coper then rehabilitation should focus on controlling symptoms and returning the individual to ADL and low demand sport. If gait compensation strategies are still present then a subject is not going to progress to the more challenging activities. Compensation strategies have been identified in the current study but this doesn't tell us whether or not without these compensation strategies ACLD subjects would have performed even worse and whether they are needed to maintain knee stability. If rehabilitation corrected them would these individuals perform better? Does there need to be more emphasis on relearning limits of stability in more realistic settings other than the physiotherapy gym and the injured individuals realising that they need to go through this process?

Analysis of functional activities in the clinical setting provides clinicians with a greater understanding of what these activities involve. This will allow them to provide more appropriate advice to patients about activities that it is safe for them to return to. It will also enable clinicians to set more realistic rehabilitation goals and together this may improve patient adherence (Scherzer et al. 2001) and improve treatment outcome, reducing the number of episodes of knee giving way that create further damage to the knee (Scavenius et al. 1999; Allen et al. 2000). Current findings indicate that if gait has not recovered sufficiently by 40 days post injury or if there are high sporting demands, individuals are less likely to become a coper. Even within our coper group very few individuals had the goal of returning to pivoting and cutting sports because they did not participate in them pre-injury. So in recreational athletes should the aim of rehabilitation be limited to returning an individual to ADL and straight line sporting activities only and not high levels of pivoting and jumping?

5.15.2 A functional approach to rehabilitation

A functional approach to rehabilitation is advocated in many published guidelines for ACLD and ACL reconstructed individuals. This refers to reintroducing individuals to activities that form the basis of their sport once they have full range of motion, good muscle control and swelling and pain have stabilised (Bruckner & Khan 1993; Kvist 2004a). A functional approach also advocates using functional tests to evaluate suitability for returning to sport (Kvist 2004a). The aim of practicing these functional activities is that it will transfer to improved performance during sport (Magill 2007). Evidence from the current study indicates that there needs to be an even greater emphasis on functional performance within rehabilitation. Key factors involved in a more functional approach are:

- Reintroducing functional activities from the start of rehabilitation. Initially this will be gait and then advancement through a progression of functional activities that are relevant to the patient and increasingly challenge knee stability.

- Evaluating functional performance using a 2D clinical movement analysis system so that functional activities can be monitored. This can be used to evaluate if performance has recovered or to identify movement compensations that need to be addressed in the rehabilitation. This is essential for achieving functional goals.
- Better use of feedback within rehabilitation to improve functional performance. This will involve movement feedback within the treatment session on performance errors, successes and information on how to improve performance.
- In addition the patient may need to be doing a regime of strengthening, perturbation and cardio-vascular training. This can be done independently, leaving the physiotherapy sessions free to focus on functional activities and feedback.

Further research is required before adopting this more functional approach such as, understanding what variables are required for good performance of functional activities and understanding the stages of relearning movement following ACL rupture. Further work is also required on how to best use and incorporate movement feedback into rehabilitation. This is discussed further in chapter 5.19.

5.15.3 Treatment length

Based on the findings of this study for all the activities it is anticipated that full functional recovery on average could take up to 5 months or longer. It may be even slower if an individual has not attended a full course of rehabilitation or was delayed receiving treatment. There are no clear guidelines in the literature suggesting how long it could take ACLD individuals to return to sport but anything between four to six months post injury (Kvist 2004a) to never returning. For the clinician this indicates that individuals could be attending physiotherapy over a prolonged period of time.

5.16 Summary of clinical implications

The following is a summary of the clinical recommendations based on the findings of current study:

- There is a low level of coping particularly in individuals with a high level of activity pre-injury. There is potentially a higher rate of coping in individuals who did not participate in pivoting and landing activities pre-injury.
- A full recovery of gait is required for safe progression to more challenging activities. Identifying non-copers is essential for goal setting, advice and tailoring treatment. This can be achieved as early as 40 days post injury using gait movement variables. Overall recovery can take up to 5 months.
- Jogging and run and stop are ideally suited as milestones that also provide some information on recovery of symptoms. They are less suited to measuring outcome over time.
- Hopping distance as an outcome measure may have its limitations as not all individuals will be able to perform this activity. Poorer performance of the uninjured leg has also been found in ACLD individuals so is not good as a comparison.

- Functional movement analysis provides useful outcomes using relatively simple equipment that can be used to evaluate recovery and guide treatment through feedback. This information was used to form the basis for the next stage of the research; which was to develop an exploratory trial evaluating the effectiveness of using these variables as feedback to guide treatment.
- The type of feedback evaluated in the current investigation did not improve performance. Further consideration of how to best implement and training to maximise usage is required.
- Based on the results of current rehabilitation methods should the goal of treatment just be back to ADL and straight line activities?

5.17 Dissemination methods to improve clinical utilisation of movement feedback

The physiotherapists in this study had difficulties interpreting data on movement variables, implementing the feedback into practice and using this information to guide rehabilitation. Further dissemination to overcome these issues and improve clinical use is required. One way of achieving this is for healthcare professionals, sport coaches and movement analysts to work as a multi professional team to facilitate recovery and rehabilitation. This is an approach that is applied to other specialities such as the management of cerebral palsy (Lofterod et al. 2007) and stroke rehabilitation to improve clinical outcomes (Woo et al. 2008). This method of service delivery would allow other anatomical factors such as tibial plateau slope angle and patella tendon insertion angle (Shin et al. 2007b; Liu & Maitland 2003) to be incorporated into treatment planning through the expertise of other disciplines. These are factors that are often not considered in physiotherapy but can affect treatment outcome (Shin et al. 2007b; Liu & Maitland 2003).

The current study demonstrates the need for clinical guidelines and treatment algorithms to direct the content of rehabilitation based on the presence of biomechanical deviations, to ensure that the most effective treatment modalities are implemented. This is an approach that has been developed for functional problems following total hip arthroplasty in patients that failed conventional physiotherapy (Bhave et al. 2007). Although not evaluated through an RCT this rehabilitation algorithm resulted in 94% of patients reporting an excellent long term outcome according to the Harris hip score (Harris 1969).

Multi-professional working and the development of treatment algorithms need to be considered when implementing movement feedback or biomechanical variables into clinical research and practice. This will ensure that biomechanical data is fully analysed and interpreted in a manner that will influence the treatment given and reduce the emphasis on individual physiotherapists to analyse, interpret and implement biomechanical information whilst still promoting a functional approach to rehabilitation.

5.18 Limitations Part 1

This part of the research was exploratory and the intention was to analyse the data descriptively by modelling recovery. The decision to perform statistics was made retrospectively based on the results of this descriptive analysis and patient numbers. No power analysis was performed to calculate sample size for the sub-groups but in any future studies this would be required. Based on the findings of the current investigation 27 subjects would be required per group (non-copers versus coper/adapters). This is based on an effect size of 0.69 (gait velocity), power of 0.80 and a one tailed t test. It is necessary to combine the copers and adapters because the level of coping was so low (8%), making it unrealistic to have a group of copers on their own. The limitation of this is that the adapters do not 'recover' and do not report a satisfactory outcome; they describe restricted functioning as a means of preventing instability. This will be reflected in their level of participation and also in their functional performance.

Despite the large number of subjects recruited and measured longitudinally, insufficient numbers were able to perform the more demanding activities such as hopping. This meant that no statistical analysis could be carried out on these challenging activities or for the functional sub-groups of ACLD individuals.

Other factors that have been found to alter gait performance such as swelling and muscle strength (Snyder-Mackler et al. 1995; Torry et al. 2000) have not been measured. These factors could have influenced sub-group differences in functional performance. These could easily be measured using the sub scales of the Cincinnati knee rating system.

There are a number of factors that could have affected the quality of the data collected. Firstly video recordings and patient treatments were carried out simultaneously within a busy physiotherapy department and the clinical space had to accommodate activities that were taking place in the gym at the same time as individual data collection. Occasionally this resulted in the camera not being placed in the ideal location; either too close or too far away from the subject. This potentially affected the accuracy of the data processing because if individuals were too small in the field of capture it was difficult to be as accurate when locating landmarks. If individuals over filled the field of view then accuracy of pin pointing a landmark improved but part of the activity was often missed. Occasionally run and stop data could not be collected because this activity required large amounts of space in which to perform it and could not be carried out if classes were taking place and using large areas of the gym space.

Lower limb markers were not required to measure knee and ankle joint angles, an on screen goniometer was aligned along the length of the thigh, lower leg and base of the foot and the intersection points of the lines gave the angle. Based on the findings of this study for the HDA during gait and the literature, it would also have been useful to measure hip joint angle, as movement adaptations would also have been expected at this joint. To do this, markers would have been required on the skin over the greater tuberosity and on the pelvis as alignment points for the onscreen goniometer.

It was not possible to evaluate run and rapid direction change because it did not occur in a plane that was perpendicular to the camera, resulting in distortion of the angles. This was a limitation because a recent review has highlighted the lack of relationship between straight line activities and rapid turning performance (Sheppard & Young 2006). This means that none of the activities used in the current this study evaluated run and rapid direction change which is required for assessing individual suitability for contact sports.

Some inaccuracies occur due to the speed that the activity is performed, even though SiliconCoach allowed the video to be processed at 50Hz this was not always enough for hopping and run and stop and the exact frame required for the movement time point would not have been captured. For example during hopping the exact point of heel contact during landing may not be available, the closest frame may be slightly before initial contact or slightly after at which time the whole foot may be in contact with the ground. The overall impact of this was low because a number of trials were captured.

This study was evaluating movement performance, to do this in more depth variables that assessed movement consistency, stability and adaptability were required (Magill 2007). This could have included measuring activities on different surfaces, combining with another activity such as catching a ball or evaluating unanticipated movement. The analysis of run & stop was particularly limited and analysing one variable is not sufficient to evaluate performance and conclude whether ACLD subjects are or are not safe to perform it. Other variables that could have been included are approach velocity and length of the deceleration phase.

The movement data collected indicated that many of the movement variables fell within the 'normal limits' set by the control subjects but this could not be tested statistically because all of the individual patient follow-ups were at different times. If we had been able to apply statistical tests then we would have done equivalency testing. This doesn't look for differences but confirms that populations are the same. This may be important because a score may say that an individual scores the same as an uninjured population but does that mean they are truly recovered and no different to that population.

5.19 Limitations Part 2

There were some limitations in how well the randomisation was carried out, particularly towards the end of the recruitment. The accuracy of the randomisation was checked by cross referencing the computer generated randomisation list against the list of patients written down by the recruiting physiotherapists and the researcher's record of ACLD patients attending the clinic and which treatment group they ended up in. Based on this, the randomisation process worked well for the first 89 of the 115 patients that were recruited onto the investigation. This means a further 26 patients were recruited and didn't follow the randomisation list. From the final cohort of patients that were followed up at 5 months post injury this affected 5 patients in the FB and no-FB groups. The main reason why the randomisation process started to breakdown towards the end of the recruitment period was due to a change in administrative procedures within physiotherapy for booking patients into treatment. As extra staff became involved it became more difficult to control and check where the ACLD patients were going for treatment. There could also have been a loss of motivation by the recruiting physiotherapist because they were originally informed that they would only need to recruit 80 patients but due to the low follow-up rate this number kept increasing.

An alternative method of randomisation that could have been considered was cluster randomization (Kerry & Bland 1998). In this approach the treatment site would have been randomly assigned as either the FB or no-FB treatment instead of each individual patient. This would have permitted individuals to continue to attend the physiotherapy department within the catchments that they lived and would hopefully have improved compliance with the research. It would also have reduced the administrative errors that resulted in individuals not attending for the rehabilitation they had been randomised onto. The limitations of this approach are that a larger sample size would have been required as a result of reduced power with this method (Kerry & Bland 1998). The second limitation is that the researcher would have had to travel across the trust to video movement feedback sessions; this would have been difficult due to time restraints; the researcher continued with clinical work throughout the duration of the project. Therefore this method of randomisation would not have been practical in this research due to the frequency of the video movement analysis sessions. In the future for other physiotherapy trials evaluating the effectiveness of treatment that only involve baseline and follow-up data collection this may be a suitable alternative.

There were two potential sources of follow-up bias between the two rehabilitation groups. Firstly ACLD patients in the FB group had more interaction with the researcher than the patients in the no-FB group and could therefore have received unintentional feedback and encouragement. Secondly the ACLD patients in the FB group potentially had more contact with physiotherapists and had a greater amount of rehabilitation because they were only contacted for follow-up if they had attended physiotherapy at least once; patients who attended no physiotherapy at all were not contacted. In contrast patients in the no-FB group were contacted regardless of whether they had/had not attended any rehabilitation sessions. This occurred because the no-FB subjects did not have any contact with the researcher over the first 5 months of their recovery, so the researcher was not aware of what rehabilitation they had been receiving until they were reviewed at the 5 month follow-up. Differences in the amount of rehabilitation each group received were evaluated statistically, based on the amount of sessions documented in the physiotherapy notes. Overall the groups were found to have received the same amount of physiotherapy sessions, although there were patients in the no-FB group that had no physiotherapy at all.

No baseline measurements were taken for the movement variables; this had not been practical due to the number of patients, different rehabilitation locations and only one researcher. The main limitation of this is that we were unable to evaluate the effectiveness of the FB intervention over time. It is possible that if the groups had been different at baseline but had the same level of functional recovery at five months, then our conclusions regarding the effectiveness of incorporating movement feedback in rehabilitation may have been different. Finally no base line measurements meant that we were unable to perform an intention to treat analysis. This meant that further subjects that subjects who did attend physiotherapy and did receive movement feedback but were not available for evaluation at 5 months could have been included in the analysis.

Finding a statistical difference between these two rehabilitation methods at five months post injury may have been over ambitious with this pathology and using these movement variables. This is indicated in our results from part 1; we concluded that all ACLD individuals may be expected to make a functional recovery to within normal limits and not perform in a dissimilar manner to healthy subjects for the movement variables. Therefore subtle differences in performance between the feedback treatment groups would not have been identified. It may have been more appropriate to measure the speed of recovery which would have required baseline measurements as already discussed.

Integrating research into clinical practice did have challenges ranging from making sure that patients attended the correct department for treatment, ensuring that the physiotherapists treating them were part of the study, that the physiotherapist delivered the correct intervention and that appointments were scheduled for when the gym was available for data collection. Most of the problems arose because individuals were being asked to perform duties different to normal practice or following a different procedure. Specific limitations included administrative staff not booking patient referrals marked as part of the study in with the correct physiotherapist or forwarding marked referrals to other departments that were not participating in the research. Physiotherapists were required to schedule and book appointments differently to allow movement analysis to take place when the gym was available and so that the feedback could be integrated into practice. Over the duration booking appointments because increasingly difficult as the gym because busier with classes reducing flexibility and the time available for data collection.

There were several limitations related to the feedback that have already been discussed in chapter 5.8.2 and solutions identified. In summary these included the delay between movement analysis and receiving the feedback and difficulties interpreting the feedback. Solutions include more specific training, further exploration of the cut-off values for functional adaptations and developing feedback to permit immediate feedback.

There were several limitations associated with the semi-structured interviews. Firstly the researcher was inexperienced with this methodology and there were too many questions. Interview 1 should have started with a closed question to find out if the physiotherapists found the feedback useful. Instead this was presumed and the questioning launched straight into finding out which aspects of the feedback were most relevant. For interview 2 overall aims had been to establish how similar the rehabilitation had been between the FB and no-FB rehabilitation. To achieve this, questions were kept open and the prompting to a minimum. The trade-off for this was that the rehabilitation principles used by the physiotherapists were not identified and instead physiotherapists were allowed to focus too much on progression of individual exercises.

5.20 Future Research

Based on the research framework proposed by Campbell et al. (2000) part 1 of this study was the modelling phase, where the components of the intervention were identified. These components were movement variables for functional activities and it was proposed that these could influence treatment outcome by providing the treating physiotherapist with movement feedback on patient performance of these activities. The effectiveness of this was evaluated in part 2 of the research. The findings were that feedback did not result in any difference in outcome because either feedback does not influence recovery and functioning or factors related to the feedback used and study design resulted in no treatment effect of the feedback. Therefore in the research framework developed by Campbell et al. (2000) the modelling and exploratory trial phases needs to be revisited and the components of the ACLD rehabilitation and their mechanism for influencing treatment re-evaluated before developing a pragmatic randomised controlled trial in the clinical setting. The findings of the current investigation will now be discussed in accordance with the modelling and exploratory phases of the research framework that has been adopted.

The findings of both part 1 and 2 consistently indicate that movement adaptations for relatively unchallenging activities such as gait persist and that there is a high level of non-coping at 12 months post injury. Due to the exploratory nature of this investigation the link between the movement adaptations early in rehabilitation (1 month) and their ability to predict non-coping has not been established and this would be the direction for future research on this topic. Predictive studies to identify ACLD sub-groups are required so that the best treatment for a particular individual is given. The goals of treatment could then be made very clear to the patient from the beginning; non-copers need rehabilitation to make them safe prior to surgery and educated on how to manage their knee in the short term, this would include return to straight line activities only. The rehabilitation of potential copers would aim to return them to their pre-injury level of activity. A logistic regression analysis would be required to evaluate ability to predict non-coping. Based on the results of the current investigation and the literature the five predictor variables to be included in the model are: gait speed, non-injured step length, cadence, pre-injury activity level and injury. For the more challenging activities of distance hop and run and stop further clarity is required about which movement variables predict how well ACLD individuals can perform these activities. This would be done through linear regression. No work has been carried out evaluating the predictive relationships between movement variables for distance hop and run and stop. The outcome variable for distance hop would be 'distance' and for run and stop would be 'time to complete'.

