CHARLES UNIVERSITY IN PRAGUE

FACULTY OF PHYSICAL EDUCATION AND SPORT

DEPARTMENT OF PHYSIOTHERAPY

INSTRUMENTAL GAIT ANALYSIS IN THE ACL PATIENT

Diploma Thesis

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Prague, April 2011

UNIVERZITA KARLOVA V PRAZE
FAKULTA TĚLESNÉ VÝCHOVY A SPORTU

PŘÍSTROJOVÁ ANALÝZA CHŮZE U PACIENTŮ S LÉZÍ NEBO PO PLASTICE LCA

Diplomová práce

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Vypracovala: **Bc. Anna Lalaeva**

Praha, duben 2011

I declare that this is my personal work which I elaborated using the literature listed. Neither this work, nor any significant part, has been used to gain any other or similar academic title.

....

Anna Lalaeva, Prague, 2011

Prohlašuji, že jsem závěrečnou diplomovou práci zpracovala samostatně a že jsem uvedla všechny použité informační zdroje a literaturu. Tato práce ani její podstatná část nebyla předložena k získání jiného nebo stejného akademického titulu.

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Bc. Anna Lalaeva, Praha, 2011

Acknowledgements:

I would like to express my gratitude and appreciation for the initial insight into the topic and subsequent help with the elaboration of this thesis to my supervisor Agnieszka Kaczmarská . I would further like to thank all the employees of the gait labs both at my home faculty as well as at CASRI for the initial inspiration as well as practical insight into the topic of gait analysis. Last but not least I would like to thank my family and partner for their support.

Poděkování

Ráda bych poděkovala Mgr. Agnieszce Kaczmarské Ph.D., za uvedení do dané problematiky a za pomoc při vypracování mé diplomové práce. Dále všem zaměstnancům laboratoře chůze FTVS UK a CASRI za inspiraci a praktické poznatky o problematice analýzy chůze. V neposlední řadě děkuji své rodině a partnerovi.

Abstract

Title: Instrumental Gait Analysis in the ACL Patient

Aim: to present an up to date review on the topic of instrumental analysis of straight ahead gait on a plain surface (both over-ground and on a treadmill) in ACL patients (both deficient and reconstructed). A second aim is to introduce the clinician (especially in the field of physiotherapy/rehabilitation) to the topic of gait analysis and its specific use for the ACL patient.

Methods: a systematic review on the topic

Results The review answers the questions of what instrumentation, phases of gait and variables is best to use/measure for clinical purposes. It also identifies and discusses three main gait strategies used by ACL patients: quadriceps avoidance, knee stiffening, pivot shift avoidance.

Keywords: gait, analysis, walking, clinical, instrumental, anterior cruciate ligament, ACL, deficient, reconstruction, injury

Abstrakt

Název: Přístrojová analýza chůze u pacientů s lézí nebo po plastice LCA

Cíle: předložit aktuální rešerši na téma přístrojové analýzy chůze vpřed po rovném povrchu jak po zemi, tak i na běžícím pásu u pacientů s lézí nebo po plastice LCA. Druhým cílem je seznámit zdravotnické pracovníky, zejména v oblasti fyzioterapie / rehabilitace, s tématem analýzy chůze a jejího specifického použití u pacientů s lézí nebo po plastice LCA.

Metody: zpracování metodou rešerše

Výsledky: rešerše odpovídá na otázky, jaké přístroje, fáze chůze a proměnné, je nejlépe používat/měřit pro klinické účely. Také se identifikují a popisují tři hlavní strategie chůze: se sníženým zapojením m.quadriceps (quadriceps avoidance), se sníženým pohybem kolenního kloubu (knee stiffening), s omezením pohybů typu pivot-shift (pivot – shift avoidance).

Klíčová slova: chůze, analýza, klinická, instrumentální, přední zkřížený vaz, Ligamentum Cruciatum Anterius, LCA, léze, rekonstrukce, zranění

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List of Abbreviations

ACL	anterior cruciate ligament
ACLD	anterior cruciate ligament deficient
ACLR	anterior cruciate ligament reconstructed
BPTB	bone patellar tendon bone (graft)
C	copers
CLE	contralateral lower extremity
d.	days
E	extension
EMG	electromyography
F	flexion
FDHO	frequency of a modified force driven harmonic oscillator
HAM	hamstrings (graft)
m.	months
n	number (of articles)
NC	non-copers
NSD	not significantly different
vs.	versus
w.	weeks
y.	years

List of Figures and Tables

1 Introduction

The anterior cruciate ligament (ACL) is one of the passive stabilizers of the knee joint ensuring relative stability not only in the anterior direction but also resists hyperextension, internal rotation, external rotation, valgus and varus forces. Injuries to the ACL, however, are said to be the most common injuries to the knee especially in sports. Once the ligament is torn it is unable to heal. There are two treatment solutions to an ACL tear: the surgical and the conservative or non surgical. The success of the treatment largely depends on the rehabilitation that follows the injury/surgery. Prescription of such a program greatly depends on the needs of the individual patient.

The work of the ACL is mostly evident during some activity. Gait being the most common and necessary form of activity is an obvious choice for examination. Once the ACL is inefficient in its stabilizing, dynamic stabilizers mainly the muscles must ensure the stability of the knee. Why is it, however, that some patients feel completely stable during gait after an ACL tear while other often encounter instability? The strategy that so called “copers” use is not evident in observational gait analysis. Only a combination of electromyography (EMG), force plates and 3-D video recording may answer this question. Even so, is it possible to teach this strategy to “non-copers” that continued to have instability periods after their injury? If so, what are the best techniques to do so and why? These and further questions will be evaluated in this work.

Gait analysis is a fast evolving science. Technology and equipment considered novel and rare ten years ago, is now routinely used for research. Theories of muscle activation during gait after an ACL injury/surgery previously considered true by most in the field are now being disproven with new theories evolving. For an average clinician, such as an orthopedic surgeon or physiotherapist, it would prove quite hard to keep up with the rapidly changing technology and paradigm if they are not directly involved in this area. Putting aside the main question of what are the benefits of instrumental clinical gait analysis, many other questions arise pertaining to this topic. These questions may be for instance: what equipment to use, what variables to measure/calculate, what phase of gate should be measured and so on. This work will try to reveal the answers to these questions by summarizing what has already been done and what has proven most efficient.

Although many studies have been published about gait analysis on patients with ACL deficiency or reconstruction, there is to date only a few reviews (31; 46; 54) that deal with this specific issue (in the last 10 years). Hart et al. (31) only deal with one variable (knee flexion/extension moment) measured in gait analysis and include studies as far back as 1990. Lewek et al. (46) look into the issue of copers and non-copers as well as perturbation training with the most recent study included in the review being from 2002. Papadonikolakis et al. (54) addresses the question of ACLD patients with their most recent sited article being from the year 2001. More so, few previous reviews (on articles published before the year 2000) address the problem in such a way as to show the usefulness of this abundant data to the clinician.