The timing and method of applying the feedback also required further consideration. One of the limitations of the feedback in the current investigation was the delay between the timing of the measurement and receiving the feedback, therefore the value of immediate feedback and the method by which this feedback is delivered needs to be explored. To eliminate many of the limitations of performing a trial in the clinical setting the effects of the immediate feedback would be best evaluated over a single session of providing movement feedback. In a follow-up session the retention of any change in performance and transfer to a different lower limb skill could be evaluated. Alternative methods of applying the feedback are to use video and provide immediate feedback for just a couple of variables that can be quickly processed. Their result could be superimposed onto a chart of uninjured subject performance (like that developed in part 1 of the PhD) as a method of providing visual feedback. Innovative methods of providing audible feedback could also be developed, for example during challenging activities time taken to stabilise the whole body centre of pressure after completion of a task. If this falls outside that of healthy subjects the performer will be alerted by a sound. The value of auditory feedback has been demonstrated in two investigations that have included an adequate control group to compare performance against, in a landing task and when learning to step over an obstacle with minimum clearance (McNair et al. 2000; Lam & Dietz 2004). Recently a rotatory kinaesthetic device has been developed for use with

ACLD individuals (Muaidi et al. 2007a). This has the potential to provide feedback on the amount of rotation at the knee during closed chain activities. The advantage of this during rehabilitation is that patients can learn to control the amount of rotation and therefore control any instability that they might experience. Its limitation is that it can not be applied to sports specific manoeuvres which are most challenging to knee stability.

Of key importance for the success of all the feedback methods suggested above is that the information needs to be feedback to the clinician or patient in a simplistic manner that is easy to interpret and integrate into practice. Therefore the number of variables giving feedback on in a session needs to be kept to a minimum, so using movement variables that best represent overall performance or a summary variable that captures the overall success of performing an activity is required, which may vary between tasks (Vereijken et al. 1997; Ko et al. 2001).

In line with this it is necessary to re-evaluate the cut-off criterion (within 1 SD of the control mean) that has been used to identify 'recovered' performance. Based on the results of part 1 ACLD individuals would expect to recover close to the control mean, this will be a required especially if returning to sport. Therefore a tighter criterion such as 0.5 or 0.25 from the control mean needs to be explored (Norman et al. 2003) as discussed in chapter 5.8.3.2. At this stage training for the physiotherapists responsible for delivering the feedback will need to be considered based on the findings of the current investigation. This will include further information and training on how to interpret the feedback data, how this relates to performance and treatment and how to integrate the feedback into clinical practice. If favourable results are found by revisiting the modelling and exploratory trial phases of the research for these alternative forms of feedback then the research could be progressed to evaluate the effectiveness of the movement feedback in the clinical setting through a randomised control trial.

In the current investigation the concept of function has been related to the 3 levels of the ICF model with function relating to 'structure', functional to 'activities and performance' and functioning to 'participation'. Most of the findings correspond to the activities and performance level. The only outcomes that have evaluated participation were the SF-36, aspects of the Cincinnati knee rating system and the telephone questionnaire to allow classification into the functional sub-groups. It would be recommended in future research that greater connections are made between the functional and functioning levels by incorporating other appropriate outcome measures or more complete analysis of the outcome measures used if treatment group differences are found at the activities and performance level.

6.0 Conclusions

The overall aim of this research was to develop a more functional approach to ACLD management and physiotherapy rehabilitation in line with the ICF model of functioning and rehabilitation. The research was carried out in two progressive phases using the research framework for complex interventions proposed by Campbell et al. (2000). Part 1 of this study was the modelling phase, during which functional recovery of ACLD subjects was modelled over time from acute injury in the clinical setting, using a 2D video analysis system that enabled evaluation of functional movements using various time-distance variables and joint angles. This method allowed for a range of activities to be analysed, all of which posed different challenges to the ACLD knee at the various stages post injury. This was in line with the 'activities' level of the ICF model.

Gait analysis was performed in the early stages when it was unsafe to perform sports specific functional activities. In general recovery of gait was found to take up to 90 days to reach 'normal limits' of within 1SD of the control mean and 120 days before stabilising at the control mean. When individuals were sub-grouped into copers, adapters and non-copers the copers and adapters were distinguishable because they recovered to within normal limits by 40 days post injury and continued to recover back to the control mean. In contrast the non-copers had a slower recovery that fluctuated at the lower border of the normal limits; in summary, they did not make a complete recovery. Statistical analysis between sub-groups confirmed that at 4 months post injury ACLD non-copers continued to walk with slower velocity, shorter step length, lower cadence, increased knee flexion and reduced non-injured leg hip displacement angle. Kinematic explanations for altered gait performance can direct and inform rehabilitation. Altered knee and in particular hip joint angles indicate the need for improving neuromuscular control of the hip extensors and quadriceps especially during gait re-education. Hopping distance was found to take up to five months post injury to recover. This activity was less informative than gait for planning and directing early management because it could not be introduced until later when the acute symptoms had resolved and it did not distinguish between ACLD sub-groups in a manner that could guide treatment. The jogging variables and joint angles of distance hop and R&S analysed in this study provided little information on functional recovery over time to direct rehabilitation. For jogging it appears that there may be a threshold point after which individuals can jog, making it more useful to use this activity as a milestone to compare recovery against. Overall functional recovery has been found to take a considerable amount of time. This means that patients may need to be treated in physiotherapy until five months post injury and advised not to return to sport until a full recovery is demonstrated on activities such as distance hopping. Further clarification is required but clinical application of models of functional recovery could be used by clinicians to compare individual patient performance against and indicate if a patient's functional recovery is following a typical path of recovery. This will provide a clinician with outcome information that allows for early decision making on long term management and can direct rehabilitation methods. This feedback could lead to a more complete or faster recovery, potentially improving pre-surgical outcomes and was therefore used to form the basis of the movement feedback evaluated in part 2 of this research. The final recommendation from this part of the study was that individuals with high sporting demands are unlikely to return to their pre-injury level of participation without experiencing episodes of giving way, so achievable rehabilitation targets need to be set with the ACL patient.

The second part of this study was an exploratory phase developing the movement variables identified in part 1 into a feedback treatment modality that could improve rehabilitation outcome and level of functioning (participation level of the ICF). Therefore part 2 of the research evaluated the effectiveness of providing treating physiotherapists with individual ACLD patient movement feedback on improving overall functional performance and outcome. The same 2D video analysis system that was used to model functional recovery in part 1 was used to gather feedback data on joint angles and time-distance variables. On follow-up at 5 months post injury there was no difference in performance or outcome between the FB and no-FB treatment groups for gait, one legged hop, distance hop or run and stop. Therefore feedback or this mode of feedback did not result in better functional performance or participation than no-FB. Descriptive analysis suggested that individuals in the FB rehabilitation groups did perform slightly better at 5 months post injury, no-FB subjects performed towards the lower boundary of the 'normal limits' which was 1SD from the mean of healthy controls. Despite this the overall finding was that regardless of treatment both groups had the same recovery.

There were some limitations in the feedback, subjects recruited and rehabilitation that may have weakened the treatment effect of the movement feedback and contributed to the non-significant results. The type of feedback may not have been effective; physiotherapists had difficulty interpreting the 'normal limits' which were set as within 1SD of the control mean. In addition it appears that this cut off value for the 'normal limits' may have been too lenient making the feedback less effective at informing appropriate treatment. The implication is that the rehabilitation target should be for ACLD performance to retrun to the control mean. The timing of the feedback was not given on the day of treatment and this delay may have made it less relevant to treatment, in the future it would be worthwhile developing a system to provide immediate feedback. The physiotherapists also reported a learning effect over time of using the feedback, resulting in their treatment evolving as the study progressed and based on the semi-structured interviews there did not appear to be any difference between the FB and no-FB rehabilitation. Development of the training for the physiotherapists may improve interpretation of the feedback, utilisation to guide rehabilitation and incorporation into treatment. Finally part 2 of the study was underpowered; the sample size was insufficient, which could have contributed to the non-significant findings.

In any future studies it would be necessary to return to the modelling phase of the research framework for complex interventions and identify more effective ways of providing feedback such as auditory or visual feedback given immediately and explore the most relevant movement variables to functional performance. An exploratory trial could then be developed to evaluate the effectiveness of the feedback at altering performance in a controlled environment, over a singular session, before progressing to the next phase, a pragmatic randomised control trial in the clinical setting, where many confounding variables need to be controlled in this challenging research environment.

Lastly the functional performance of a combined group made up of all the ACLD subjects from part 2 of the current investigation were compared to controls to evaluate how recovered the ACLD subjects were. Based on this analysis it was found that the ACLD subjects still demonstrated marked movement compensation strategies for gait, distance hop and R&S. This indicated that the ACLD subjects had an incomplete recovery at the ICF 'activity' level; it also excluded functional recovery as the reason why there were no differences between the 2 feedback groups at 5 months post injury and provided further support for the findings from part 1 of the research, of continuing movement adaptation.

This study has generated preliminary data on which to develop a more functional approach to ACLD management and rehabilitation. With further clarification movement variables may be used to evaluate outcome and inform long term decision making. Within rehabilitation an emphasis on functional movement needs to begin immediately post injury, starting with gait and progressing through functional activities that increasingly challenge knee stability and are relevant to treatment goals. The rehabilitation target should be for ACLD individuals to recover movement performance back to the control mean. Two dimensional movement analyses can generate performance data on functional activities to feedback to the patient, to improve outcome and direct the content of rehabilitation. This study demonstrated that the clinically based video analysis system provided detailed insight at all stages of rehabilitation on the speed, timing and completeness of recovery for functional tasks that are directly relevant to the rehabilitation goals.

7.0 References

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Appendix 1: Literature search strategy

Stage 2 search used for the Medline database

Search 1:

1	exp Anterior Cruciate Ligament/
2	exp Rupture/
3	exp Rehabilitation/
4	movement adaptation$.mp
5	compensation strateg$.mp
6	exp Gait/
7	exp Treatment Outcome/
8	long?term outcome$.mp
9	distance hop.mp
10	hop$.mp
11	cutting.mp
12	pivoting.mp
13	exp Joint Instability/
14	exp Feedback
15	squatting.mp
16	exp Jogging/
17	exp movement
18	exp Biomechanics/
19	exp Video Recording/
20	or/2-19
21	1 and 20
22	exp Surgery/
23	reconstruction.mp
24	22 or 23
25	21 not 24
26	limit 25 to yr=1998-2007

Search 2:

1	exp Feedback/
2	exp Motor Skills/
3	exp Rehabilitation
4	exp Learning
5	1 and 2 and 3
6	limit 5 to yr=1998-2007
7	1 and 2 and 4
8	Limit 7 to yr=1998-2007
9	6 or 8

exp = explode
/ = subject heading search
mp = keyword search

Appendix 2: Ethical approval

Documentation of the ethical approval initially gained from Bro Taf and then the South East Wales Local Research Ethics Committee and the Cardiff and Vale NHS trust research board. The patient information sheets and consent forms used in part 1 and 2 of the study are also enclosed.

Coleg Meddygaeth Prifysgol Cymru
University of Wales College of Medicine

Adran Addysg Ffisiotherapi / Department of Physiotherapy Education

Cyfarwyddwr Addysg Ffisiotherapi
Director of Physiotherapy Education
Professor N. P. Palastanga, MA, BA, FCSP, DMS, Dip. TP
Pro-Vice Chancellor
Director of Department
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Q8

CONSENT FORM

ACUTE KNEE INJURY REHABILITATION: Using biomechanical and clinical outcomes to evaluate best practice

The patient should complete the whole of this sheet himself/herself **(Please circle one)**

1. Have you read **and understood** the patient information sheet, Version No: 1... Date: 22/12/02................. **[✓ YES]/NO**

   (Please take a copy home with you to keep)
2. Have you had an opportunity to discuss this study and ask any questions? **YES/NO**
3. Have you had satisfactory answers to all of your questions? **[✓ YES]/NO**
4. Have you received enough information about the study? **[✓ YES]/NO**
5. Who has given you an explanation about the study?

   Dr/Mr/Ms ....
6. Sections of your medical notes relating to your participation in the study may be inspected by responsible individuals from (company name) or from regulatory authorities. All personal details will be treated as **STRICTLY CONFIDENTIAL**.

   Do you give your permission for these individuals to have access to your records? **[✓ YES]/NO**
7. Do you understand that you are free to withdraw from the study:
   - At any time?
   - Without having to give a reason?
   - Without affecting your future medical care?
   - That details of your participation up to the time of withdrawal will be stored anonymously on file and may be used in the final analysis of data **[✓ YES]/NO**

Ysgol Astudiaethau Gofal-Iechyd, Tŷ Dewi Sant, Mynydd Bychan, Caerdydd CF14 4XN
School of Healthcare Studies, Tŷ Dewi Sant, Heath Park, Cardiff CF14 4XN
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8. Has the doctor discussed circumstances when compensation may be due? **YES/NO**

9. Have you had sufficient time to come to your decision? **YES/NO**

10. Do you agree to participate in this study? **YES/NO**
11. Do you agree to your GP being advised of your participation in this study? **YES/NO**

PATIENT

Signed ……………………………………………………………………………
Date ………………………………………………………………………………
Name (BLOCK LETTERS) ………………………………………………………

INVESTIGATOR

Signed ……………………………………………………………………………
Date ………………………………………………………………………………
Name (BLOCK LETTERS) ………………………………………………………

WITNESS

Signed ……………………………………………………………………………
Date ………………………………………………………………………………
Name (BLOCK LETTERS) ………………………………………………………

I have explained the study to the above patient and he/she has indicated his/her willingness to take part.

22/12/02 Number 1

School of Healthcare Studies
Dean *Deon* M J Booy BA MA TDipCOT ILTM

Department of Physiotherapy
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CONSENT FORM

ACUTE KNEE INJURY REHABILITATION: Using biomechanical and clinical outcomes to evaluate best practice

The patient should complete the whole of this sheet himself/herself **(Please circle one)**

1. Have you read **and understood** the patient information sheet, Version No: 2... Date: 7/10/04................. **YES/NO**

   (Please take a copy home with you to keep)

2. Have you had an opportunity to discuss this study and ask any questions? **YES/NO**

3. Have you had satisfactory answers to all of your questions? **YES/NO**

4. Have you received enough information about the study? **YES/NO**

5. Who has given you an explanation about the study?

   Dr/Mr/Ms ....

6. Sections of your medical notes relating to your participation in the study may be inspected by responsible individuals from (company name) or from regulatory authorities. All personal details will be treated as **STRICTLY CONFIDENTIAL.**

   Do you give your permission for these individuals to have access to your records? **YES/NO**

7. Do you understand that you are free to withdraw from the study:
   - At any time?
   - Without having to give a reason?
   - Without affecting your future medical care?
   - That details of your participation up to the time of withdrawal will be stored anonymously on file and may be used in the final analysis of data **YES/NO**

8. Has the doctor discussed circumstances when compensation may be due? **YES/NO**

9. Have you had sufficient time to come to your decision? **YES/NO**

10. Do you agree to participate in this study? **YES/NO**
11. Do you agree to your GP being advised of your participation in this study? **YES/NO**

PATIENT

Signed ....
Date ....
Name (BLOCK LETTERS) ....

INVESTIGATOR

Signed ....
Date ....
Name (BLOCK LETTERS) ....

WITNESS

Signed ....
Date ....
Name (BLOCK LETTERS) ....

I have explained the study to the above patient and he/she has indicated his/her willingness to take part.

22/12/02 Number 1

Coleg Meddygaeth Prifysgol Cymru
University of Wales College of Medicine

Adran Addysg Ffisiotherapi / Department of Physiotherapy Education

Cyfarwyddwr Addysg Ffisiotherapi
Director of Physiotherapy Education
Professor N. P. Palastanga, MA, BA, FCSP, DMS, Dip. TP
Pro-Vice Chancellor
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Q8

INFORMATION SHEET (STUDY 1 and 2)

Acute Knee Injury Rehabilitation: Using clinical and biomechanical outcomes to evaluate best practice

WHAT IS THE PURPOSE OF THE STUDY?

The aim of this study is to monitor functional recovery over time of individuals with acute knee injuries and create a reference database of values for uninjured subjects. This will allow us to identify a criteria that predicts who will have a good outcome from physiotherapy from those that do not. Because the system we have for measuring function is continuing to develop further work needs to be done to validate this movement analysis system.

WHY HAVE I BEEN CHOSEN?

If you have attended the Acute Knee Screening Service at the University Hospital of Wales or have been referred to the physiotherapy department for treatment of an acute knee injury then you will have been asked to participate in this study. In addition, control subjects with no knee injuries are also being recruited so that we are able to compare how the different groups move.

WHO IS ORGANISING THIS STUDY?

Kate Button a Chartered Physiotherapist, who works at the University Hospital of Wales as an Extended Scope Physiotherapist specialising in acute knee injuries and rehabilitation.

WHAT WILL HAPPEN TO ME IF I TAKE PART?

If you are a patient with an acute knee injury then you will continue to attend the physiotherapy department for treatment of your knee injury but at set time intervals additional measurements will be taken on your knee. This will include; two questionnaires to be completed by yourself that rate your knee symptoms and function; clinical tests conducted by the physiotherapist and an analysis of the way that you move over a range of functional activities using a digital video camera. Muscle activity will also be measured using sticky surface electrodes that lie on the skin overlying certain muscles. This is non invasive and should not cause you any discomfort. The functional activities analysed will be progressed so that initially the analysis will be of walking but this will be extended to include jogging, distance hop, run and stop and rapid change of direction. The timing of when you are ready to perform these activities will be dictated by the symptoms you experience in the knee.
If you are a control subject you will be videoed walking and muscle activity measured whilst performing the functional activities listed above.

WHAT ARE THE POSSIBLE RISKS OF TAKING PART?

If you are a patient then the distance hop, run and stop and rapid change of direction tests are designed to test the stability of the knee so there is a possibility that you could experience a sensation of giving way or increased pain. To ensure that the likelihood of this happening are kept to a minimum you will not have to do any activities that you are not confident about achieving and you will be free to withdraw from the study at any time. The data will be collected from a physiotherapist experienced in working with people with acute knee injuries.

WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?

Participating in this study will not alter the treatment you receive so there will not be any direct benefit to you, although your symptoms will be monitored more comprehensively. Ultimately this information will lead to better rehabilitation, development of a profile of variables that effectively monitors functional recovery and development of a system that identifies individuals at an early stage that are not improving with physiotherapy and stops them receiving unnecessary treatment.

You will be told if important information about this study becomes available which might affect your willingness to continue taking part. If at any time the researchers consider it in your best interest they will withdraw you from the study and explain the reasons.

There will be no restrictions placed on your normal activities / lifestyle.

WHAT IF SOMETHING GOES WRONG?

If you are harmed whilst participating in this study there are no special compensation arrangements but if this is due to someone's negligence then you may have grounds for legal action. However, if you have any cause to complain about any aspect of the way you have been approached or treated during the course of this study then the normal National Health Service complaints mechanisms are available to you.

CONFIDENTIALITY – WHO WILL KNOW I AM TAKING PART IN THE STUDY?

All Information collected about you during this study will be kept strictly confidential and stored securely. Any information that leaves the hospital will anonymous so that you cannot be recognised from it. The Clinical Director of the Emergency Unit and specialist knee Orthopaedic Surgeons have given their approval for this research. With your consent your GP will be notified that you are participating in this study so that a record can be made in your medical notes.

LREC APPROVAL

Bro Taf Research Ethics Committee has given approval for this study.

WHAT WILL HAPPEN TO THE RESULTS OF THE STUDY?

Once the study is completed participants can obtain a copy of the results from the contact address below.

CONTACT FOR FURTHER INFORMATION

If you have any further questions about this study please contact Kate Button on 02920 742625 or Michelle Evans on 02920 744587.

Thank you for taking the time to read this information sheet and I look forward to your response in the near future.

Kate Button, Chartered Physiotherapist 22/12/02

Coleg Meddygaeth Prifysgol Cymru
University of Wales College of Medicine

Adran Addysg Ffisiotherapi / Department of Physiotherapy Education

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Q8

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WHY HAVE I BEEN CHOSEN?

If you have attended the Acute Knee Screening Service at the University Hospital of Wales or have been referred to the physiotherapy department for treatment of an acute knee injury then you will have been asked to participate in this study. In addition, control subjects with no knee injuries are also being recruited so that we are able to compare how the different groups move.

WHO IS ORGANISING THIS STUDY?

Kate Button a Chartered Physiotherapist, who works at the University Hospital of Wales as an Extended Scope Physiotherapist specialising in acute knee injuries and rehabilitation.

WHAT WILL HAPPEN TO ME IF I TAKE PART?

If you are a patient with an acute knee injury then you will continue to attend the physiotherapy department for treatment of your knee injury but at set time intervals additional measurements will be taken on your knee. This will include; two questionnaires to be completed by yourself that rate your knee symptoms and function; clinical tests conducted by the physiotherapist and an analysis of the way that you move over a range of functional activities using a digital video camera. Muscle activity will also be measured using sticky surface electrodes that lie on the skin overlying certain muscles. This is non invasive and should not cause you any discomfort. The functional activities analysed will be progressed so that initially the analysis will be of walking but this will be extended to include jogging, distance hop, run and stop and rapid change of direction. The timing of when you are ready to perform these activities will be dictated by the symptoms you experience in the knee.
If you are a control subject you will be videoed walking and muscle activity measured whilst performing the functional activities listed above.

WHAT ARE THE POSSIBLE RISKS OF TAKING PART?

If you are a patient then the distance hop, run and stop and rapid change of direction tests are designed to test the stability of the knee so there is a possibility that you could experience a sensation of giving way or increased pain. To ensure that the likelihood of this happening are kept to a minimum you will not have to do any activities that you are not confident about achieving and you will be free to withdraw from the study at any time. The data will be collected from a physiotherapist experienced in working with people with acute knee injuries.

WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?

Participating in this study will not alter the treatment you receive so there will not be any direct benefit to you, although your symptoms will be monitored more comprehensively. Ultimately this information will lead to better rehabilitation, development of a profile of variables that effectively monitors functional recovery and development of a system that identifies individuals at an early stage that are not improving with physiotherapy and stops them receiving unnecessary treatment.

You will be told if important information about this study becomes available which might affect your willingness to continue taking part. If at any time the researchers consider it in your best interest they will withdraw you from the study and explain the reasons.

There will be no restrictions placed on your normal activities / lifestyle.

WHAT IF SOMETHING GOES WRONG?

If you are harmed whilst participating in this study there are no special compensation arrangements but if this is due to someone's negligence then you may have grounds for legal action. However, if you have any cause to complain about any aspect of the way you have been approached or treated during the course of this study then the normal National Health Service complaints mechanisms are available to you.

CONFIDENTIALITY – WHO WILL KNOW I AM TAKING PART IN THE STUDY?

All Information collected about you during this study will be kept strictly confidential and stored securely. Any information that leaves the hospital will anonymous so that you cannot be recognised from it. The Clinical Director of the Emergency Unit and specialist knee Orthopaedic Surgeons have given their approval for this research. With your consent your GP will be notified that you are participating in this study so that a record can be made in your medical notes.

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CONTACT FOR FURTHER INFORMATION

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Thank you for taking the time to read this information sheet and I look forward to your response in the near future.

Kate Button, Chartered Physiotherapist 22/12/02

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INFORMATION SHEET (PART 3) Version 2 7/10/2004

Acute Knee Injury Rehabilitation: Using clinical and biomechanical outcomes to evaluate best practice

WHAT IS THE PURPOSE OF THE STUDY?
To develop and evaluate an 'enhanced' rehabilitation program for individuals that have ruptured their ACL. This aims to improve the level of activity that individuals can perform at with this injury without experiencing episodes of giving way.

WHY HAVE I BEEN CHOSEN?
You are one of fifty individuals that have been chosen to take part in this investigation because you attended the Acute Knee Screening Service at the University Hospital of Wales with an acute knee injury and have been referred to the physiotherapy department for treatment.

WHO IS ORGANISING THIS STUDY?
Kate Button a Chartered Physiotherapist, who works at the University Hospital of Wales as an Extended Scope Physiotherapist specialising in acute knee injuries and rehabilitation.

WHAT WILL HAPPEN TO ME IF I TAKE PART?
You will continue to attend the physiotherapy department for treatment of your knee injury but will be randomly assigned to one of two groups to receive the ordinary or enhanced physiotherapy. Both groups will receive the same amount of treatment and will be based around exercise and advice. The quality of the treatment received by the 'ordinary' physiotherapy group will still be of the highest standard and based around current concepts on the management of these injuries, so you will not be receiving poor treatment. At set time intervals additional measurements will be taken on your knee. This will include questionnaires to be completed by yourself that rate your knee symptoms and function; clinical tests conducted by the physiotherapist and an analysis of the way that you move over a range of functional activities using a digital video camera. Muscle activity will also be measured using sticky surface electrodes that lie on the skin overlying certain muscles. This is non invasive and should not cause you any discomfort. The functional activities analysed will be progressed so that initially the analysis will be of walking but this will be extended to include jogging, distance hop, run and stop and rapid change of direction. The timing of when you are ready to perform these activities will be dictated by the symptoms you experience in the knee. You will be reviewed at five and twelve months for all of these measures to be carried out.

WHAT ARE THE POSSIBLE RISKS OF TAKING PART?

The distance hop, run and stop and rapid change of direction are designed to test the stability of the knee so there is a possibility that you could experience a sensation of giving way or increased pain. To ensure that the likelihood of this happening are kept to a minimum you will not have to do any activities that you are not confident about achieving and you will be free to withdraw from the study at any time. The data will be collected from a physiotherapist experienced in working with people with acute knee injuries.

Most importantly participating in this study will not affect the surgery that you may or may not be on a waiting list for.

WHAT ARE THE POSSIBLE BENEFITS OF TAKING PART?

This research may lead to better treatment of individuals with a ruptured ACL so that you can perform at a more satisfactory level of activity. Coupled with previous research we have conducted we will be able to identify at an early stage individuals that will respond well to physiotherapy. This will stop those that do not from receiving unnecessary treatment and allow them to be place on a more appropriate pathway of care early.

You will be told if important information about this study becomes available which might affect your willingness to continue taking part. If at any time the researchers consider it in your best interest they will withdraw you from the study and explain the reasons.

There will be no restrictions placed on your normal activities / lifestyle.

WHAT IF SOMETHING GOES WRONG?

If you are harmed whilst participating in this study there are no special compensation arrangements but if this is due to someone's negligence then you may have grounds for legal action. However, if you have any cause to complain about any aspect of the way you have been approached or treated during the course of this study then the normal National Health Service complaints mechanisms are available to you.

CONFIDENTIALITY – WHO WILL KNOW I AM TAKING PART IN THE STUDY?

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LREC APPROVAL

Bro Taf Research Ethics Committee has given approval for this study.

WHAT WILL HAPPEN TO THE RESULTS OF THE STUDY?

Once the study is completed participants can obtain a copy of the results from the contact address below.

CONTACT FOR FURTHER INFORMATION

If you have any further questions about this study please contact Kate Button on 02920 742625 or Michelle Evans on 02920 744587.

Thank you for taking the time to read this information sheet and I look forward to your response in the near future.

Kate Button, Chartered Physiotherapist

Appendix 3 : Movement feedback

The movement feedback sheet that was given to the treating physiotherapists in part 2 of the investigation summarising individual ACLD performance.

NAME: DATE:
VISIT:

HEIGHT	
WEIGHT	
AGE	
GENDER	
PRE-INJURY ACTIVITY	
CURRENT ACTIVITY	

SWELLING

NIL	SMALL	MODERATE	LARGE

PRIORITY:

ROM

	LEFT	RIGHT
FLEXION		
EXTENSION		

PRIORITY:

GAIT

	ACL SUBJECT	CONTROL MEAN +/-1SD	CONTROL MIN/MAX	PRIORITY
Velocity		1.27 TO 1.62	0.72 TO 1.81	
Cadence		105 TO 127	70 TO 142.8	
Step length (injured)		0.67 TO 0.82	0.6 TO 0.915	
Step length (non-injured)		0.67 TO 0.82	0.6 TO 0.915	
Knee angle at heel strike		0 TO 9	-6 TO 13	
Ankle angle at heel strike		2 TO 9	-2 TO 18	

OBSERVATIONS

	Compensation present	PRIORITY
No movement compensation		
No arm swing		
Using brace		
Using walking aid		
Asymmetric gait		

NAME: DATE:
VISIT:

ONE LEGGED SQUAT

	ACL SUBJECT	CONTROL MEAN +/-1SD	CONTROL MIN/MAX	PRIORITY
Peak knee flexion angle (PKF)		60 TO 93	58 TO 107	
Ankle angle at PKF		28 TO 36	27 TO 38	
Knee valgus/varus at PKF		-15 TO 20	-25 TO 26	

OBSERVATIONS

	Compensation present	PRIORITY
No movement compensation		
Unable to keep balance		
Unsteady but keeps balance		
Excessive hip/pelvis ROM		
Excessive knee valgus/varus		
Unable to perform		

NAME: DATE:
VISIT:

DISTANCE HOP

	ACL SUBJECT	CONTROL MEAN +/-1SD	CONTROL MIN/MAX	PRIORITY
Hop distance injured leg		1.07 TO 1.72	0.65 TO 1.98	
Hop distance non-injured leg		1.07 TO 1.72	0.65 TO 1.98	
Knee angle at initial contact		9 TO 20	1 TO 27	
Ankle angle at initial contact		-11 TO 15	-32 TO 22	
Peak knee flexion angle		42 TO 59	34 TO 77	
Ankle angle at peak knee flexion		2 TO 14	-14 TO 19	
Knee range		28 to 45	21 to 56	
Ankle range		-8 to 19	-23 to 44	

OBSERVATIONS

	Compensation present	PRIORITY
No compensation		
Insufficient take off		
Multiple hops to stabilise		
Stabilises using other foot		
Multiple failed attempts		
Excessive use of arms / trunk		
Unable to perform		

NAME: DATE:
VISIT:

RUN AND STOP

	ACL SUBJECT	CONTROL MEAN +/-1SD	CONTROL MIN/MAX	PRIORITY
Knee angle at initial contact		6 TO 19	1 TO 30	
Ankle angle at initial contact		-6 TO 16	-26 TO 18	
Peak knee flexion angle		35 TO 51	26 TO 62	
Ankle angle at peak knee flexion		-5 TO 7	-9 TO 13	
Knee range		24 TO 37	19 TO 46	
Ankle range		-14 TO 8	-21 TO 33	

OBSERVATIONS

	Compensation present	PRIORITY
No compensation strategy		
Places other foot on ground		
Decelerates on other leg		
Slower approach speed		
Multiple failed attempts		
Multiple hops to decelerate		
Changes deceleration strategy		
Excessive use of arms / trunk		
Unable to perform		

Appendix 4: Questionnaires

This contains the questionnaires used in the study, these are: SF36, Cincinnati knee rating system and telephone questionnaire at 12 months follow-up.

SF-36 ASPECTS OF YOUR HEALTH

PARTICIPANT NAME: DATE:

1. In general, would you say your health is: (Please tick one)

Excellent	
Very Good	
Good	
Fair	
Poor	

2. Compared to one year ago, how would you rate your health in general now? (Please tick one)

Much better than one year ago	
Somewhat better now than one year ago	
About the same as one year ago	
Somewhat worse now than one year ago	
Much worse now than one year ago	

3. The following questions are about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much?

(Please tick one option on each line.)

Activities	Yes, Limited A Lot	Yes, Limited A Little	Not Limited At All
Vigorous activities, such as running, lifting heavy objects, participating in strenuous sports			
Moderate activities, such as moving a table, pushing a vacuum cleaner or playing golf			
Lifting or carrying groceries			
Climbing several flights of stairs			
Climbing one flight of stairs			
Bending, kneeling, or stooping			
Walking more than a mile			
Walking half a mile			
Walking one block			
Bathing or dressing yourself			

4. During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of your physical health? (Please tick either yes or no to each question.)

	YES	NO
Cut down on the amount of time you spent on work or other activities		
Accomplished less than you would like		
Were limited in the kind of work or other activities		
Had difficulty performing the work or other activities (for example, it took extra effort)		

5. During the past 4 weeks, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)? (Please tick either yes or no to each question.)

	YES	NO
Cut down on the amount of time you spent on work or other activities		
Accomplished less than you would like		
Didn't do work or other activities as carefully as usual		

6. During the past 4 weeks, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbours, or groups? (Please tick one box.)

Not at all	
Slightly	
Moderately	
Quite a bit	
Extremely	

7. How much physical pain have you had during the past 4 weeks? (Please tick one box.)

None	
Very mild	
Mild	
Moderate	
Severe	
Very Severe	

8. During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)? (Please tick one box.)

Not at all	
A little bit	
Moderately	
Quite a bit	
Extremely	

9. These questions are about how you feel and how things have been with you during the past 4 weeks. Please give the one answer that is closest to the way you have been feeling for each item. (Please place one tick on each line)

	All of the Time	Most of the Time	A Good Bit of the Time	Some of the Time	A Little of the Time	None of the Time
Did you feel full of life?						
Have you been a very nervous person?						
Have you felt so down in the dumps that nothing could cheer you up?						
Have you felt calm and peaceful?						
Did you have a lot of energy?						
Have you felt downhearted and blue?						
Did you feel worn out?						
Have you been a happy person?						
Did you feel tired?						
Has your physical health or emotional problems interfered with your social activities (like visiting with friends, relatives etc.)						