1.1 Aim

The aim of this thesis is to search for, analyze and present up to date, evidence based information concerning the use of instrumental clinical gait analysis for patients after an ACL injury or reconstruction. This thorough analysis as well as synopsis will be preceded by a general overview of the topic of instrumental gait analysis in the clinic in relation to the ACL and the knee at large. This will include familiarization with modern techniques, technology and variables measured.

2 Theoretical Overview

2.1 Gait Analysis in General

2.1.1 Nomenclature of the Gait Cycle

One of the most confusing aspects of gait analysis is that there are several different subdivisions of the gait cycle itself and even when some names may coincide such as “midstance” they may mean a different part of gait. Below (figure 1) is a summary of the most popular authors of gait classification and their subdivision. One is advised to pay strict attention to the part of the cycle indicated with percentage and not with names when reading studies on this topic.

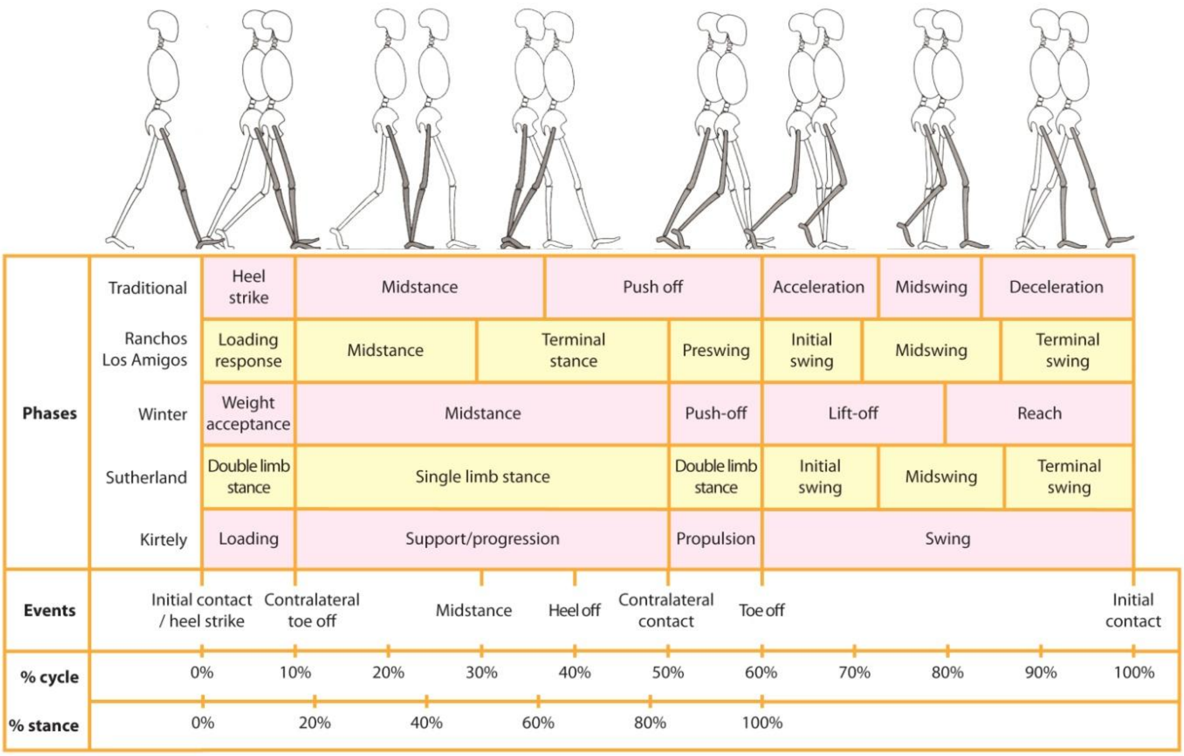

Figure 1 The gait cycle according to different authors compiled from several sources (38; 44; 56)

2.1.2 Gait Parameters

This section will familiarize readers that are not acquainted with gait analysis in their daily work (such as physiotherapists and general practitioners) with the basics in the area. Normative value can be found in appendix 2 through 6..

Termporal-spatial

Parameters including the time it takes to go through different phases of the gait cycle, speed of gait, cadence (the number of steps per minute) as well as stride length. There parameters do not require a full gait analysis system and may be monitored with the help of a stopwatch or other simple electronic devices. Since both speed and amplitude modification (for example adjusting one's step length to lines on the walkway) alter temporal parameters, it is important to measure them to ensure consistency in larger gait analysis examinations. Stance duration is said to decrease due to ipsilateral pain or instability and increase due to contralateral instability (38). This should be taken into account when measuring gait in ACL patients.

Kinematics

Gait kinematics refers to the measurement of angles, positions, velocities and accelerations of body segments and joints. The knee first (0% – 15% of cycle) undergoes flexion with a maximum of approximately 18°. This is followed by a period of extension (15% - 40 % of cycle) and a second period of flexion (40% - 70%) to a maximum of 65° (56). Peak knee flexion is one of the most common parameters used in the analysis of ACL patients. It has to be taken into account that maximal flexion is achieved in swing phase and that the peak knee flexion mentioned in literature usually assumes that of the first peak (up to 20% of the gait cycle). Total range or excursion is the maximal used range of motion in the joint, i.e. the extension plus the flexion. Although sagittal plane motion can be calculated from 2D measurements it is subject to parallax and perspective errors (38). On the other hand 3D kinematics has disadvantages of its own such as the many techniques to choose from, many of which require special staff and time, the accuracy of skin markers is only as good as their placement and alignment (20). The knee also undergoes a small amplitude of movement in the transverse and frontal plain (56) which is more difficult to record and calculate and is less frequently used.

Moments

Table 1 Interpretation of muscle activity from knee joint moments (38)

Moment		Muscle
internal	flexor	hamstrings
	extensor	quadriceps
external	flexor	quadriceps
	extensor	hamstrings

Joint moments are calculated using inverse dynamics which is usually included in the software used for gait analysis itself. Although moments reflect the force exerted on the joint, they are often used to infer muscle activity (table 1).

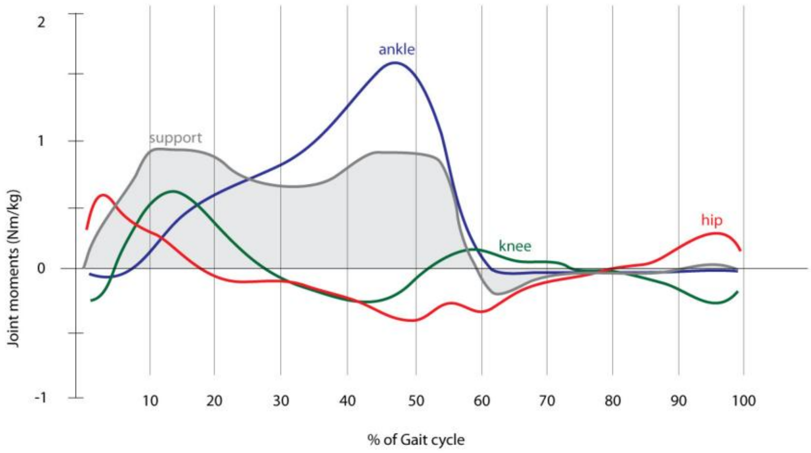

Figure 2 Support moment as the sum of individual joint moments modified from (69)

Total support moment is often reported in literature and is calculated by summing the individual moments of the hip, knee and ankle at any given time (figure2). More important than the total support moment is the contribution of the individual joint moments to the support moment. Thus the contribution of the knee joint would be equal to the knee moment divided be the support moment (expressed as a percentage).