11. How TRUE or FALSE is each of the following statements for you? (Please place one tick on each line)

	Definitely True	Mostly True	Don't Know	Mostly False	Definitely False
I seem to get sick a little easier than other people					
I am as healthy as anybody I know					
I expect my health to get worse					
My health is excellent					

Thank you for filling in this questionnaire.

Participant Name: Date Completed: Visit No:

Cincinnati Knee Rating System:
Symptom Rating Scales, Patient Perception Scale

1. Directions: Using the key below, circle the appropriate boxes on the four scales below which indicate the highest level you can reach without having symptoms.

Scale	**Description**
10	Normal knee, able to do strenuous work/sports with jumping, hard pivoting
8	Able to do moderate work/sports with running, turning, and twisting: symptoms with strenuous work/sports
6	Able to do light work/sports no running, twisting or jumping: symptoms with moderate work/sports
4	Able to do activities of daily living alone; symptoms with light work/sports
2	Moderate symptoms (frequent, limiting) with activities of daily living
0	Severe symptoms (constant, not relieved) with activities of daily living

1. Pain

☐ 10 — ☐ 8 — ☐ 6 — ☐ 4 — ☐ 2 — ☐ 0

2. Swelling (actual fluid in the knee; obvious puffiness)

☐ 10 — ☐ 8 — ☐ 6 — ☐ 4 — ☐ 2 — ☐ 0

3. Partial Giving-Way (partial knee collapse, no fall to the ground)

☐ 10 — ☐ 8 — ☐ 6 — ☐ 4 — ☐ 2 — ☐ 0

4. Full Giving-Way (knee collapse occurs with actual falling to the ground)

☐ 10 — ☐ 8 — ☐ 6 — ☐ 4 — ☐ 2 — ☐ 0

2. Patient grade: Rate the overall condition of your knee at the present time. Circle one number below, using the scale below.

1	2	3	4	5	6	7	8	9	10
	poor		fair		good				normal

Poor – I have significant limitations that affect activities of daily living.
Fair – I have moderate limitations that affect activities of daily living, no sports possible.
Good – I have some limitations with sports but I can participate, I compensate.
Normal/excellent – I am able to do whatever I wish (any sport) with no problems.

Cincinnati Knee Rating System:
Sports Activity Scale, Activities of Daily Living Function Scales, Sports Function Scales

3. Sports Activity Scale

Select a level based on the frequency that you exercise. Within that level circle a number that corresponds to the statement that best summarises the activities you currently participate in.

Level 1 (participates 4-7 days/week)

100 Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
95 Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
90 No running, twisting, jumping (cycling, swimming)

Level 2 (participates 1-3 days/week)

85 Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
80 Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
75 No running, twisting, jumping (cycling, swimming)

Level 3 (participates 1-3 times/month)

65 Jumping, hard pivoting, cutting (basketball, volleyball, football, gymnastics, soccer)
60 Running, twisting, turning (tennis, racquetball, handball, ice hockey, field hockey, skiing, wrestling)
55 No running, twisting, jumping (cycling, swimming)

Level 4 (no sports)

40 I perform activities of daily living without problems
20 I have moderate problems with activities of daily living
0 I have severe problems with activities of daily living: on crutches, full disability

4. Activities of Daily Living Function Scales

Tick one statement for each activity that best describes your ability

1. Walking

Check one box

40 ☐ normal, unlimited
30 ☐ some limitations
20 ☐ only 3-4 blocks possible
0 ☐ less than 1 block; cane, crutch

2. Stairs

Check one box

40 ☐ normal, unlimited
30 ☐ some limitations
20 ☐ only 11-30 steps possible
0 ☐ only 1-10 steps possible

3. Squatting/kneeling

Check one box

40 ☐ normal, unlimited
30 ☐ some limitations
20 ☐ only 6-10 possible
0 ☐ only 0-5 possible

Sports Function Scales

Tick one statement for each activity that best describes your ability

1. Straight running

Check one box

100 ☐ fully competitive
80 ☐ some limitations, guarding
60 ☐ definite limitations, Half speed
40 ☐ Not able to do

2, Jumping/landing on affected leg

Check one box

100 ☐ fully competitive
80 ☐ some limitations, guarding
60 ☐ definite limitations, half speed
40 ☐ Not able to do

3. Hard twists/cuts/pivots

Check one box

100 ☐ fully competitive
80 ☐ some limitations, guarding
60 ☐ definite limitations, half speed
40 ☐ Not able to do

NAME: **VISIT:** **DATE:**

OCCUPATIONAL RATING SCALE

Tick the response that best describes what you actually do at work. Tick one response per factor.

FACTOR 1 sitting		**FACTOR 2** Standing/ walking		**FACTOR 3** walking on uneven ground		**FACTOR 4** squatting		**FACTOR 5** climbing		**FACTOR 6** Lifting/carrying		**FACTOR 7** pounds carried	
8-10 hrs/day		0 hr/day		0 hr/day		0 times/day		0 times/day		0 times/day		0-5lbs	
6-7 hrs/day		1 hr/day		1 hr/day		1-5 times/day		1 flight, 2 times/day		1-5 times/day		6-10lbs	
4-5 hrs/day		2-3 hrs/day		2-3 hrs/day		6-10 times/day		3 flights, 2 times/day		6-10 times/day		11-20lbs	
2-3 hrs/day		4-5 hrs/day		4-5 hrs/day		11-15 times/day		10 flights/ ladders		11-15 times/day		21-25lbs	
1 hr/day		6-7 hrs/day		6-7 hrs/day		16-20 times/day		Ladders with weight 2-3 days/week		16-20 times/day		26-30lbs	
0 hr/day		8-10 hrs/day		8-10 hrs/day		More than 20 times/day		Ladders daily with weight		More than 20 times/day		More than 30lbs	

ACUTE KNEE INJURY REHABILITATION:

TELEPHONE QUESTIONNAIRE

Participant name: Telephone number:

Date telephoned:

I am phoning on behalf of Kate Button from the physiotherapy department at the University Hospital of Wales, to follow up on the research that you have been involved in following your knee injury. Could I ask you a few questions about how your knee

QUESTIONS	
Have you returned to your pre-injury sports or exercise?	YES/NO
What exercises are you currently participating in and how many hours per week?	
Have you had an ACL reconstruction?	YES/NO
If yes, when?	
Do you experience any episodes of full giving way?	YES/NO
Do you have any other symptoms in the knee? If yes what?	YES/NO
Have you made any trips to the GP over the past 7 months? If yes how many?	YES/NO
Have you taken any prescriptions for your knee over the past 7 months? If yes what?	YES/NO
Do you have any other concerns regarding our knee? If yes what?	
Check address	

Thank you for your time.

Appendix 5: Published manuscripts

Based on the results of this investigation two manuscripts have been published in peer reviewed journals. A third has been has been accepted for publication in Physical Therapy in Sport. This appendix contains copies of all 3 manuscripts.

ORIGINAL ARTICLE

Measurement of functional recovery in individuals with acute anterior cruciate ligament rupture

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Objectives: To measure functional recovery following acute anterior cruciate ligament (ACL) rupture using a simple and reliable clinical movement analysis system. Clinic based methods that simultaneously quantify different aspects of movement over a range of activities and model functional recovery will help guide rehabilitation.

Methods: A longitudinal study was used to measure gait variables at initial physiotherapy attendance and then at monthly intervals using a digital camcorder and computer for quantitative analysis. Jogging and distance hopping were added during recovery. A sample of 63 ACL deficient subjects entered the study and 48 subjects were measured at least three times. To determine the pattern of recovery, repeated measurements were analysed using a least square fit of the data.

Results: Gait variables took between 95 and 130 days post injury to reach the control mean and stabilise shortly after this. Hopping distance for the injured leg took 62 days to recover to within normal limits and 5 months post injury to reach the control mean. Jogging was already within the control limits at 30 days post injury and demonstrated little change with recovery.

Conclusions: Functional recovery of multiple variables has been modelled. In the early phase of post injury, gait velocity seems to be the most useful variable to measure improvement. Recovery of more challenging activities appears to take an average of 5 months. Therefore, patients may need to be monitored in physiotherapy until this time and advised not to return to sport until sufficient recovery is demonstrated on activities such as distance hopping.

Following anterior cruciate ligament (ACL) rupture, altered levels of physical performance and secondary meniscal damage are commonly cited as complications with non-operative management.[1–4] Despite this, not all ACL deficient (ACLD) individuals will choose to have a reconstruction. For these patients, physiotherapy rehabilitation is crucial to help them maximise their knee function and return to a level of activity that is safe.[5–7] In the United Kingdom this is complicated by long surgical waiting lists that can delay those subjects who require surgery receiving a reconstruction[8,9] and places a greater emphasis on rehabilitation and patient self management pre-operatively.

If an individual is receiving rehabilitation, it is important that any change in their functional ability is measured over time. This will help the clinician to make decisions about the appropriateness of treatment, to assess if the patient is achieving functional milestones, and to give advice on what activities/sport are safe for the individual to undertake.[10] Functional outcome measures are recognised as having a valuable role in helping clinicians make decisions because the functional tests reflect the type of activities that patients target as acceptable outcomes.[11–13]

A number of studies have analysed the biomechanics of functional activities such as gait, jogging, hopping, and cutting manoeuvres in ACLD knees. They have analysed compensation strategies that include changes in joint reaction forces, moments, and powers.[14–20] These studies have not collected data longitudinally, they have been restricted to individuals with chronic ACL tears, and their movement analysis systems do not fulfil the requirements of a clinical gait analysis system.[21]

Some validated measurement tools do exist to predict which ACLD individuals will do well with rehabilitation or delayed surgical management.[22,23] Although they are valuable screening tools, they do not provide information on the pattern of recovery over time. They have also only been designed and tested on athletes who regularly participate in activities requiring a high degree of pivoting and so may not be appropriate for those individuals who participate in leisure activities and sport at a lower level.

This means that there is a lack of information available about the course of recovery following an ACL rupture and its transition from an acute to chronic status. Important rehabilitation questions such as: how long does recovery take, at what stages is it safe to progress to more complex activities, and do functional activities ever fully recover, are left unanswered. Therefore, the aim of this study was to measure functional recovery following ACL rupture in the clinical setting.

METHODS

Subjects

Over the recruitment period from May 2001 to November 2003, 281 individuals attended the Acute Knee Screening Clinic (AKSS) at the University Hospital of Wales (UHW) and were diagnosed with an acute ACL rupture, which was confirmed by MRI. Sixty three of these ACLD individuals lived in the UHW physiotherapy catchment area, and on this basis were invited to enrol in the study. A convenience sample of 61 control subjects without a history of knee damage, were recruited from the same catchment area to match the ACL subjects. Participants were excluded from the study if they were under 18 or over 50 years of age, had other neurological or musculoskeletal pathology that would alter their performance, had received acute arthroscopies, and had

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Abbreviations: ACL, anterior cruciate ligament; ACLD, ACL deficient; AKSS, Acute Knee Screening Clinic; UHW, University Hospital of Wales

Table 1 Mean and standard deviations of the participant characteristics comparing the ACL and control groups

Characteristic	Mean (SD)	95% CI	p value
Height (cm)			
ACL	171.7 (9.4)	4.34 to 3.14	0.912
Control	171.9 (9.4)		
Age (years)			
ACL	27.5 (7.7)	−2.83 to 1.88	0.961
Control	27.6 (5.6)		
Weight (kg)			
ACL	72.9 (13.0)	−4.81 to 6.45	0.899
Control	72.5 (13.8)		
Gender			
ACL	Male/female		0.775
Control	Male/female		

The 95% confidence intervals of the difference between groups and the significance level calculated through an independent *t* test are shown (α level = 0.05).

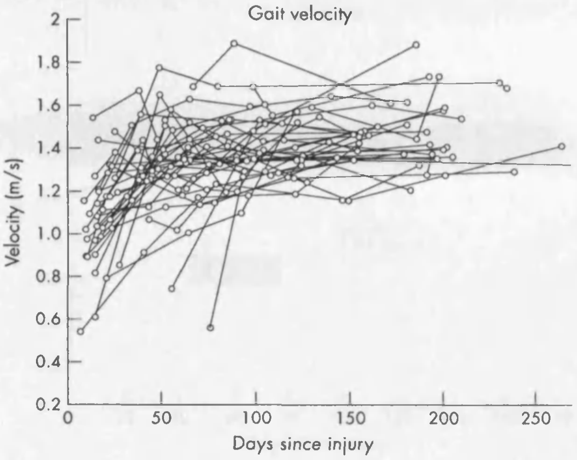

Figure 1 Recovery over time of gait velocity for each individual ACLD patient. Each data collection visit is represented by an empty circle with a line joining individual visits.

locked knees or combined ACL and posterior cruciate ligament injuries. However, ACL injuries combined with MCL tears or asymptomatic meniscal tears were included. This study was approved by the South Wales Local Research and Ethics Committee. All patients followed a standardised rehabilitation program that incorporated strengthening and neuromuscular control activities. This was staged according to symptoms and time post injury.[24 25]

Repeated measurements over time

On initial attendance all ACL patients were given a study information sheet. Data collection started on their second visit after they had provided written informed consent. Forty eight participants underwent a minimum of three movement analysis recording sessions and were therefore included in this sample. Recordings for gait analysis were made at approximately monthly intervals. As they progressed through rehabilitation, jogging and distance hopping were also recorded if subjects had minimal resolving effusion, full range of knee motion, and no episodes of full giving way.[23–27]

Clinical movement analysis

All data collection took place in the gym of the physiotherapy department at UHW. The walkway used was 15 m long. Two sticks with markers at either end were placed midway along the walkway, parallel to each other and 1 m apart for calibration and data processing. A digital camcorder (SONY Digital Handycam DCR-PC110E) was placed 6 m away from the walkway and 1 m above the ground on a tripod perpendicular to the direction of movement. Instructions given to the subjects for gait and jogging were to move at their comfortable speed along the length of the walkway. Two trials were collected, one in either direction.

Table 2 Summary of patient characteristics for the recruited ACLD sample (1) and all ACLD subjects who attended the AKSS (2)

Characteristic	Group	Mean (SD)	Range	Ratio, M/F
Age, years	1	27.5 (7.7)	18–53	
	2	29.6 (9.2)	15–58	
Gender	1			38/25
	2			170/44

M/F, male/female.

For maximal hopping distance, subjects were instructed to start on their testing limb, hop as far as they could, and land on their testing limb, maintaining their balance until instructed to move away. Distance was measured on both the injured and non-injured limbs of patients.

Data analysis and processing

All data were processed using a SONY VAIO FX105 laptop with DVGait and MATLAB 12 software. Individual frames corresponding to events of interest were saved from the video and stored as JPEG files. For gait and jogging these were three heel strikes of the subject walking in either direction and for hopping frames corresponding to pre take off and landing. Temporal information of these events was obtained from frames from the display in DVGait (resolution: 25 frames per second). For stage two of the processing, a program was purpose written in MATLAB. The two 1 m sticks were used to calibrate the area between them and create a grid so that the placement of the foot (location of the heel in contact with the floor at heel strike) relative to the calibration sticks could be measured. This spatial information was obtained automatically by the computer after the operator had indicated the heel location by means of a cross hair displayed on the computer screen. Once this temporal and spatial information was processed, the following variables could then be analysed by the computer: gait and jogging velocity, cadence, step length, gait step length symmetry, and maximal hopping distance.

The reliability of this system for calculating gait velocities has been found to be high, with an inter-tester reliability of ICC = 0.99 and reliability between assessors and an optoelectric timer of ICC = 0.98.[28]

Statistical analysis

Independent *t* tests and χ^2 tests were used to compare the ACL and control groups. The same approach was used to check that the ACL subject sample participating in the study was representative of the larger population of all ACL subjects attending the AKSS. As indicated earlier, ACLD subjects needed to have a minimum of three monthly recordings of their gait to be entered for further analysis. Data from the

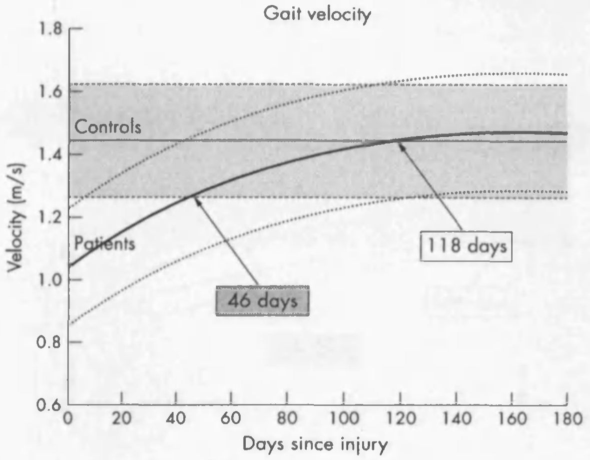

Figure 2 Recovery over time of gait velocity. The ACLD group is indicated by the solid curved line with 1 SD indicated by the dotted lines. The reference values derived from the control group (average ± 1 SD) are indicated by the horizontal shaded band with straight grey lines.

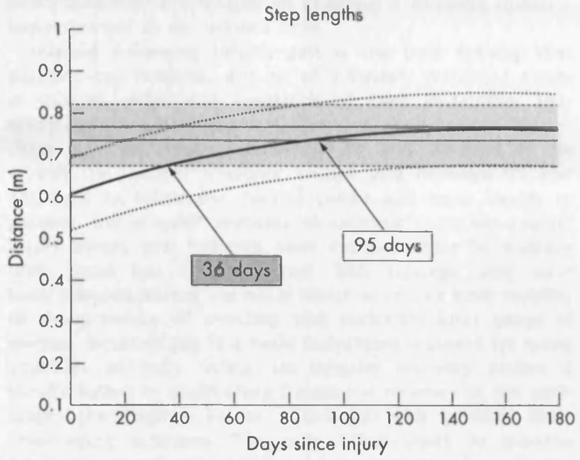

Figure 4 Recovery over time of step lengths. The ACLD group is indicated by the solid curved line with 1 SD indicated by the dotted lines. The reference values derived from the control group (average ± 1 SD) are indicated by the horizontal shaded band with straight grey lines.

control group were used to calculate means and standard deviations (SD) of the different parameters. Members of the ACL group were classified as having recovered to within a normal range when their values were within ±1 SD of the control mean.[29] Changes over time indicative of functional recovery in the ACL group were modelled using a least square fit of the data. Because functional recovery was non-linear, a third order polynomial curve fit was used with "days since injury" as the independent variable to a maximum of 180 days since injury. In addition, 1 SD around this fit line was calculated.

All data from the control and ACL groups were plotted against time (in days) to permit a descriptive exploration of recovery. Two events were noted: the time when the ACL group returned within the range of values found in the control group (average ±1 SD) and the time when the ACL group returned to the average value of the control group.

RESULTS

The control and ACLD groups were matched for age, height, weight, gender, and activity levels (table 1).

Patient characteristics of the ACL sample recruited in this investigation compared to all ACLD subjects who attended the AKSS are summarised in table 2.

Gait

The raw data for recovery of gait velocity for each individual ACLD subject over time have been plotted in fig 1 for the purpose of illustration. The average recovery for all gait variables have been plotted in figs 2–5. The first gait variable to return to within the control reference value was cadence,

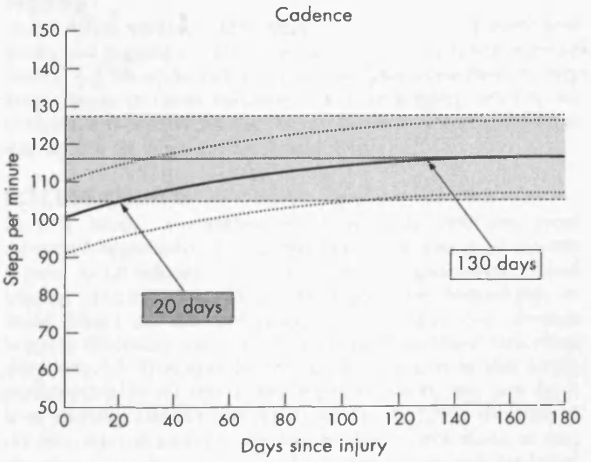

Figure 3 Recovery over time of cadence. The ACLD group is indicated by the solid curved line with 1 SD indicated by the dotted lines. The reference values derived from the control group (average ± 1 SD) are indicated by the horizontal shaded band with straight grey lines.

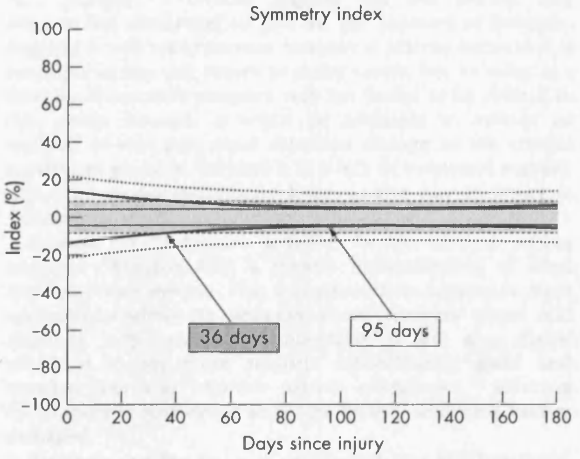

Figure 5 Recovery over time of step length symmetry. The ACLD group is indicated by the solid curved line with 1 SD indicated by the dotted lines. The reference values derived from the control group (average ± 1 SD) are indicated by the horizontal shaded band with straight grey lines.

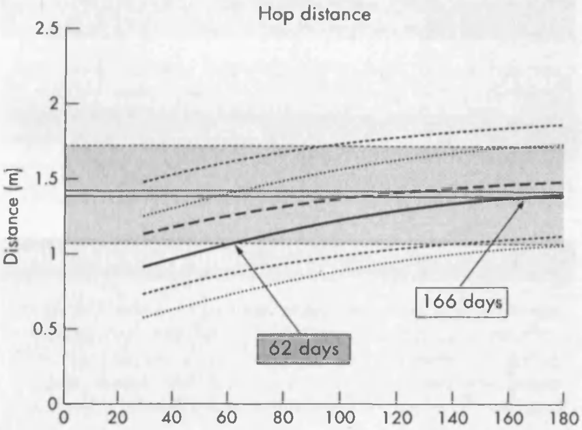

Figure 6 Recovery over time of maximal hopping distance. The ACLD group is indicated by the solid curved line with 1 SD indicated by the dotted lines. The reference values derived from the control group (average ± 1 SD) are indicated by the horizontal shaded band with straight grey lines.

followed by step length, step symmetry, and gait velocity. Once all the gait variables stabilised at the control mean, both groups walked at a self selected velocity of 1.43 m/s, with a cadence of 116 steps per minute, step length of 0.73 m, and 5% asymmetry between limbs.

Hopping distance

Recovery of hopping distance from the time of injury for the injured and non-injured limbs is plotted in fig 6. At 166 days post injury, the average hopping distance of the injured limb in the ACLD subjects was 1.3 m and starting to stabilise close to the control average of 1.4 m. Initially the hopping distance of the non-injured ACLD limb was shorter than that of the control subjects but by 108 days post injury had reached the control mean. The difference in hopping distance between the injured and non-injured limb decreased with time from injury.

Jogging

Some ACLD subjects start jogging as early as 30 days post injury and jogging velocity, step length, and cadence were all within ± 1 SD of the control subjects. Over time there is very little change in these variables. Average jogging velocity for controls was 3 m/s and for ACLD subjects 2.9 m/s. Average step length for both groups was 1.1 m.

DISCUSSION

In this study, a number of functional activities were measured repeatedly during recovery in a group of acutely injured ACLD patients. The results for the gait variables and jogging velocity analysed in this study, are comparable to those found in the literature,[16 18 20 30 31] but the average hopping distances are slightly shorter than those described elsewhere.[13 32] This may be due to the subjects in this study participating in all levels and types of sport, not just high level pivoting and cutting activities. The hopping distance of the non-injured limb did recover to the control mean as was expected,[33] but the results of other studies have indicated that this may not always be the case.[32] The initial reduction in hopping distance in the non-injured limb could have been due to over protection in the acute stage post injury.[31] This would indicate that it is not appropriate to use contralateral performance as a reference to evaluate if hopping distance has recovered in the injured limb.

Initially following injury, gait is the only activity that patients can perform, due to an effusion, restricted range of motion, pain, and sensation of knee instability. This study indicated that gait variables took far longer to recover than was anticipated, between 20 and 46 days to be within the control reference values and between 95 and 130 days to reach the control mean and even longer to plateau. Initial quick recovery of cadence to within control limits meant that patients were compensating by walking with more but shorter steps. This strategy may have been adopted during the acute phase to ensure knee stability in the presence of swelling and restricted knee range of motion. Because gait is a basic movement required for many activities of daily living, its lengthy recovery makes it ideally suited to monitoring functional recovery in the early stages post injury, before individuals can perform more challenging activities. The only other study to monitor functional recovery of ACLD subjects over time found using visual analysis that it took between 2.8 and 4 weeks to achieve independent, non-antalgic gait.[34] The speed of this recovery is possibly due to using a different less sensitive method of gait analysis.

Distance hopping had a slower recovery than gait and jogging and was stabilising at 5 months post injury. This would indicate that it is a more difficult activity for ACLD subjects and should be introduced later in rehabilitation.[24] Unlike gait and jogging, it challenges a different aspect of knee stability. In order to successfully land from a hop, individuals need to be able to control large vertical and, in particular, knee joint shear forces, coupled with large extensor moments and rapid deceleration.[15 35 36] Although hopping distance is an easy measure, it would not be recommended that a decision about return to sport is made from this variable alone. Several other studies have demonstrated that a battery of outcome measures need to be used to predict if an individual can return to contact sport.[13 22 23]

Jogging velocity, cadence, and step lengths demonstrated very little change during recovery. Cadence and step length did recover to the control mean, but the jogging velocity for ACLD subjects consistently performed just below this. There is some disagreement in the literature as to whether jogging velocity and cadence do fully recover following ACL rupture.[14 16] Overall jogging did not provide any information additional to gait on the recovery of function. Jogging is still an important functional activity because it is essential for the safe return to many sports, but its value as a functional outcome measure was not found to be evident in this study. Instead, it might be advisable to include an analysis of run and rapid direction change in the clinical movement analysis, because it is a lack of rotational stability that often causes individuals' knees to give way on return to full activity.[1 17]

Analysis of functional activities in the clinical setting provides clinicians with a greater understanding of what these activities involve. This will allow them to provide more appropriate advice to patients about recovery times and activities they can safely undertake. It will also enable clinicians to set more realistic rehabilitation goals and together this may improve patient compliance,[38] reducing the number of episodes of knees giving way and being further damaged.[1 39]

Based on our results, it is anticipated that full functional recovery on average could take up to 5 months or longer. It may be even slower if an individual has not attended a full course of rehabilitation or was delayed receiving treatment. There are no clear guidelines in the literature suggesting how

What is already known on this topic

Functional recovery following acute ACL rupture has not previously been measured longitudinally using clinically relevant functional variables. Important rehabilitation questions about length of recovery and time to return to sport remain unanswered.

What this study adds

Functional recovery has been measured using simple clinical variables and has been found to take up to 5 months. Clinicians can use this information to give better advice to patients about individual recovery and provide more structure for rehabilitation on the basis of functional activities.

long it could take ACLD individuals to return to sport, but anything between 4 months post injury to never returning have been reported.[5 40] For the clinician this indicates that individuals could be attending physiotherapy over a prolonged period of time, requiring significant amounts of treatment.

Compared to all patients attending the AKSS, this study sample of ACL subjects contained more female subjects and a greater proportion of individuals participating in sports requiring a high degree of pivoting. This is probably due to the presence of a sports college within the catchment area. This makes it all the more surprising that, despite the higher proportion of high level athletes in this sample, recovery of the functional variables still took a considerable time.

Measuring functional recovery of ACLD patients from initial injury over time in the clinical setting is unique. Analysis of gait provided information on movement compensations and recovery in the early stages following injury, when it would be unsafe to perform sports specific functional activities such as hopping. The jogging variables analysed in this study provided little information on functional recovery. Clinicians can compare this model of functional recovery with individual patient performance to see if patient function is following a typical path of recovery. Overall functional recovery has been found to take a considerable amount of time: 3–4 months for gait and 5 for hopping. This means that patients may need to be treated in physiotherapy until this time and advised not to return to sport until a full recovery is demonstrated on activities such as distance hopping.

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Competing interests: none declared

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COMMENTARY

This article addresses a clinically relevant topic, that is, functional recovery after anterior cruciate ligament injury. The approach of monitoring the functional restoration of the individual patient or athlete definitely appears worthwhile. It provides the clinician and/or therapist with information that will be useful for recommendations regarding the athlete's return to sporting activities. It is especially helpful that the authors monitored different activities that provided varying levels of challenge to the knee joint. Therefore, the information presented here should help when devising specific training regimes for individual patients in order to help them regain full functional performance.

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ELECTRONIC PAGES

Online short and case reports

The following electronic only articles are published in conjunction with this issue of *BJSM*

Sit to stand transfer: performance in rising power, transfer time and sway by age and sex in senior athletes

J B Feland, R Hager, R M Merrill

Objective: To observe the differences in performance variables of the sit to stand transfer (as measured on the NeuroCom Balance Master) in a population of senior athletes.

Method: A convenience sample of 173 subjects aged 50 years and older. Data were obtained from voluntary participation in a health fair offered at the annual Huntsman World Senior Games in St George, Utah, USA. All sit to stand tests were performed on the NeuroCom Balance Master. The measured parameters were weight transfer time (WTT), rising power (force exerted to rise), and centre of gravity sway (COG sway) during the rising phase.

Results: A significant difference was found between stratified age groups (50–64 and 65+ years) on rising power. There was also a sex difference in rising power. No significant differences were found in weight transfer time or COG sway.

Conclusion: While rising power decreases with increasing age in senior athletes, WTT and COG sway remain similar regardless of age or sex. The maintenance of these other two variables (WTT and COG sway) may be attributable to physical activity and/or participation in sport.

(*Br J Sports Med* 2005;**39**:e39) http://bjsm.bmjjournals.com/cgi/content/full/39/9/e39

Thrower's fracture of the humerus with radial nerve palsy: an unfamiliar softball injury

P Curtin, C Taylor, J Rice

A fracture of the normal humerus in a healthy young adult most commonly results from significant direct trauma. Throwing sports have become increasingly popular outside of North America and bring with them a novel injury mechanism for clinicians. A 21 year old woman sustained a "thrower's fracture" of the distal humerus and radial nerve palsy while throwing a softball. She was treated by internal fixation. Her fracture united, and radial nerve neurapraxia resolved after 8 weeks. Clinicians should be aware of this entity so that prodromal symptoms can be recognised early and thrower's fractures are not investigated unnecessarily.

(*Br J Sports Med* 2005;**39**:e40) http://bjsm.bmjjournals.com/cgi/content/full/39/9/e40

ORIGINAL ARTICLE

Classification of functional recovery of anterior cruciate ligament copers, non-copers, and adapters

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Objectives: (*a*) To identify whether differences exist in the pattern of recovery with respect to functional outcomes for acutely ruptured anterior cruciate ligament deficient (ACLD) copers, adapters, and non-copers. (*b*) To identify clinically relevant outcomes that could distinguish between three functional subgroups.

Methods: A longitudinal study was used to measure gait variables and distance hop at regular intervals after injury using a digital camcorder and computer for quantitative analysis. A sample of 63 ACLD subjects entered the study; 42 subjects were measured at least three times. At 12–36 months after injury, subjects were classified as functional copers, adapters, or non-copers on the basis of which of their preinjury activities they had resumed. To determine the pattern of recovery, repeated measurements were analysed using a least squares fit of the data.

Results: 17% of ACLD subjects were classified as functional copers, 45% as adapters, and 38% as non-copers. Only 5% of those who participated in high demand activities before injury returned to them. ACLD copers had recovered above the control mean for all gait variables by 40 days after the injury. Hopping distance did not recover to the control mean. Non-copers struggled to recover to control limits and remained borderline for all the gait variables.

Conclusions: Distinctive patterns of functional recovery for three subgroups of ACLD subjects have been identified. Gait variables and activity level before injury were the most useful variables for distinguishing between the subgroups. If potential for recovery is identified early after injury, then appropriate treatment can be given.

Surgical reconstruction is regarded as the optimal treatment for patients with anterior cruciate ligament deficiency (ACLD) who want to return to high demand activities or patients who experience giving way episodes.[1 3] However, some will choose conservative management.[4 5] Most orthopaedic surgeons (80%) agree that physiotherapy is useful in the conservative management of the ACLD knee, and 85% of their patients attend preoperative physiotherapy.[1 2]

Distinct differences in functional outcomes for patients with ACLD can be expected when they are separated into copers, non-copers, and adapters on the basis of which preinjury activities they have returned to.[5–9] Clinically, failure to separate patients into subgroups can result in overestimation or underestimation of a patient's overall performance,[10] and the most appropriate care will not be given.[8] This accounts for the mixed outcomes that have been found in the numerous studies that have evaluated long term function.[11–18]

Several studies have developed evaluation schemes to enable identification of potential ACLD copers.[5 7 19] Although they are valuable screening tools, they do not provide information on the pattern of recovery over time for the individual subgroups. They have only been designed and tested on athletes who regularly participate in high level activities and do not allow early decision making about the long term management. This means that clinicians face a dilemma when evaluating an ACLD patient's potential for recovery. The aim of this study was to identify whether differences are evident in the pattern of recovery with respect to functional outcomes for three subgroups of patients with ACLD: copers, adapters, and non-copers. Clinically relevant outcomes for distinguishing between subgroups were also identified.