Power

Joint power is the product of joint moment and joint angular velocity. Positive figures indicate power production (and concentric muscle activity) while negative ones power absorption (and eccentric muscle activity) by the joint (70; 79). Due to the great amount of calculation involved, this parameter is subject to great error (38). A decrease in power absorption especially in the knee and hip may indicate the possibility of developing osteoarthritis in the future.

Muscles

To get an accurate measure of muscle activity (figure 3) EMG is performed on key muscles. Data from EMG can be analysed in many different ways. The following parameters may be derived from EMG data: on/off (when the muscle starts and stops activity), peak muscle contraction (at what time in the cycle as well as how much), onset to peak interval (how long it takes the muscle to reach maximum activity after activation starts), the duration of activation (time that has elapsed from on to off). It is important to pay attention to the normalization of EMG data as some examiners may normalize it to maximum isometric contraction while others to activity in calm standing.

Another often calculated parameter in EMG is so called co-contraction which is usually measured in antagonist muscles. A combination of medial and/or later hamstring and quadriceps is most often investigated around the knee. The simultaneous activity of two muscles may be calculated using the method proposed by Rudolph et al. EMGS/EMGLx(EMGS+EMGL) where EMGS refers to the activity of the less active muscle and EMGL that of the more active muscle (61).

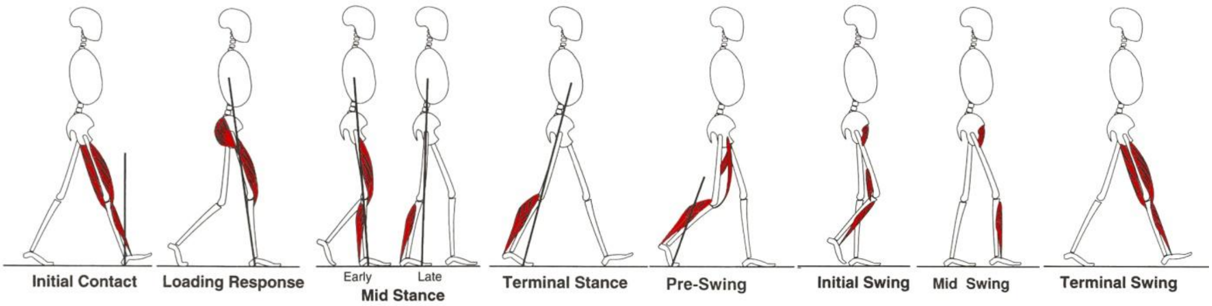

Figure 3 Activation of major muscle groups during the gait cycle. Modified from Perry et al (56).

2.1.3 Clinical Applications

Git analysis has long been applied in the clinical setting for some disorders. One publication stated the following as the most important: cerebral palsy, parkinsonism, muscular dystrophy osteoarthritis, rheumatoid arthritis, lower limb amputation, stroke, head injury, spinal cord injury, myelodysplasia, multiple sclerosis. It has been used to plan surgeries (cerebral palsy, multiple joint disease), manufacture special insoles, prescribe footware, plan and monitor physiotherapy (in various diseases including hemiplegia), prediction of future problems (such as foot ulceration in peripheral neuropathy), monitoring the manufacture and use of orthesis and prosthesis (79).

2.2 The Anterior Cruciate Ligament

The anterior cruciate ligament runs from the medial side of the lateral femoral condyle to the medial tibial eminence (48). It is said to be made up of two to three bundles: the anteromedial and the posterolateral as well as an intermediate bundle. These bundles are rather a functional subdivision than an anatomical one (65). The ACL is the primary restraint to anterior translation of the tibia against the femur and a major secondary restraint to internal rotation, especially when the joint is near full extension (48). In addition the ACL resists hyperextension of the knee, valgus and varus stress as well as external rotation of tibia (65).

It is generally widely accepted that hamstrings support the ACL with a posterior shear force on the tibia especially in almost full flexion, while the quadriceps, on the other hand increase the load on the ACL with an anterior shear force especially in almost full extension. Although the soleus and gluteus maximus do not cross over the knee they have a considerable impact on it. If the lower extremity is fixed on the ground (stance phase of gait) the soleus is able to assist in knee extension by pulling the tibia posteriorly thereby aiding the ACL in resisting anterior translation of the tibia (figure 4). The gluteus maximus, however, produces a posterior shear force on the femur resulting in an increased load on the ACL. Additionally the gastroclemius also increases the load on the ACL (65).

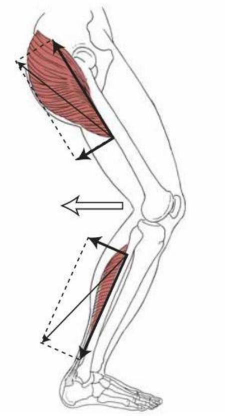

Figure 4 Action of gluteus maximus and soleus on the knee (44)

2.2.1 Examination

ACL injuries being some of the most common especially in certain sports require strict treatment and evaluation guidelines. While treatment and therapy have rapidly improved over the years, evaluation and examination methods have not progressed so rapidly. While gait analysis has long been used in the laboratory for studies concerning ACL injuries, clinically it used to be a farfetched idea. What options do clinicians actually have when examining patients after an ACL injury, be it before surgery, to evaluate rehabilitation or to allow a sportsman/woman to train again?

Clinical Examinations

Currently some of the most popular criteria used for hospital release, rehabilitation progress, or the start of training, is comparison of the maximum voluntary isometric quadriceps strength with the contralateral lower extremity. This is far from satisfactory, not only does this not show the functionality of the muscle (further discussed in the section on quadriceps strength), it also undermines the fact that the four heads of the muscle react differently to injury and are usually not equally strong and not equally important for knee stability (74). The fact that this test only measures one out of three types of contractions is also a limitation. Several studies (that are mentioned in the appropriate sections) have found that the contralateral lower extremity also changes many aspects of muscle activation. The question then arrises, whether an almost equal result in the test means that there is improvement in the injured extremity or that there is decreased activity in the contralateral extremity and only minor improvement in the injured one. Another popular test is the Lachman test (or any other test that measures the difference in anterior laxity) which is said to be quite sensitive at detecting the actual injury (48) but this cannot be used in order to evaluate the functionality and stability of the joint as it would not explain why some patients (copers) have little or no instability with an injured ACL. Range of motion may be useful to detect big changes in the initial phases of rehabilitation where there is a great decrease that is easily measureable. Gait does not require a great range of motion (about 60 to 70 degrees) on the part of the knee (44), but any limitation in this measurement will have an impact on gait. The problem arises, however, when there is no limitation in the range of motion in supine position but the patient does not seem to use the entire range during gait. Even subtle differences in the actual extent of the flexion and extension during daily activities would have a big impact on the patient.

Functional Examinations

According to the latest guidelines (48):

> *"Clinicians should utilize easily reproducible physical performance measures, such as single-limb hop tests, to assess activity limitation and participation restrictions associated with their patient's knee stability and movement coordination impairments, to assess the changes in the patient's level of function*

> *over the episode of care, and to classify and screen knee stability and movement coordination. (Recommendation based on weak evidence.)"*

Functional tests that have been studied in literature involve different kinds of single leg hops such as single-limb hop for distance, single-limb triple crossover hop for distance, single-limb triple hop for distance, and single-limb 6-m timed hop. Even though this may be a fairly good way to access the global function of the knee, the evidence to support this is rather weak (48). The information from these tests are only about how far or how fast the patient is able to perform the task and does not asses the way (stereotypes used) in which it is done. Some patients may hide pain or other discomfort due to a desire to achieve a better score.

Outcome Measure

According to the latest guidelines (48):

> *"Clinicians should use a validated patient-reported outcome measure, a general health questionnaire, and a validated activity scale for patients with knee stability and movement coordination impairments. These tools are useful for identifying a patient's baseline status relative to pain, function, and disability and for monitoring changes in the patient's status throughout the course of treatment (Recommendation based on strong evidence.)"*

There are quite a few questioners that evaluate the outcome of rehabilitation or surgery as well as the initial functionality of the patient. Below are mentioned some of the most popular outcome measures as reviewed in the guidelines. The Medical Outcomes Study 36-item Short Form (SF-36) is one of the most popular general health outcome measure which may be used to follow up on treatment. The Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS) is able to assess the functional limitations of the knee according to self report. The Knee Injury and Osteoarthritis Outcome Score (KOOS) is most effective in young active individuals. The International Knee Documentation Committee 2000 Subjective Knee Evaluation Form (IKDC 2000) is able to evaluate patient improvement. Other possibly useful forms are the Lysholm Knee Scale, the Cincinnati Knee Rating Scale, the Tegner Activity Level Scale, the Marx Activity Level Scale (48).

These questioners and scores are either based totally on subjective perceptions of the patient or on the objective findings by the clinician with the use of the previously mentioned examination techniques, or a combination of both. Subjective functionality and/or pain at certain activities, however, does not tell the clinician if certain muscles are used for certain activities or if the patient, even though problem-less at present, is at great risk of osteoarthritis in the near future. Moreover the outcome measures mentioned above are either not specific to the knee at all or specific only to the knee and don't take into consideration the specific problems an ACL patient may encounter.

2.2.2 Clinical gait analysis

The guidelines do not mention the use of gait analysis as an examination or evaluation tool. Have they forgotten about this helpful tool or is there another reason for the omittance? Although there is an overwhelming amount of research using gait analysis as a methodology to investigate different aspects of ACL injury or reconstructive surgery, few and far between are the studies that mention gait analysis as a useful clinical tool. It is true that several articles (22; 34; 35) mention the clinical application of their findings but this is rare and often inconclusive as each study is usually focused on measuring only one small aspect of gait. There are no reviews that mention what should be measured in the clinical setting to evaluate the progress of rehabilitation or the necessity of surgery.

One has to take into account the possibility that gait analysis remains an inefficient examination tool for many clinicians for ACL patients as there are no guidelines for its application and evaluation, it also requires special training, equipment and space.

The following criteria have been established for patient evaluation tools (58):

1. The measured parameter(s) must correlate well with the patient's functional capacity.
2. The measured parameter must not be directly observable and semi-quantifiable by the physician or therapist.
3. The measured parameters must clearly distinguish between normal and abnormal.
4. The measurement technique must not significantly alter the performance of the evaluated activity.

5. The measurement must be accurate and reproducible.
6. The results must be communicated in a form which is readily identifiable

Another important question that often arises with the mention gait analysis for ACL patients is if it is cost effective. As mentioned above, clinicians have very few options when it comes to objective evaluation of patient progress and the various criteria are far from satisfying. Taking into account the wide range of diseases that gait analysis can be applied to, the training and equipment needed will be able to benefit a wide range of patients. Many hospitals have already either established a gait lab as part of their own facilities or have an agreement to send their patients to an external lab. This is usually in connection to cerebral palsy or any of the other previously mentioned disorders. With the correct instructions of how to apply and interpreted data from gate analysis to benefit the ACL patient, this tool will become indispensible for clinicians.

3 Methodology

The diploma thesis was written in the form of a literature review.

3.1 Population

No strict criteria have been established for the populations investigated in the individual studies to be reviewed. For each article/study, however, the following points about the population researched were noted and judged for comparison purposes:

- Proportion of male and female subject
- Age – was there a narrow age range specified, was there a very wide range
- Activity level
    - Athlete – professional, non-professional (how many trainings per week)
    - ACL risk sports (football, skiing etc)
    - Average population or non-sport population
- Injury – for acute/ pre surgery/ conservative chronic treatment
    - was the mechanism of injury recorded
    - were subjects with damage to other soft tissue excluded from the study
    - was the ACL tear confirmed with objective clinical tests such as Lachman, anterior drawer, MRI etc.
- Stage of recovery
    - was there a wide range of time after injury/ surgery
    - Were there groups according to stage of recovery e.g. acute, chronic etc.
    - how was each stage defined: acute (less than 1 month, 2 weeks etc.), chronic (more than 2, 10 or 15 years), etc.
- Type of reconstruction
    - was the type of reconstruction (mainly BPTB and hamstring) distinguished/limited or were subjects with all types of reconstruction put into the same group
    - were the reconstructions performed by the same surgeon
- Subjects should not have any other orthopeadic, neurologic or internal problems. There should not be any serious previous injuries and there should be a healthy contralateral lower extremity

- Control – healthy subjects
    - were control subjects present in the study or was the contralateral extremity taken as the control
    - was the control group matched by parameters? If yes, by which ones?