METHODS

Subjects

Over the recruitment period from May 2001 to November 2003, 281 patients attended the Acute Knee Screening Service at the University Hospital of Wales with an acute anterior cruciate ligament (ACL) rupture, which was confirmed by magnetic resonance imaging. Potential participants were excluded from the study if they were under 18 or over 50 years of age, had other relevant neurological or musculoskeletal pathology, required an urgent knee arthroscopy, had combined ACL and posterior cruciate ligament injuries, or did not live in the University Hospital of Wales catchment area for physiotherapy. This resulted in 63 patients with ACLD being invited to participate in the study. Only 42 were eligible to be included in the final analysis; 21 were excluded because they did not have a minimum of three movement analyses or were not contactable for the telephone follow up 12–36 months after the injury. A convenience sample of 61 control subjects without a history of knee damage were recruited from the same catchment area to match the patients with ACLD. This study was approved by the South Wales Local Research and Ethics Committee. All patients followed a rehabilitation programme that emphasised full range of motion, muscle strengthening, and neuromuscular control activities. Treatment was staged according to symptoms and time after injury.[20 21]

Repeated measurements over time

A minimum of three movement analysis recordings between zero and five months after injury was required for each subject. Five months was chosen as the cut-off point for data collection on the basis of our earlier findings.[22] This showed no change in the functional outcome measures after five months. The number of days after injury on which individual

Table 1 Characteristics of the anterior cruciate ligament deficient (ACLD) group and control group

Characteristic	ACLD	Control	95% CI	*t* Value	p Value
Height (cm)	171.7 (9.4)	171.9 (9.4)	4.34 to 3.14	−0.111	0.912
Age (years)	27.5 (7.7)	27.6 (5.6)	−2.83 to 1.88	−0.50	0.961
Weight (kg)	72.9 (13.0)	72.5 (13.8)	−4.81 to 6.45	0.128	0.899
Male/female	38/25	35/26		0.775	

Values are mean (SD). The 95% confidence intervals (CIs) of the difference between groups and the significance level calculated through an independent *t* test are shown (α level = 0.05).

data collection sessions took place for each subject was recorded and used in the analysis.

Clinical movement analysis

Gait data collection started once all subjects had provided written informed consent. Distance hopping was recorded if subjects had minimal resolving effusion, full range of knee motion, and no episodes of full giving way.[5 7 23 24] All data collection took place in the gym of the physiotherapy department. The walkway used was 15 m long. Two sticks with markers at either end were placed midway along the walkway, parallel to each other 1 m apart for calibration and data processing. A digital camcorder (SONY Digital Handycam DCR-PC110E) was placed 6 m away from the walkway on a tripod perpendicular to the direction of movement set at 1 m high. Subjects were instructed to move at a comfortable speed along the length of the walkway. Two trials were collected, one in either direction.

For maximal hopping distance, subjects were instructed to start on the limb being tested, hop as far as they could, and land on the same limb, maintaining their balance until instructed to move away.

Follow up

At 12–36 months after injury, subjects were followed up with a telephone questionnaire. They were asked about episodes of knee instability and current work and sport activities. This was compared with their preinjury activity level, and they were then classified as functional copers, adapters, or non-copers. A coper is defined as a patient who has returned to their preinjury level of work and sport with no limitations in their performance. An adapter is someone who has reduced their work or sport level or changed activities to prevent their knee fully giving way.[7] Non-copers are patients who fail to return to their preinjury activities and are experiencing episodes of full giving way with work, activities of daily living, or low demand, non-pivoting sports. Our definition of a non-coper has been adapted from that of Eastlack *et al*[7] to improve its suitability for use with an ACLD population that mainly includes recreational athletes.

Data analysis and processing

All data were processed using a Sony Vaio FX105 laptop with DVGait and MATLAB 12 software. Individual frames corresponding to events of interest were saved from the video and stored as JPEG files. For gait analysis, these frames were three heel strikes of the subject walking in either direction, and, for hopping, two frames corresponding to before take off and landing. Temporal information of these events was obtained in frames from the display in DVGait (resolution 25 frames per second). For stage 2 of the processing, a program was purpose written in MATLAB. The two 1 m sticks were used to calibrate the area between them and create a grid so that the placement of the foot (location of the heel in contact with the floor at heelstrike) relative to the calibration sticks could be measured. This spatial information was obtained automatically by the computer after the operator had indicated the heel location by means of a cross hair displayed on the computer screen. Once this temporal and spatial information had been processed, the following variables could be analysed by the computer: gait velocity, cadence, step length, gait/step length symmetry, and maximal hopping distance.

Table 2 Summary of patient characteristics for the anterior cruciate ligament deficient (ACLD) sample recruited (group 1) and all ACLD subjects who attended the Acute Knee Screening Service (group 2)

Characteristic	Group 1	Group 2
Age (years)	27.5 (7.7) (18–53)	29.6 (9.2) (15–58)
Male/female ratio	38/25	170/44

Ages are mean (SD) (range).

The reliability of this system for calculating gait velocities has been found to be high, with an intraclass correlation coefficient of 0.99 for inter-tester reliability and 0.98 for reliability between assessors and an optoelectric timer.[25] The intraclass correlation coefficient for intrarater reliability of measuring hopping distance using the method described above was 0.99.

Statistical analysis

Independent *t* tests and χ^2 tests were used to compare the ACLD and control groups. The same approach was used to check that the ACLD subject sample participating in the study was representative of the larger population of all ACLD subjects that attended the Acute Knee Screening Service. As indicated above, ACLD subjects needed to have a minimum of three monthly recordings of their gait to be entered for further analysis. Data from the control group were used to calculate means and standard deviations for the different variables.

Changes over time indicative of functional recovery in the ACL groups were modelled using a least squares fit of the pooled data for each subgroup. Because functional recovery was non-linear, a third order polynomial curve fit was used with days since injury as the independent variable to a maximum of 150 days since injury. One standard deviation around the fit lines was also calculated. Four fit lines were plotted against time (in days) to permit a descriptive exploration of recovery. These fit lines are: the overall mean recovery of all ACLD subjects together with the mean recovery of the subgroups of copers, adapters, and non-copers. Two events were noted: the time when the ACLD groups returned to within the range of values found in the control group (mean (SD)); the time when the ACLD groups returned to the mean value of the control group. The ACLD groups were classified as having recovered to within the normal range when their values were within ±1SD of the control mean.[26]

Table 3 Characteristics of each of the anterior cruciate ligament deficient subgroups

	Copers	Adapters	Non-copers	F value (significance)
Age (years)	28.7 (8.0)	29.8 (8.5)	27.31 (6.74)	0.455 (0.638)
Height (cm)	169.17 (12.73)	173.57 (7.2)	170.56 (10.29)	0.327 (0.725)
Weight (kg)	71.33 (14.18)	72 (11.24)	71.78 (10.09)	0.05 (0.995)
Female/male ratio	5/2	6/13	6/10	
Activity level before injury				
Level 1	2	16	12	
Level 2	1	0	2	
Level 3	4	3	2	
Total	7	19	16	

Values are mean (SD) or number of subjects. Activity levels: level 1, contact sports with a high pivoting and jumping demand; level 2, non-contact sport with moderate pivoting and jumping demands; level 3, non-contact sport with low/no pivoting or jumping.

RESULTS

Subjects

Table 1 summarises the characteristics of the control and ACLD groups. All the ACLD subjects who participated in this study were matched to the control subjects for age, height, weight, and activity levels.

Table 2 summarises the patient characteristics of the ACLD sample recruited in this investigation compared with all ACLD subjects who attended the Acute Knee Screening Service. Both ACLD groups had similar mean ages, age ranges and a greater proportion of male than female patients, although the male/female ratio is lower for group 1.

Table 3 summarises the characteristics of each functional subgroup. Of the 42 subjects followed up at 12 months 17% were classified as copers, 45% as adapters, and 38% as non-copers. Overall, only 5% of subjects who participated in high demand activities before injury returned to them.

Gait

Figures 1–3 show the mean recovery for all gait variables for each of the functional subgroups. Table 4 summarises the number of days after injury when the ACLD subgroups and the mean of all ACLD subjects reached "normal limits" set by the control subjects.

Initially after injury there is a trend for all gait variables for all ACLD subgroups to be below the normal limits set by control subjects. With time, the recovery plot for each of the subgroups becomes more distinct as they disperse from each other relative to the control mean. If ACLD patients are not subdivided and instead are plotted as one group, then it appears that on average they all recover to the control mean.

For the non-copers, velocity recovered and plateaued at the lower limit of the normal range set by the control subjects. Step length returned to within 1SD of the control mean but then deteriorated and stabilised just within the "normal" control range. For cadence, all groups recovered to within 1SD of the control mean; copers were already within this range from the early days after injury. Overall there was a trend for the adapters to recover and plateau close to the control mean, the copers just above this, and the non-copers at the lower limit of the normal range set by the controls. For all gait variables, the copers had the quickest recovery and were within normal limits by 40 days after injury.

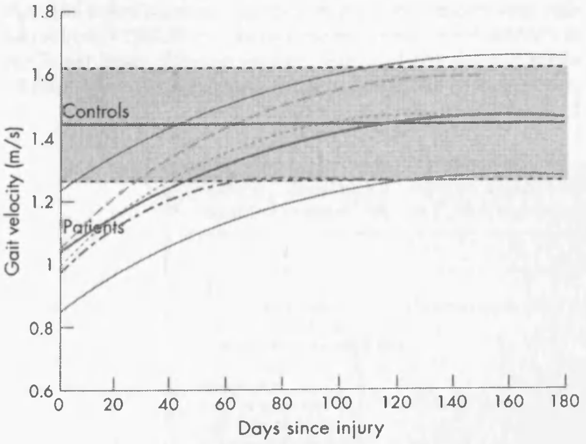

Figure 1 Recovery of gait velocity over time for the three functional subgroups and the mean recovery of all the anterior cruciate ligament deficient subjects. The ACLD group as a whole is indicated by the solid curved line with 1 standard deviation indicated by the thinner solid lines. ACL copers are indicated by the dashed line; adapters by the dotted line and non-copers by the dot dashed line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with grey band.

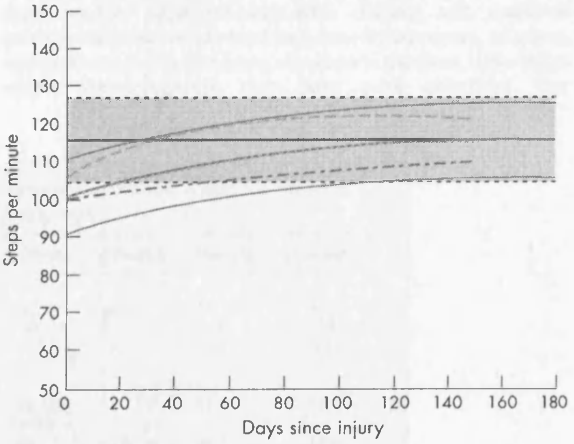

Figure 2 Recovery of gait cadence over time for the three functional subgroups and the mean recovery of all the anterior cruciate ligament deficient subjects. The ACLD group as a whole is indicated by the solid curved line with 1 standard deviation indicated by the thinner solid lines. ACL copers are indicated by the dashed line; adapters by the dotted line and non-copers by the dot dashed line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with grey band.

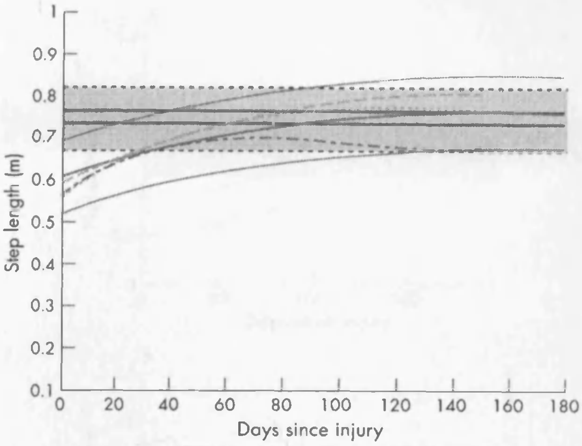

Figure 3 Recovery of gait step length over time for the three functional subgroups and the mean recovery of all the anterior cruciate ligament deficient subjects. The ACLD group as a whole is indicated by the solid curved line with 1 standard deviation indicated by the thinner solid lines. ACL copers are indicated by the dashed line; adapters by the dotted line and non-copers by the dot dashed line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with grey band.

Hopping distance

Pain, swelling, and instability stopped 10 of the ACLD subjects in the non-coper group from hopping. This means that the results are based on the performance of a small sample, introducing bias into the results. Figure 4 shows the mean recovery for hopping distance for each of the functional subgroups. Table 5 summarises the number of days after injury when the ACLD subgroups and the mean of all ACLD subjects reached "normal limits" set by the control subjects.

On average, the whole sample of ACLD patients recovered to the control mean. When they were separated into copers, adapters, and non-copers, it was found that, although non-copers initially hopped the shortest distance, by 150 days after the injury they hopped the furthest. This was greater than the mean hopping distance of the controls and was only just within +1SD of the control mean. Copers were already at the lower limit of being within ±1SD of the control mean 30 days after the injury, but did not reach the control mean.

DISCUSSION

Between 12 and 36 months after injury, ACLD patients were classified as functional copers, non-copers, or adapters on the basis of which of their preinjury activities they had successfully returned to without episodes of giving way. Most were adapters and non-copers, a finding that is well documented in the literature. We also found fewer copers than documented elsewhere; coping was almost non-existent in patients who had high sporting demands.[6 11 14 16–18 27] The recovery for each of our functional subgroups was plotted over time for a range of biomechanical variables during gait and distance hop, with the aim of identifying different patterns of functional recovery for each group. Distinct differences between the copers, adapters, and non-copers were found. Functional copers and adapters did recover to within normal limits, but the non-copers remained borderline. However, our results need to be interpreted with caution, as they have not been tested statistically and no attempt has been made to calculate the sensitivity or positive prediction rates of these variables. All the subgroups were matched for age, height, and weight, eliminating the influence that these characteristics had on the gait recovery plots.[28]

Initially after injury, all ACLD subjects, regardless of subgroup, compensated with a lower gait velocity and shorter step length. For most gait variables, the non-copers struggled to return within normal limits set by the controls. Conversely, all gait variables for the copers returned to well within normal limits by 40 days after injury. This meant that copers were distinguishable from the non-copers at this time on the basis of these simple gait variables. The functional adapters had a recovery similar to the copers, but it was not possible to identify a time after injury when these patients could be distinguished from the copers. In a health service with long surgical waiting lists, it would be beneficial to be able to prioritise cases with the greatest functional loss. If non-copers are identifiable by 40 days after injury, then this fits in well with current practice and guidelines about when ideally to perform an ACL reconstruction.[2 29]

Other studies that have compared similar gait variables between ACLD subgroups or between controls and ACLD subjects have found a full recovery of gait variables or have not shown gait compensation strategies.[8 10 22 30–32] Most of these studies used subjects with chronic ACL tears, or subjects were not subdivided into functional copers, adapters, and non-copers. By grouping all subjects together, differences within the subgroups may have gone unnoticed. Our

Table 4 Summary of number of days to recovery and maximum values for anterior cruciate ligament deficient (ACLD) subgroups during gait

	Copers	Adapters	Non-copers	Mean
Gait				
Days to be within ±1SD of control mean (1.43 m/s)	27	40	70	46
Days to reach control mean	60	93	N/A	118
Mean recovery value (m/s)	1.59	1.47	1.25	1.47
Cadence				
Days to be within ±1SD of control mean (116 steps/min)	Already within	17	52	19
Days to reach control mean	36	N/A	N/A	155
Mean recovery value (steps/min)	116	115	110	116
Step length				
Days to be within ±1SD of control mean (0.73 m)	28	32	39	36
Days to reach control mean	57	60	N/A	85
Mean recovery value (m)	0.81	0.77	0.69	0.77

N/A, did not reach control mean.

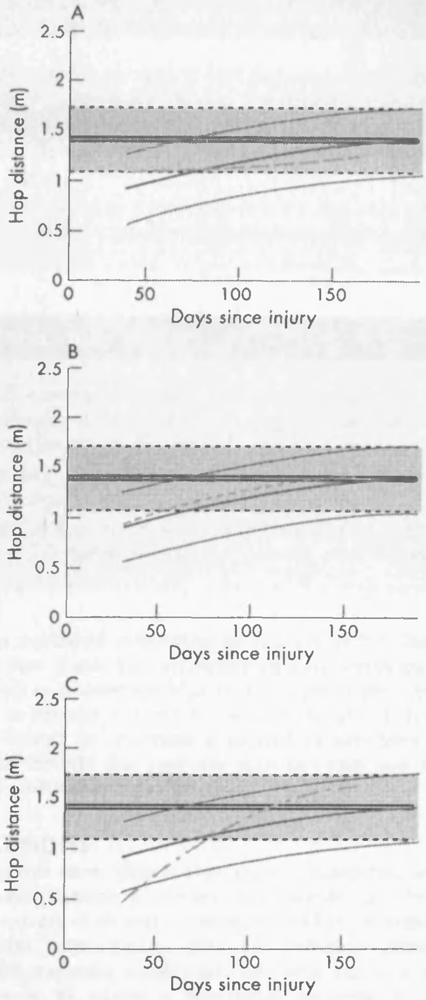

Figure 4 Recovery of hopping distance over time for the three functional subgroups (A, copers; B, adapters; C, non-copers) and the mean recovery of all the anterior cruciate ligament deficient subjects. The ACLD group as a whole is indicated by the solid curved line with 1 standard deviation indicated by the thinner solid lines. The ACL subgroup in each graph is indicated by the dashed line. The reference values derived from the control group (average ± 1 standard deviation) are indicated by the horizontal line with grey band.

non-copers experienced episodes of full giving way with work, activities of daily living, or low demand, non-pivoting sports. Therefore, unlike copers and adapters, they may show compensation strategies during gait to successfully perform activities of daily living. The only other study to monitor recovery of gait over time found that it took 2.8–4 weeks to achieve independent, non-antalgic gait.[11] The speed of this recovery is possibly the result of not separating patients into functional subgroups and using a less sensitive method of qualitative observation.

The second functional activity analysed in this study was hopping distance. This is regarded as a more challenging activity for an ACLD knee because of large shear forces and extensor moments and being representative of sporting manoeuvres.[9 34] Therefore compensation strategies may be expected in all subgroups of ACLD knees. No other studies have compared hopping distance between copers, adapters, and non-copers using an analysis comparable to ours. The mean hopping distance for copers and adapters in this study falls into the range (96–155 cm) found in generalised populations of ACLD subjects.[9 15 17 35 36] The distance hopped by non-copers in the present study is surprisingly high. In part, this may be explained by the fact that not all non-copers were able to hop for fear of the knee giving way, potentially introducing a bias. This problem was also encountered by Rudolph *et al*,[9] and, although it confirms that hopping is a more challenging task when assessing knee stability, it does mean that our results need to be interpreted with caution.

There are two possible explanations that may have contributed to the coper subgroup hopping a shorter distance. The first is that, before injury, most of the coper group did not participate in activities requiring a high degree of jumping and pivoting, so overall may never have had the ability to perform as well at the distance hop. The second explanation may be that a functionally stable knee involves knowledge of the limits of knee stability, achieved at the expense of distance hopped.[37]

Gait is generally not recognised as a functional activity to evaluate performance after acute ACL rupture, but the results of this study indicate that it has greater potential to assist clinical decision making than distance hopping up to five months after injury. All patients were able to walk so were able to participate in this study, and there was no selection bias unlike in the hopping sample. Other studies have highlighted limitations of analysing hopping distance. Patients with poor functional scores still achieve hop distance symmetry and distance within normal limits.[5 7 38 39] The advantage of using video for data collection over other cheaper and simpler methods is that joint angle data were also collected. This allows a more complete movement analysis and provides explanations for compensation strategies.

A further distinguishing feature between our ACLD subgroups was the level of sports participation before injury. The non-copers and adapters played sports requiring a high level of jumping and pivoting before injury, whereas the copers did not. This is supported by previous studies which have found that patients who spent more hours a week participating in jumping and cutting sports before injury have a poorer outcome.[6 19] From our results it would indicate that, in addition to the gait variables, activity level before injury is one factor that should help to distinguish between the functional subgroups.

The overall outcome of ACLD patients with conservative management was poor despite all receiving physiotherapy

Table 5 Recovery of hopping distance for anterior cruciate ligament deficient (ACLD) subjects

	Copers	Adapters	Non-copers	Mean
Days to be within ±1SD of control mean (1.3 m)	Already within	51	72	63
Days to reach control mean	Does not reach	128	105	168
Mean maximal distance at 5 months (m)	1.22	1.41	1.61	1.4

What is already known on this topic

- ACLD copers, adapters, and non-copers are known to perform differently during functional activities and have different outcomes
- Failure to subclassify patients may result in inappropriate care
- Current evaluation schemes are for use only with high level athletes and do not allow early decision making

What this study adds

- ACLD copers, adapters, and non-copers had distinct differences in their pattern of gait recovery by 40 days after injury
- Clinically, gait can be used to distinguish between the subgroups
- Distance hop was not found to be useful in subclassifying ACLD patients up to five months after injury

based on published rehabilitation guidelines.[20] [21] Our results indicate that, if gait has not recovered sufficiently by 40 days after injury or if there are high sporting demands, a patient is unlikely to become a coper. So, should the aim of rehabilitation be limited to returning a patient to activities of daily living and straight line sporting activities only and not high levels of pivoting and jumping?

CONCLUSIONS

Uniquely, we have shown that copers, adapters, and non-copers have patterns of recovery that are distinct from each other. Recovery of all gait variables to within "normal limits" by 40 days after injury may be valuable clinically to distinguish between subgroups. Hopping distance was not found to be as useful a functional outcome as gait for subclassifying ACLD patients up to five months after injury. We found a very low rate of functional coping in ACLD subjects with high sporting demands.

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Competing interests: none declared

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Original research

Recovery in functional non-copers following anterior cruciate ligament rupture as detected by gait kinematics

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Abstract

Objectives: To evaluate if gait compensation strategies for selected kinematic variables can be identified in anterior cruciate ligament (ACL) deficient non-copers using two-dimensional (2D) clinical gait analysis.
Design: Prospective observational design, repeated measures.
Setting: University hospital, out-patients department.
Patients: Sixty-three patients that attended the acute knee screening service were diagnosed with an acute ACL rupture and consented to participate. A sub-set of 15 copers/adapters and 13 non-copers were eligible for final analysis because they were contactable for sub-classification and had gait analysis at 1 and 4 months post-injury.
Main outcome measures: 2D video gait analysis for sagittal plane hip, knee and ankle kinematics and time–distance variables.
Results: At 4 months post-injury non-copers demonstrated significantly less recovery of knee angle ($F_{(1,1)} = 5.79$, $p<0.024$), hip displacement angle ($F_{(1,1)} = 4.89$, $p<0.036$), step length ($F_{(1,1)} = 6.80$, $p = 0.015$), cadence ($F_{(1,1)} = 5.85$, $p = 0.023$) and velocity ($F_{(1,1)} = 10.89$, $p = 0.003$), compared to copers/adapters. Also non-copers demonstrated altered correlations between gait parameters.
Conclusion: At 4 months post-injury non-copers had an inferior gait performance compared to copers/adapters for kinematics and time–distance variables. 2D clinical kinematic gait analysis, particularly of the hip and knee can inform early rehabilitation techniques and monitor recovery.

Keywords: Anterior crucuate ligament rupture; Gait; Video analysis; Rehabilitation; Kinematics

1. Introduction

Surgical management is often considered the treatment of choice following ACL rupture. Despite this, in the UK, a proportion of individuals who are recreational athletes will be managed conservatively and others will require rehabilitation whilst waiting on surgical lists. For these individuals the aim of rehabilitation is to help them achieve their maximal level of function (Francis, Thomas, & McGregor, 2001; Marx, Jones, Angel, Wickiewicz, & Warren, 2003).

To assist clinical decision making it is essential that anterior cruciate ligament deficient (ACLD) individuals are sub-classified into copers, adapters and non-copers because each sub-group performs differently (Alkjaer, Simonsen, Jorgensen, & Dyhre-Poulsen, 2003; Button, van Deursen, & Price, 2006; Eastlack, Axe, & Snyder-Mackler, 1999; Rudolph, Eastlack, Axe, & Snyder-Mackler, 1998; Rudolph, Axe, Buchanan, Scholz, & Snyder-Mackler, 2001). These have so far been differentiated by the pre-injury activities patients manage to return to without episodes of giving way. A coper has been defined as an individual who has returned to their pre-injury work and sport with no limitations in their performance. An adapter is someone who has reduced

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or changed their work or sport to prevent their knee fully giving way. Non-copers are individuals who fail to return to their pre-injury sport or work and experience full giving way with work, activities of daily living (ADL) and light non-pivoting sports (Alkjaer, Simonsen, Jorgensen, & Dyhre-Poulsen, 2003; Eastlack et al., 1999; Rudolph et al., 2001).

Non-copers pose a particular rehabilitation challenge, not only do they perform badly with an ACLD knee but they are also at risk of creating further damage in the knee due to repeated episodes of giving way (Maffulli, Binfield, & King, 2003; von Eisenhart-Rothe, Bringmann, Siebert, Reiser, Englmeier, Eckstein et al., 2004). It would be advantageous if information on functional performance was available to identify non-copers early and to inform rehabilitation to improve function in the short term, whilst awaiting surgery.

There is no consensus on what gait compensation strategies are used in ACLD sub-groups (Rudolph et al., 1998; Rudolph et al., 2001). The reasons for this are the use of different ACLD populations in studies such as chronic (Alkjaer et al., 2003) versus acute ACLD (Hurd et al., 2007) and different data collection and analysis methods for example normalizing to leg length (Rudolph et al., 2001) versus not normalizing and the use of different sub-classification systems (Kvist, 2004; Rudolph et al., 2001). Kinetic and EMG movement compensations have been frequently analysed but are difficult to measure clinically. Functional movement adaptations through the recovery period have hardly been studied using longitudinal studies in a clinical environment. This is essential information that is required to allow clinicians to monitor recovery and response to treatment and can be used to direct rehabilitation techniques. In our previous work, time–distance variables were modelled descriptively and non-copers were found to make a borderline recovery. The current study will build on this analysis by including kinematic variables, evaluating if the relationships between variables recover and testing sub-group gait adaptations statistically. Therefore the aim of this investigation was to evaluate gait compensation strategies for selected kinematic and time–distance gait variables in ACLD non-copers. This was done using a simple system for 2D gait analysis within the clinical setting and was part of a larger longitudinal study (Button, van Deursen, & Price, 2005; Button et al., 2006). For the current investigation it was proposed that the non-copers would continue to walk with kinematic compensation strategies at 4 months post-injury.

2. Methods

2.1. Subjects

Two hundred an eighty-one individuals attended the Acute Knee Screening Service (AKSS) between May 2001 and November 2003 with an acute ACL rupture. Sixty-three individuals consented to participate and were recruited onto the longitudinal study. Individuals had to fulfil an inclusion criteria of; an acute ACL rupture diagnosed by clinical assessment but confirmed by magnetic resonance imaging, be aged between 18 and 50 years, have no other relevant neurological or musculo-skeletal pathology, not require an urgent knee arthroscopy or have a combined ACL and posterior cruciate ligament rupture, live in the University Hospital of Wales (UHW) catchment for physiotherapy. A subset of 15 coper/adapters and 13 non-copers were eligible for the current study due to availability of gait analysis at 1 and 4 months post-injury and were contactable at 12 months post-rupture for sub-classification. Four months was selected as the follow-up time for data collection because it was anticipated that gait would be recovered (Button et al., 2005). All patients followed a rehabilitation programme that emphasized full range of motion, resolution of swelling, muscle strengthening principally of the hamstrings and quadriceps but also the hip extensors and calf muscles and neuromuscular control exercise for activities of daily living and sporting activities that were relevant to the patient. Treatment was staged according to symptoms and time post-injury (Fitzgerald, Axe, & Snyder-Mackler, 2000; Manal & Snyder-Mackler, 1996). This study was approved by the South Wales Local Research and Ethics Committee.

2.2. Follow-up

To be classified as an ACLD coper/adapter or non-coper subjects were followed up with a telephone questionnaire at 12 months post-injury. Participants were asked if they had experienced any full giving way of the knee and what work/sport activities they were currently able to participate in. This was compared to their pre-injury activity level and then individuals were sub-classified into copers, adapters and non-copers. Due to the small number of copers, we have combined the copers and adapters into one group for the analysis. From a rehabilitation standpoint within the National Health Service (NHS) this is justified because these patients are able to function well at ADL and low demand sports whilst waiting for surgery. It is the non-copers who are at high risk of creating further long-term damage to the knee due to the repeated episodes of giving way.

2.3. Clinical movement analysis

Data collection took place in the gym of the physiotherapy department once all subjects provided written informed consent. Two calibration sticks were placed midway along a 15 m walkway, parallel to each other and 1 m apart. A digital camcorder (SONY

Digital Handycam DCR-PC110E) was placed 6 m away from the walkway, on a 1 m high tripod, perpendicular to the direction of movement. Subjects were instructed to move at their comfortable speed along the length of the walkway. Two trials were completed, one in either direction. Each subject's height, weight, age and gender were documented and used to check that sub-groups were matched and that these factors were not responsible for any gait deviations. Leg length was not measured as previous research has found a strong correlation with height and concluded that they can be used interchangeably (van der Walt & Wyndham, 1973).

2.4. Data analysis and processing

Ankle, knee and hip kinematics were processed in the sagittal plane using a SONY VAIO FX105 laptop and SiliconCOACH software version 6, manufactured by SiliconCOACH ltd, which allows the digital recording to be analysed at 50 frames per second. Individual AVI files were saved for each gait trial. These were then analysed frame by frame until the frame corresponding to HS was identified for both the injured and non-injured legs. The trailing leg was also analysed at this point and corresponded to late stance. A computerized goniometry tool was aligned over specific landmarks to obtain the joint angles that are described in Table 1. The hip displacement angle (HDA) is the difference in hip angle between the leading and trailing leg at heel strike (HS) and is theorized to represent the functional hip range of motion at this time point. HDA, leg length and to a lesser degree knee joint angle all contribute to step length. HDA reflects the hip joint influence on step length without any contribution from the knee joint whose motion may be altered in patient with an acute knee injury. These relationships are visually represented in Fig. 1.

Temporal-spatial data were processed using a SONY VAIO FX105 laptop with DVGate and Mathworks-MATLAB software, version 6.5. Individual frames corresponding to events of interest were saved from the video and stored as JPEG files. These frames were three heel strikes of the subject walking in either direction. Temporal information of these events was obtained in frames from the display in DVGate (resolution: 25 frames per second). For stage two of the processing a programme was purpose-written in MATLAB. The two 1-m sticks were used to calibrate the area between them and create a grid so that the placement of the foot (location of heel contact with the floor at heel strike) relative to the calibration sticks could be measured. This spatial information was obtained automatically by the computer after the operator had indicated the heel location by means of a cross-hair displayed on the computer screen. Once this temporal and spatial information was processed, the following variables were analysed by the computer; gait velocity, cadence and step length which was defined as the distance between the heels of both legs at HS (Fig. 1).

Table 1
Method used to obtain joint angle measurements

Joint angles	Goniometer alignment
Ankle angle	Centrally along the length of the lower leg and along the base of the foot. The intersection point was at the base of the foot.
Knee angle	Centrally along the length of the injured femur and lower leg. Intersection point is at the centre of the knee joint.
Hip displacement angle	Centrally along the length of both femurs, angle measured at intersection point on pelvis.

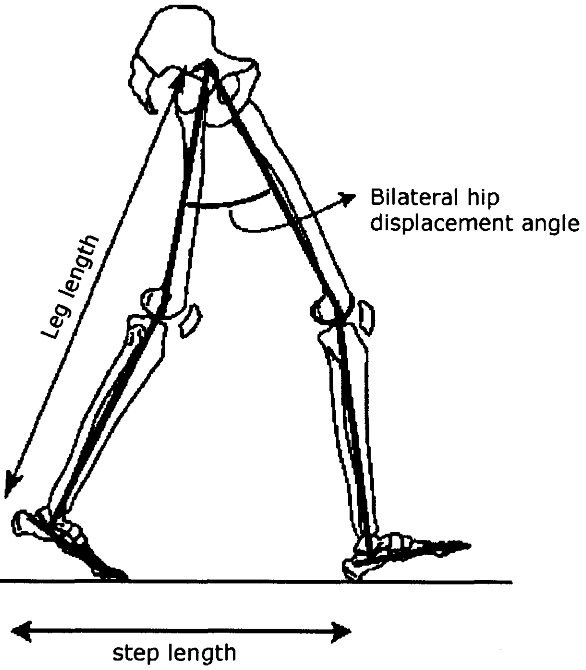

Fig. 1. Measurement of hip displacement angle and its relationship to step length and leg length.

A reliability study was performed for calculating joint angles and gait velocity using this movement analysis system. Measurement of gait velocity was found to be excellent, with an intertester reliability of ICC = 0.99 and reliability between assessors and an opto-electric timer of ICC = 0.98 (van Deursen, Button, & Lawthom, 2001). The between day intratester reliability of using SiliconCoach pro to measure joint angles is excellent or good; ICC = 0.87 for the HDA, ICC = 0.75 for the knee angle and ICC = 0.78 for the ankle angle. The accuracy of measuring kinematics using a single camera 2D analysis was not measured in the current investigation but has been evaluated by McLean, Walker, Ford, Myer, Hewett, and van den Bogert (2005). They found high correlation between a single camera 2D and a three-dimensional (3D) movement analysis system for intersubject difference for coronal plane knee kinematics ($r^2 = 0.58$–0.64). This equates to a correlation of $r = 0.76$–0.80.

2.5. Statistical analysis

A mixed design repeated measures ANOVA was used to compare two factors; time of measurement (1 and 4 months post-injury) and ACL sub-group (copers/adapters versus non-copers). We interpreted a significant interaction between these factors when we found an alpha level of lower than 0.05. Independent *t*-tests and χ^2 were used to compare the height, weight, age and gender between ACLD sub-groups and between this sub-set of ACLD individuals and the larger population of all ACLD subjects that attended the AKSS. This was to check that the sub-set analysed was representative of all the ACLD patients that were seen in the AKSS.

Pearsons' product moment correlations were used to evaluate the relationship between the time–distance variables and selected kinematic variables in the non-copers at 4 months post-injury. A correlation was interpreted as significant when the alpha level was lower than 0.05. To facilitate interpretation of these findings the correlations are compared to those of uninjured healthy subjects from the literature and our own data.