3.2 Data Collection

Articles for analysis were gathered from available internet resources according to the following inclusion criteria:

- Search in following databases/search engines: EMBASE, Ovid, ProQuest, Medline, Wiley Interscience
- Search with a combination of the following words: acl, anterior cruciate ligament, gait, gait analysis, walking, dynamic stability, rehabilitation, physiotherapy, physical therapy, exercise
- Articles found in references of other articles with the above mentioned key words in their name.
- Published in the year 2000 or latter

Articles were then eliminated on the first level by reading through the abstracts or by a quick read through according to the following exclusion criteria

- Written in language other than English, Russian, Czech or Slovak
- Subjects with other injuries for e.g. distortion, soft tissue damage, posterior cruciate ligament, collateral ligaments, meniscus etc.
- Experiment was not done on live humans (on animals, in vitro, on cadavers, computer simulation etc.)
- Analysis performed on any other activity than straight ahead walking on a plain surface
- Poorly described gait analysis methodology,

The remaining articles were then read through thoroughly to exclude any overlooked articles and identify methodology, measurements, outcomes and limitations

4 Results

Table 2 Summary of the studies investigating gait analysis in ACL patients

Fist author year	Title	Interven-tion	Subj-ects	Time	Instruments	Variables	Plane	Gait phase	Limitations
Alkjaer 20003 (1)	Evaluation of the walking pattern in two types of patients with ACLD: copers and non-copers	none	ACLD (C, NC)	C 39 m., NC 55 m.	Video analysis, force plates, EMG	angles, moments, muscles, co-contraction	sagittal	stance	< 10 subjects, shoes
Andriacchi 2005 (2)	Interactions between kinematics and loading during walking for the normal and ACL deficient knee	none	ACLD	127 m.	Video analysis, force plates	angles, translation, moments,	sagittal, transverse	stance, swing	< 10 subjects, C and NC, acute and chronic
Bacchini 2009 (3)	Gait analysis in patients undergoing ACL reconstruction according to Kenneth Jones' technique	none	ACLR	6 m.	Video analysis, force plates	temporo-spatial, angles, moments, power, muscles,	sagittal, frontal	stance, swing	< 10 subjects, no control group (CLE used)
Beard 2001(4)	Reconstruction does not reduce tibial translation in the cruciate-deficient knee an in vivo study	reconstruction	ACLD/R	ACLD 47 m. ACLR 6.3m.	Video analysis, force plates	angles, translation	sagittal	stance, swing	heterogenity (giving way, 2 different surgeries), no control grouop
Boerboom 2001 (7)	Atypical hamstrings electromyographic activity as a compensatory mechanism in ACLD	none	ACLD (C, NC)	C 39 m., NC 22 m.	EMG, goiniometrers	angles, muscles	sagittal	stance, swing	heterogenity (menisectomy), < 10 subjects
Bush-Joseph 2001 (8)	Dynamic Function After ACL Reconstruction with Autologous Patellar Tendon	none	ACLR	22 m.	Video analysis, force plates	angles, moments	sagittal	stance	
Butler 2008 (9)	Gait mechanics after ACL reconstruction: implications for the early onset of knee osteoarthritis	none	ACLR	5.3 y.	Video analysis, force plates	angles, moments	frontal	stance	shoes, graft type not specified
Button 2005 (10)	Measurement of functional recovery in individuals with acute ACL rupture	none	ACLD	n/a	camcorder	termporo - spatial	sagittal	heal strike	C and NC

Button 2008 (11)	Recovery in functional non-copers following ACL rupture as detected by gait kinematics	none	ACLD (NC, C)	1 m., 4 m.	camcorder	termporo - spatial, angles	sagittal	heal strike	parallax error, no control group (CLE used), other injury
Chmielewski 2001 (13)	Biomechanical evidence supporting a differential response to acute ACL injury	none	ACLD (potential C)	3.4 w.	Video analysis, force plates	angles, moments, GRF	sagittal	stance	other injury (acute graft rupture), shoes, control from literature (CLE used)
Chmielewski 2002 (14)	Development of dynamic knee stability after acute ACL injury	Perturbation training	ACLD	22 d.	EMG	muscles	n/a	stance	< 10 subjects, no control group (CLE used), subjects also did agility and strength training, C and NC
Chmielewski 2005 (12)	Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral ACL rupture	Perturbation training	ACLD (potential C)	acute	Video analysis, force plates, EMG, footswitches , perturbation platform	angles, muscles, co-contractions	sagittal	100 ms pre heal strike, weight acceptance	unknown time post injury/time of comensation with training
Courtney 2005 (15)	Central somatosensory changes and altered muscle synergies in subjects with ACL deficiency	none	ACLD (adapters, C, NC)	C 69 m., NC 90 m., Adapters 59 m.	EMG, pressure switch	muscles, co-contractions	n/a	stance, swing	< 10 subjects,acute and chronic, shoes, treadmill, other injury
Coury 2006 (16)	Change in knee kinematics during gait after eccentric isokinetic training for quadriceps in subjects submitted to ACL reconstruction	eccentric isokinetic training	ACLR	9 m.	goniometer	angles	sagittal, frontal	stance, swing	< 10 subjects, treadmill, malalignment
Decker 2004 (19)	Gait retraining after ACL reconstruction	gait retraining (2 methods)	ACLR	6 w., 12 w.	Video analysis, force plates	temporo-spatial, angles, moments, power	sagittal	stance	< 10 subjects, shoes, treadmill, differneces in temporo-spatial could affect other variables
Favre 2006 (20)	A new ambulatory system for comparative evaluation of the three-dimensional knee kinematics, applied to ACL injuries	reconstruction BPTB	ACLD/R	ACLD 14 m., ACLR 1 y.	gyroscopes	angles	sagittal, transverse, frontal	stance, swing	< 10 subjects, shoes, treadmill, acute and chronic (ACLD), no control group (CLE used)
Ferber 2002 (21)	Gait mechanics in chronic ACL deficiency and subsequent repair	reconstruction BPTB	ACLD/R	ACLD 5.7 y., ACLR 3m.	Video analysis, force plates, EMG	angles, moments, power, muscles	sagittal	stance	C and NC

Ferber 2004 (23)	Bilateral accommodations to ACLD and surgery	reconstruction BPTB	ACLD/R	ACLD 5.7 y., ACLR 3m.	Video analysis, force plates	angles, moments, power	sagittal	stance	
Ferber 2003 (22)	Gait perturbation response in chronic ACLD and repair	reconstruction BPTB	ACLD/R	ACLD 5.7 y., ACLR 3m.	Video analysis, pertubation force plate	angles, moments, power	sagittal	stance	
Fuentes 2011 (25)	Gait adaptation in chronic ACL-deficient patients: Pivot-shift avoidance gait	none	ACLD	22 m.	Video analysis, force plates	angles, moments	sagittal, frontal	terminal stance	sandals, treadmill, C and NC
Gao 2010 (26)	Alterations in three-dimensional joint kinematics of ACL-deficient and -reconstructed knees during walking	none	ACLD, ACLR	ACLD 3 m. , ACLR 3-12 m.	Video analysis, force plates	temporo-spatial, angles	sagittal, transverse, frontal	stance, swing	acute and chronic (ACLR), C and NC, heterogenity (graft type), temporo-spatial differences may affect other variables
Georgoulis 2003 (28)	Three-dimensional tibiofemoral kinematics of the ACL-deficient and reconstructed knee during walking	reconstruction BPTB	ACLD, ACLR	ACLD 7.6 w., ACLR 30 w.	Video analysis	angles	sagittal, transverse, frontal	stance, swing	other injury
Georgoulis 2006 (27)	A novel approach to measure variability in the ACLD knee during walking: the use of the approximate entropy in orthopaedics	none	ACLD	19.9 m.	Video analysis	variability	sagittal	stance, swing	treadmill, shoes, no control group (CLE used), C and NC
Gokeler 2003 (30)	The relationship between isokinetic quadriceps strength and laxity on gait analysis parameters in ACLR knees	none	ACLR	26 w.	Video analysis, force plates	angles, moments	sagittal	stance	shoes, heterogenity (activity level), no control group, C and NC
Hartigan 2009 (32)	Perturbation training prior to ACL reconstruction improves gait asymmetries in non-copers	Perturbation training	ACLR/D (NC)	ACLD 9 w., 12 w., ACLR 6 m.	Video analysis, force plates	angles	sagittal	midstance	< 10 subjects, no control group (CLE used), heterogentiy (graft type)
Hooper 2002 (33)	Gait Analysis 6 and 12 Months After ACL Reconstruction Surgery	none	ACLR	6 m., 12m.	Video analysis, force plates	anlges, moments, powers	sagittal	stance	< 10 subjects, heterogenity (surgery type, physiotherapy length), no control group (CLE used), other injuries
Houck 2003 (34)	Associations of knee angles, moments and function among subjects that are healthy and ACLD during straight ahead and crossover cutting activities	none	ACLD	low functioning 63.5 m. high functioning 52.1 m.	Video analysis, force plates	anlges, moments	sagittal	stance	< 10 subjects, shoes

Houck 2007 (35)	Influence of Anticipation on Movement Patterns in Subjects With ACL Deficiency Classified as Noncopers	none	ACLD (NC)	8.7 6 m.	Video analysis, force plates	anlges, moments, powers	sagittal	stance	acute and chronic
Hurd 2007 (36)	Knee instability after acute ACL rupture affects movement patterns during the mid-stance phase of gait	none	ACLD (NC)	11 w.	Video analysis, force plates, EMG	angles, moments, muscles, co-contraction	sagittal	midstance, weight acceptance	no control group (CLE used)
Knoll 2004 (39)	Gait adaptation in ACL deficient patients before and after ACL reconstruction surgery	reconstruction	ACLD/R	ACLD 12 d. (acute), 28 m. (chronic); ACLR 6 w., 4 m., 8 m., 12 m.	Video analysis, EMG	temporo-spatial, angles, translation, muscles	sagittal	stance, swing	C and NC, treadmill, graft type not specified
Knoll 2004 (40)	Gait patterns before and after ACL reconstruction	reconstruction	ACLD	ACLD 12 d. (acute), 28 m. (chronic); ACLR 6 w., 4 m., 8 m., 12 m.	Video analysis, EMG	temporo-spatial, angles, translation, muscles	sagittal	stance, swing	< 10 subjects, C and NC, treadmill, graft type not specified
Kvist 2001 (42)	Anterior positioning of tibia during motion after ACL injury	none	ACLD	17-35 w.	computerized goniomete, force plate, EMG	angles, translation, muscles	sagittal	stance, swing	acute and chronic, C and NC
Kvist 2004 (41)	Sagittal plane translation during level walking in poor-functioning and well-functioning patients with ACL deficiency	none	ACLD	well functioning 15-46 m., poor functioning: 25-42 m.	arthrometer	angles, translation	sagittal	stance, swing	< 10 subjects, no control group (CLE used)
Kvist 2007 (43)	Changes in knee motion pattern after ACL injury - case report	injury	ACLD	5 w.	arthrometer	angles, translation	sagittal	stance, swing	case study, before injury lower extremit was not healthy (adaptation to ACL injury)
Lewek 2002 (45)	The effect of insufficient quadriceps strength on gait after ACL reconstruction	reconstruction	ACLD, ACLR	strong 14.3 w., weak 20.8 w.	Video analysis, force plates, EMG	angles, moments, muscles	sagittal	stance	< 10 subjects, shoes

Lindström 2009 (47)	Adaptations of gait and muscle activation in chronic ACL deficiency	none	ACLD (C)	35 m.	Video analysis, force plates, EMG	angles, muscles	sagittal	stance, swing	
Lu 2006 (49)	Influence of functional bracing on the kinetics of ACL-injured knees during level walking	bracing	ACLD, ACLR	ACLR 10.3m., ACLD ?	Video analysis, force plates	moments	sagittal, frontal	stance, swing	no control group (CLE used), time post injury not specified, C and NC
Moraiti 2010 (53)	ACL reconstruction results in alterations in gait variability	none	ACLR	HAM 25 m., BPTB 21 m.	Video analysis	variability	sagittal	stance, swing	< 10 subjects, treadmill, no control group
Moraiti 2007 (52)	ACL deficiency affects stride-to-stride variability as measured using nonlinear methodology	none	ACLD	33.5 m.	Video analysis	variability	sagittal	stance, swing	< 10 subjects, treadmill, no control group, C and NC
Patel 2003 (55)	Comparison of Clinical and Dynamic Knee Function in Patients with ACLD	none	ACLD	21 m.	Video analysis, force plates	moments	sagittal	stance	acute some chronic, C and NC, heterogenity (instability)
Risberg 2009 (59)	Rehabilitation after ACL injury influences joint loading during walking but not hopping	neuromuscular + strength training	ACLD	60 d.	Video analysis, force plates	angles, moments	sagittal	stance	shoes, C and NC, no control group
Rudolph 2001 (61)	Dynamic stability in the ACL deficient knee	none	ACLD (C, NC)	C ≥ 1 y., NC ≤ 8 m.	Video analysis, force plates, EMG	angles, moments, muscles, GRF	sagittal	stance	heterogenity (menisectomy)
Scanlan 2009 (62)	Graft Orientation Influences the Knee Flexion Moment During Walking in Patients With ACL Reconstruction	none	ACLR	24 m.	Video analysis, force plates	angles (graft), moments	sagittal, frontal	n/a	
Scanlan 2010 (63)	Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees	none	ACLR	24 m.	Video analysis, force plates	angles	sagittal, transverse, frontal	stance	no control group (CLE used), heterogenity (surrgical techniques, grafts types)
Shin 2007 (64)	The patella ligament insertion angle influences quadriceps usage during walking of ACL deficient patients	none	ACLD	2-432 m.	Video analysis, force plates	angle (ligament), moments	sagittal	stance	no control group (CLE used), acute and chronic, C nad NC, < 10 subjects
Stergiou 2004 (67)	The effect of the walking speed on the stability of the ACLD knee	none	ACLD	33.5 m.	Video analysis	variability	sagittal	stance, swing	treadmill, C and NC, no control group (CLE used)