3. Results

The demographics and descriptive analysis of clinical data for the ACL copers/adapters and non-copers is summarized in Table 2. Groups were matched for age, height, weight and gender. Time–distance variables were not normalized to height because both ACLD sub-groups were matched for this variable (Hanlon & Anderson 2006). There was no difference between the ACLD subjects included in this study and all ACLD subjects seen in the AKSS over the recruitment period for age ($t = 0.01$, $p = 0.923$) and gender (χ^2 0.11, $p = 0.104$).

3.1. Gait compensations over time

There were statistically significant differences in the gait pattern between ACLD copers/adapters and non-copers over time. Gait variables that demonstrated less recovery in non-copers are summarized in Figs. 2–6. The gait of the non-copers at HS was distinguishable from that of the copers/adapters at 4 months post-injury due to a trend for reduced ankle dorsi-flexion ($F_{1,1} = 4.14$, $p > 0.05$), which is detailed in Table 3 and significantly more knee flexion of the involved limb ($F_{1,1} = 5.79$, $p < 0.02$) and smaller non-injured leg HDA ($F_{1,1} = 4.89$,

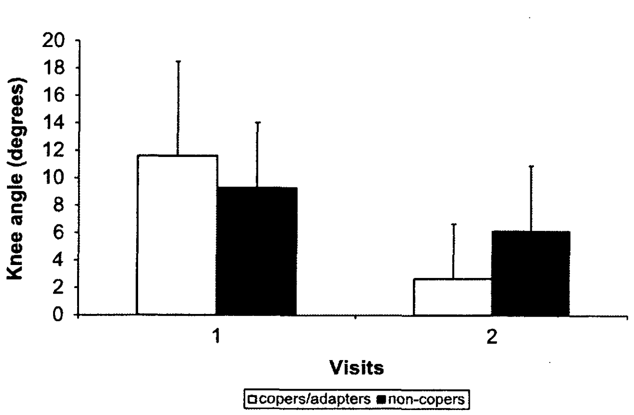

Fig. 2. Mean injured knee angles and standard deviations for ACLD sub-groups at initial contact for both visits The interaction was significant ($F_{(1,1)} = 5.79$, $p < 0.024$).

Table 2
Demographic and clinical data for the ACL sub-groups

Variable	Copers/adapters	Non-copers	*t* value (*p*-value)
Age (years), mean (S.D.)	30.6 (9.88)	27.54 (7.17)	0.925 (0.364)
Height (cm), mean (S.D.)	170.33 (11.11)	172.13 (9.76)	−0.320 (0.754)
Weight (kg), mean (S.D.)	73.5 (12.87)	70.75 (10.28)	0.446 (0.664)
BMI mean (S.D.)	25.14 (1.55)	23.87 (2.79)	1.004 (0.34)
			χ^2 value (p-value)
Gender	$F = 6$, $M = 9$	$F = 5$, $M = 8$	0.16 (0.934)
Injury type			
ACL±MCL	11	9	
ACL + meniscus±MCL	4	4	
Days from injury to full range of motion and no swelling	88	86	
Number of physiotherapy sessions	10.5	9.2	
Pre-injury activities			
Pivoting sports	11	11	
Non-pivoting sports	4	2	

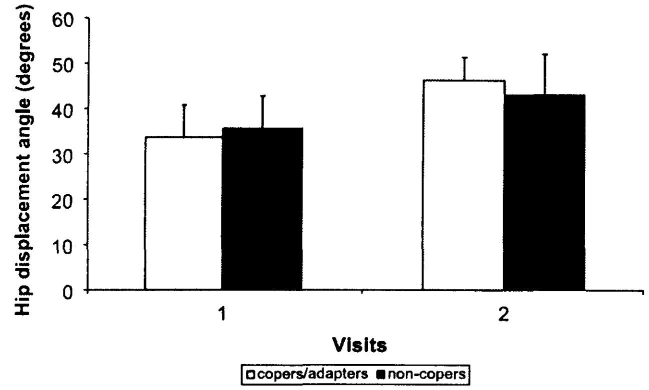

Fig. 3. Mean non-injured hip displacement angles and standard deviations for ACLD sub-groups at initial contact for both visits. The interaction was significant ($F_{(1,1)} = 4.89$, $p<0.036$).

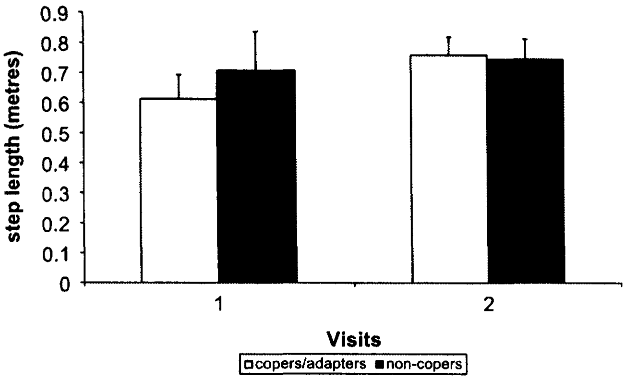

Fig. 6. Mean step length (non-injured leg) and standard deviations for ACLD sub-groups at both visits. The interaction was significant ($F_{(1,1)} = 6.80$, $p = 0.015$).

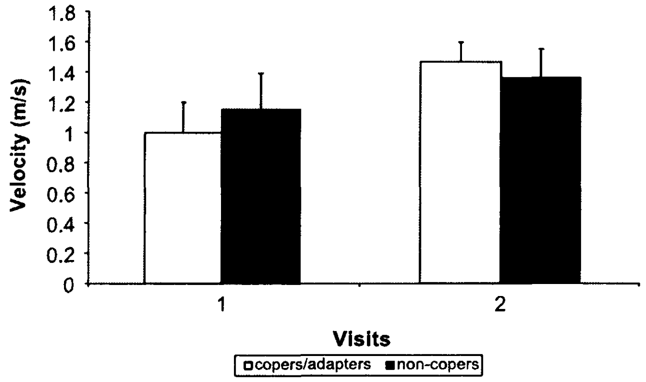

Fig. 4. Mean velocity and standard deviations for ACLD sub-groups at both visits. The interaction was significant ($F_{(1,1)} = 10.89$, $p = 0.003$).

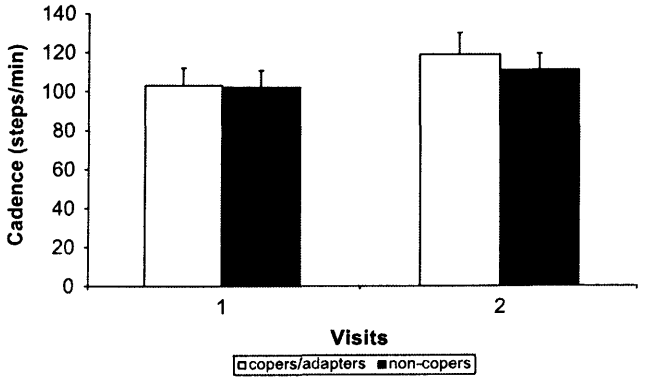

Fig. 5. Mean cadence and standard deviations for ACLD sub-groups at both visits. The interaction was significant ($F_{(1,1)} = 5.85$, $p = 0.023$).

$p<0.04$). Previously observed time–distance gait deviations for non-copers were confirmed statistically; slower velocity ($F_{1,1} = 10.89$, $p<0.003$), lower cadence ($F_{1,1} = 5.85$, $p = 0.02$) and shorter non-injured leg step length ($F_{1,1} = 6.80$, $p = 0.015$). Gait variables for which no statistical difference between sub-groups over time was found are summarized in Table 3.

The correlations between selected kinematic and time–distance variables for non-copers at 4 months post-injury are summarized in Table 4. To facilitate interpretation our own and published correlation data for healthy subjects has been used for comparison. In the literature high significant correlations have been found between gait velocity and knee flexion angle ($r = 0.78$, $r^2 = 0.60$) (Kirtley, Whittle, & Jefferson, et al., 1985; Lelas Merriman, Riley, & Kerrigan, 2003) and significant moderate correlations between hip range of motion and gait velocity ($r = 0.49$, $r^2 = 0.24, p<0.01$) (Lelas et al., 2003). For our own healthy subjects high correlations have been identified between velocity and cadence ($r = 0.83, p<0.01$) and velocity and step length ($r = 0.64$, $p<0.01$). In this non-coper group the time–distance variables and hip and gait velocity correlations resemble those of the uninjured subjects. In contrast to healthy individuals the non-copers have no significant correlation between knee flexion angle and gait velocity.

4. Discussion

Gait kinematic variables were measured prospectively at 1 and 4 months post-injury in ACLD sub-groups to evaluate for compensation strategies and to provide further insight into gait time–distance adaptations. This was carried out using an easy to apply clinical gait analysis system.

At 4 months post-injury an increase in involved limb knee flexion at HS was found in non-copers despite full passive range of motion (not reported here). Clinically this small increase in knee flexion is important because it is thought to reflect quadriceps weakness in ACLD individuals (Snyder-Mackler, Delitto, Bailey, & Stralka, 1995). Without using video analysis this adaptation is unlikely to be identifiable. In line with the increased

Table 3
Summary of ankle, knee and hip kinematics that were not statistically different between ACL coper/adapters (c/a) and non-copers (nc) at 4 months follow-up

Gait variable	Time 1c/a, mean (S.D.)	Time 1nc, mean (S.D.)	Time 2c/a, mean (S.D.)	Time 2nc, mean (S.D.)	*F* value significance
Ankle angle injured	12.87 (2.94)	13.85 (2.10)	10.97 (5.96)	12.46 (2.47)	4.138 0.052
Ankle angle non-injured	2.63 (4.27)	4.33 (4.27)	6.40 (3.92)	8.00 (4.14)	0.000 0.999
Knee angle non-injured	2.47 (2.74)	3.54 (2.50)	3.53 (3.75)	4.23 (3.91)	0.058 0.812
HDA injured	41.53 (5.48)	43.77 (5.83)	48.27 (4.90)	44.88 (13.58)	2.284 0.143
Step length injured	0.603 (0.08)	0.643 (0.106)	0.727 (0.06)	0.726 (0.078)	1.160 0.291

Table 4
The Pearson's correlations between time–distance variables and kinematics for non-copers at 4 months post-injury

	HAD (non)	Knee angle (inj)	Cadence	Step length (inj)	Step length (non)
Velocity	$r = 0.75^*$, $p<0.05$	$r = 0.19$, $p = 0.26$	$r = 0.73^*$, $p<0.05$	$r = 0.88^{**}$, $p<0.01$	$r = 0.83^{**}$, $p<0.01$

*Significant correlation.
**Highly significant correlation.

knee flexion there was a trend for reduced ankle dorsi-flexion of the involved leg at HS. This is an ankle response that has been demonstrated in more pronounced knee fixed flexion deformities (Cerny, Perry, & Walker, 1994) and it is proposed that this reduction in dorsi-flexion although not significant in this study may help to maintain limb length and therefore step length and velocity. Altered knee kinematics found in this investigation probably did not contribute to the reduction of selected time–distance variables because we did not find any correlation between these gait parameters. Underlying causes of the increased knee flexion could have been weak hip extensors and quadriceps of the injured leg (Arnold, Anderson, Pandy, & Delp, 2005; Snyder-Mackler et al., 1995). Additionally, apprehension of giving way could have resulted in increased knee flexion, which has been demonstrated in ACLD subjects (Ferber, Osternig, Woollacott, Wasielewski, & Lee, 2003). Clinical factors that could have caused altered kinematics and gait parameters (Cerny et al., 1994; Robon, Perell, Fang, & Guererro, 2000; Shrader, Draganich, Pottenger, & Piotrowski, 2004; Torry, Decker, Viola, o'Connor, & Steadman, 2000), were found to be similar between our groups, so the effects of swelling, ROM, amount of physiotherapy, activity levels and pathology are considered minimal, although differences have not been tested statistically. Increasing the knee flexion angle would potentially stabilize the knee by placing the hamstrings in a more favourable position to contribute to knee stability (Li, Rudy, Sakane, Kanamori, Ma, & Woo, 1999; Roberts, Rash, Honaker, Wachowiak, & Shaw, 1999), although there is debate about their ability to achieve this at such low flexion angles (Markolf, O'Neill, Jackson, & McAllister, 2004). This could be consistent with a proposed generalized hamstring/quadriceps co-activation pattern to stabilize the knee (Roberts et al., 1999; Rudolph et al., 2001).

The reduced non-injured HDA in the non-copers was found to be positively correlated to gait velocity, a similar relationship to that found in uninjured subjects (Lelas et al., 2003). Hip adaptations therefore had a greater impact on gait performance than knee flexion angle so addressing this in rehabilitation is potentially an important target to assist recovery. Weak hip extensors and quadriceps of the injured leg could lead to reduced hip extension and therefore a reduced HDA, step length and velocity (Arnold et al., 2005). Reduced non-injured limb HDA would contribute to knee stability by reducing the single leg support time and biomechanical load on the injured leg. This explains why no HDA adaptations were found in the uninjured limb as it was not required to contribute to stability of this limb.

To ensure appropriate management of ACLD individuals sub-classification seems essential. The five gait variables that did not recover could potentially be used in the clinical setting to identify non-copers, monitor outcome and be addressed in rehabilitation. Before concluding that an individual has recovered it might be essential to ensure that the entire set of gait variables are restored. A screening examination to identify potential copers has been developed by Fitzgerald et al. (2000). It is difficult to apply because it consists predominantly of hopping tests, which many ACLD patients could not undertake at such an early stage of recovery.

Rehabilitation focuses on resolution of acute symptoms, strengthening and improving neuromuscular control, particularly of the quadriceps and hip extensors. Neuromuscular control activities specifically within gait re-education are not always emphasized

(Chmielewski, Hurd, Rudolph, Axe, & Snyder-Mackler, 2005; Fitzgerald et al., 2000). The advantage of applying movement analysis to rehabilitation is that it permits identification of altered movement strategies, ensuring that rehabilitation is directed at the underlying causes for each individual. There is no evidence to suggest that you can prevent an individual becoming a non-coper but ideally treatment needs to start early to avoid inappropriate compensation strategies. Once an individual becomes a non-coper it may be difficult to change this situation, due to secondary damage through repeated giving way (Nelson, Billinghurst, Pidoux, Reiner, Langworthy, McDermott et al., 2006).

Very few studies have been conducted analysing gait compensation strategies in the acute phase post-ACL rupture or between ACL sub-groups over time. Studies analysing acute ACLD gait deviations give conflicting results for the kinematics and time–distance variables (Devita, Hortobagyi, Barrier, Torry, Glover, Speroni et al., 1997; Georgeoulis, Papadonikolakis, Papageorgiou, Mitsou, & Stergiou 2003; Knoll, Kiss, & Kocsis, 2004; Kvist, 2004), and there is no consensus on the gait response following acute injury. Investigations that have analysed differences in ACLD sub-groups have not found any differences in time–distance variables or hip kinematics (Alkjaer et al., 2003; Rudolph et al., 1998, 2001). In contrast to our study, others have found reduced knee flexion in non-copers at heel strike (Hurd & Snyder-Mackler, 2007; Rudolph et al., 1998, 2001). One of the major reasons why the results of our study conflict with the results of previous studies is the population of ACLD individuals analysed. Our inclusion criteria permitted inclusion of individuals with ACL ruptures combined with MCL and meniscal tears (not requiring urgent surgery). This has been done because ACL ruptures commonly present with these associated injuries and therefore represents the population that is referred for rehabilitation within the NHS in the UK. No standardized time from injury to timing of movement analysis has been used across studies. Our patients were analysed at a shorter follow-up time from injury (1 and 4 months) as opposed to one or more years post-injury in many other studies (Alkjaer et al., 2003; Rudolph et al., 1998, 2001). In these studies this delay has allowed additional time for further recovery and adaptation.

Limitations of this investigation include that we did not analyse copers/adapters separately due to the low level of coping that exists following ACL rupture resulting in small sample sizes. The gait of our ACLD subjects has not been compared to non-injured gait so the level of coper recovery is unknown. Other factors that have been found to reduce gait velocity such as pain and muscle strength (Hsu, Tang, & Jan, 2003; Robon et al., 2000; Shrader et al., 2004) have not been measured.

5. Conclusion

At 4 months post-injury non-copers walked with alterations in lower limb kinematics: increased knee flexion at heel strike, reduced non-injured leg hip displacement angle and reduced non-injured leg step length related to slower gait velocity, lower cadence. This reflects an overall poorer gait performance. An easy to use 2D clinical movement analysis system can provide kinematic explanations for altered gait performance that can direct and inform rehabilitation. Altered knee and in particular hip joint kinematics indicate the need for improving neuromuscular control of the hip extensors and quadriceps especially during gait re-education. Further clarification is required but clinical application of movement analysis methods could lead to a more complete or faster recovery, potentially improving pre-surgical outcomes.

Ethical approval

This study was approved by the South East Wales Local Research Ethics Committee before commencement of the project. The protocol reference no. is 03/4899.

Conflict of interest statement

There are no financial or personal conflicts of interest with any other person or organization that could inappropriately influence this work.

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