Teixeira da Fonseca 2004 (68)	Analyses of dynamic co-contraction level in individuals with ACL injury	none	ACLD	11.4 m.	EMG	co-contraction	n/a	n/a	acute and chronic
Torry 2004 (71)	Mechanisms of Compensating for ACLD during Gait	none	ACLD	8.9 y.	Video analysis, force plates, EMG	angles, moments, muscles	sagittal	stance	treadmill, shoes, < 10 subjects
von Porat 2006 (76)	Knee kinematics and kinetics during gait, step and hop in males with a 16 years old ACL injury compared with matched controls	none	ACLD	16 y.	Video analysis, force plates	angles, moments, powers	sagittal	stance, swing	C and NC, graft type not specified
von Porat 2007 (75)	Knee kinematics and kinetics in former soccer players with a 16-year-old ACL injury – the effects of twelve weeks of knee-specific training.	neuromuscular training	ACLD, ACLR	16 y.	Video analysis, force plates	angles, moments,	sagittal	stance, swing	heterogenity (injury/reconstruction, activity leve), C and NC, no control group
Webster 2005 (78)	Gait patterns after ACL reconstruction are related to graft type	none	ACLR	BPTB 11 m., HAM 9.3 m.	Video analysis, force plates	angles, moments	sagittal	stance, swing	
Webster 2011 (77)	Alterations in joint kinematics during walking following hamstring and patellar tendon ACL reconstruction surgery	none	ACLR	HAM 9 m., BPTB 10.9 m.	Video analysis	angles	transverse, frontal	stance	
Zhang 2003 (81)	Six degrees-of-freedom kinematics of ACL deficient knees during locomotion-compensatory mechanism	none	ACLD	5.1 y.	goniometer, footswitches	angles, translation	sagittal, transverse, frontal	stance, swing	shoes, C and NC

Subjects: ACLD – ACL deficient subjects, ACLR – ACL reconstructed subjects, ACLD/R – ACL deficient patients that underwent reconstruction and were later measured as ACLR subjects, C – copers, NC – non-copers
Time: mean time after injury or surgery (unless otherwise specified), d. – days, w. – weeks, m. – months, y. – years, BPTB – bone patellar tendon bone graft, HAM – hamstrings graft,
Limitations: only several main limitations were recorded in the table for comparative purposes: shoes/treadmill – the use of this equipment, CLE – contralateral lower extremity, acute and chronic – the inclusion of both acute and chronic patients into one group, C and NC – no distinction was made between copers and non-copers, < 10 subjects – less than ten subjects were present in one or more groups, heterogeneity () – subjects with difference in the variable in brackets were included in the same group

A total of 176 articles were found through different search engines and references. Out of these articles 17 were reviews on similar topics, 90 were rejected on either the 1st or 2nd level (see methodology section). This resulted in a total of 53 articles (table 2) that were analyzed for the review. The articles were subsequently subdivided into topics which were mentioned in the studies. The data found in the studies together with a critical review is presented below.

4.1 Quality of the Studies

Most studies were of observational type with the main aim to investigate if one or several parameters changed in ACL patients. No double blind studies were found. Although most (n=33) studies involved a control group, others compared (n=20) the injured extremities against the contralateral non-injured extremity (CLE). This CLE has been shown to have itself undergone changes (7; 11; 20; 23; 42; 68) and so cannot be considered as a valid comparison. Another fault many studies had is the number of subjects included in the study or the respective groups. Only two studies (10; 55) had more than 40 subjects in each group, with more than third of the studies (n=19) having at least one group that consisted of less than 10 subjects.

4.2 Equipment Used

4.2.1 Camera and Marker Systems

Most researchers used either Vicon (n=14) or Peak Performance (n=8) (as well as Motion Analysis, Elite and Qualysis) for their 3D camera systems with passive markers although Knoll et al used Zebris (an ultrasound based system) with pretty good results (39; 40).

Marker placement protocols were rather varied with several authors referring to the Davis (18), Kadaba (37) and Vaughan (73) protocols which were published in the 1990s when the technology was far less advanced than it is now. These protocols use markers mounted on a wand which is susceptible to vibrations during gait, although some argue that error can be eliminating by low pass filtering the data (38). Yet others (22; 30; 47; 55) used a simple method with only a few markers attached to key points. This method could easily be transferred to clinical application of gait analysis. The main landmarks used in these studies include the lateral side of the greater trochanter, lateral femoral epicondyle, lateral malleolus, and head of the fifth metatars. Both the anterior and posterior superior iliac spines may be used as well.

Although skin artefact may be responsible for significant error especially in subtle movements like the rotations of the knee, one set of authors solved this problem by using infra red sensors which were claimed by them to be more sensitive (34).

Self selected speed was usually chosen as opposed to a predefined speed so as to keep the gait as close to the natural stereotype as possible. This speed was then monitored to be constant (5% variance allowed) using a metronome or photo sensors. Although it is widely believed that speed affects especially knee kinematics (38), Stergius et a. showed that the speed of gait does not change the variance (knee flexion – extension) in chronic ACLD subject (67).

4.2.2 Force Plates

Most widely used force plates used were Bertec (n=12) and Kistler (n=8) as well as AMTI (n=4). The walkway usually had 2 built in force plates. The data from the force plates was rarely reported as pure ground reaction forces but instead was used together with other systems to calculate various parameters of gait.

4.2.3 EMG

Electromyography (EMG) was used as a means to confirm muscle activity together with the kinematic and kinetic data obtained. Usually it was used in combination with video and force plate analysis (1; 3; 12; 21; 36; 39; 40; 45; 47; 61; 71). Two studies, however, used EMG on its own (14; 68) and another three study in combination with other non-video equipment (7; 15; 42). The data received was analyzed in the most varied ways. Parameters used for comparison include: on and off time, duration length, peak amplitude (as well as time from onset to peak), integral of activity/amplitude in a specific phase/point in the cycle. The main problem with EMG data is that it requires many more subjects (hundreds) in order for the rather subtle differences to be significant. Thus, in my opinion, none of the articles included in this review can prove that no difference, as it pertains to EMG, occurred. Due to this, EMG results will be discussed only when they show a significant difference and will not be used as proof of no difference in activity.

Another issue with EMG is to what the measurements should be normalized to. Several authors normalised EMG to the peak activity of the muscle during the cycle itself (21;

39; 40; 61) as opposed to the widely recognized method of maximal voluntary isometric contraction (1; 12; 14; 36; 42; 45; 68) which can give false results due to pain or fear of damage. Benoit et al. compared three different methods of normalisation for ACLD patients on a treadmill: using the mean value during the gait cycles, the maximum value during the gait cycles and a maximum voluntary isometric contraction (5). Out of the three methods, normalisation using the mean value seemed to be the least effective.

4.2.4 Other Instruments

Other instruments used include treadmills, goniometers, footswitches, perturbation platforms and special shoes.

Although some studies show that treadmills can be used to generate gate that is similar to overground gait (50), others find certain differences in the two gaits (38). Thus treadmills should be used only in situations where they are absolutely necessary, for example, when measuring variability where long periods of uninterrupted, constant gait is needed (27; 52; 53; 67).

The use of digital goniometers mounted on the lower extremity may change the way the person walks. This is, however, a good solution if a video analysis is not affordable. Six studies in the present review used goniometers (or arthrometers) to asses joint angles (7; 16; 41-43; 81).

Another method of easily measuring angles is the use of 3D gyroscopes that are attached on straps to the thigh and ankle (similarly to the cluster method of marker attachments. One study investigating the use of gyroscopes in ACL patient revealed physiological values obtained using the device for measurements in the sagittal and transversal plane, but not in frontal plane (20).

The simplest method of measuring kinematics in 2D is mentioned in the study by Button et al., which involved the use of a camcorder, special software and a computerized goniometer (10; 11).

While some authors used shoes that the subjects brought themselves (1; 13; 20; 30; 45; 59; 71), others used standardized shoes (9; 19; 25). Older shoes which were worn by the subjects, for instance, before the injury would have adapted to the previous gait pattern and would give wrong information about the current pressure distribution. Standardized shoes are better for comparison between the subjects, but may not fit each subject similarly. The mounting of markers on shoes is an issue in itself. Is it possible to say for sure that a marker that is supposed to represent the fifth metatarsus is appropriately placed especially considering the variable heights of shoes above skin level. Does this position affect the calculations and final results? Kinsley et al. discusses the possible changes in gait in shoes and barefoot (38). On the one hand, it is true that gait without shoes may not represent our true gait as we do not usually walk without shoes; on the other hand, gait analysis in shoes makes it difficult to compare the outcome between the subjects and entire studies.

4.3 Variables Studied

4.3.1 Angles

Although most researchers opted to measure angles around the knee others also measured the angles around the hip and ankle. Some found worthy differences (21; 22) while others did not confirm any changes (1; 47; 61). In the knee itself several researchers measured movement only in the sagittal plane (11) while others used 3D measurements to calculate sagittal plane angles (52), and yet others calculated also rotations (2; 20; 26; 28; 63; 77; 81). Although several studies (9; 16; 20; 26; 28; 49; 63; 77; 81) investigated angles in the frontal plane, only five (16; 26; 49; 77; 81) had significant findings. The main reason to use 3D data for calculating sagittal plane motion would be to avoid perspective error (38). Probably the most widely cited parameters for the knee are peak knee flexion angle as well as the total range (excursion) of the knee during the cycle.

4.3.2 Moments

Most authors indicated only the type of software used for calculating the moments instead of the actual principle used behind it. Most researchers used inverse dynamics, and although it is widely criticized, it has also been shown to be a valid method (38). Actually most dispute in gait analysis is concerning moments around a joint because they are so sensitive to marker placement and type of model used for calculation. There is also an inconsistency in the use of external versus internal moments which can be quite confusing at first sight when read research. On the other hand, certain changes in moments have been found to be the measurement that can differentiate a coper from a non-coper as is discussed in the appropriate section of this work. Peak external (internal) knee flexion (extension) moment is often used to confirm or deny quadriceps avoidance gait in the absence of EMG measurements, which of course is only an assumption. Support moment which is calculate according to Winter (80) has shown to be significantly different in ACL patients. Especially import is to compare the distribution of the hip, knee and angle moments that comprise the support moment. At least one author also calculated moments in the transverse plane (25).

4.3.3 Power

Power, weather generated or absorbed, was rarely reported. When reported the changes in the knee and hip were very small (19; 21-23; 33; 76).

4.3.4 Muscles

The muscles that are most often measured are vastus lateralis, vastus medialis, semitendinosis and semimembranosis, biceps femoris, gastroclemius (medial/lateral head). Tiabialis anterior and soleus were also measured in several studies and showed notable differences (3; 14; 36; 47; 61). One thing that concerns me, however, is that sever authors tend to generalise the results found for a part of a muscle over an entire (large) muscle group. For instance a decrease in vastus medialis activity by no means suggests a decrease in the activity of the whole quadriceps femoris muscle. This often leads, in my eyes, to incorrect conclusions being made.

In addition to measuring just the muscle activity itself, it has been shown that co-contractions of antagonists can show interesting results. Quadriceps and Hamstrings co-contractions are used to define a “knee stiffening” gait strategy discussed in the appropriate section of this work.

4.3.5 Variability

A total of three studies analyzed variability using the Lyapunov exponent (52; 53; 67). All three articles were written, for the most part, by the same authors and used the same principles for calculation. One study analyzed variability using approximate entropy (27). The full application of this technique in the clinical setting for decision making is not understood to date.

4.3.6 Other Variables

Some authors (2; 4; 30) create their own calculations of tibial movement, or other variables, that cannot be compared and are discussed individually.

4.4 Phases of gate

It is widely believed that the stance phase is sufficient to analyze gait pertaining to the knee. Furthermore several authors argue that weight acceptance or heal strike coupled with midstance is sufficient for the analysis (36; 71). Midstance, however, can mean rather different parts of gait. For instance the subdivision according to the Ranchos los Amigos hospital indicates it to be between 10% and 30% of the cycle while Winter's subdivision states that it is between 10% and 50% of the cycle (38; 56). Of course authors usually specify exactly from which moment to which moment in the cycle they consider to be midstance, but this may not be evident to the common reader especially if only the abstract or conclusion is read.

There are studies that measure and analyze the swing phase. Kvist and Gillquist., for instance, showed a decreased maximal knee flexion in the swing phase of gait (42). Andriacchi and Dyrby (2) thought that the transition between swing and stance phase as well as stance and swing phases is the most important part of the cycle as it is the transition between weight bearing and non-weight bearing. Georgoulis et al. and Gao and Zheng also found significant differences in early swing phase (26; 28). Zhang et al. found significant differences even at the end of swing phase (81). If possible it is probably best to analyze the whole cycle for ACL patients but if this is not possible then the most important aspect would probably be loading – the first 10% of the cycle (initial contact, heal strike, weight acceptance). Impairments during this phase usually occur due to quadriceps weakness or pain, both of which can be associated with the ACL patient whether injured or after a reconstruction (38).

4.5 Interventions

4.5.1 Physiotherapy

The most often studied technique in physiotherapy is perturbation training as it is believed to treat the underlying cause of changes in gait Since the ACL contains vital mechanoreceptors for the knee joint it does not come as a surprise that proprioception is changed in injured subjects, changing the perception of the body and muscle activity not only around the knee joint (15; 66).

Chmielewski et al. showed that after perturbation training the integral of quadriceps femoris increased and was related to soleus and biceps femoris activity as opposed to no relationship pre-training in acute ACLD patients (14). The authors suggested that this is due to improved dynamic knee stability although parameters that measured this were absent. It is, however, difficult to draw any conclusion from this study with only 9 subjects, an absence of a control group, and with the subjects performing not only perturbation training but also agility and strength training.

Hartigan et al. showed that perturbation training in the acute stage before reconstructive surgery helps to increase and equalize total knee excursion (compared to the CLE) as opposed to strength training only, 6 months after surgery (32). As previously mentioned, the CLE cannot be used to evaluate the state of the reconstructed lower extremity. The patients were reconstructed with 2 different grafts (semitendonosis-gracilis autograft, soft tissue allograft) and it is unclear how many patients had which graft and to which groups they were allocated. Furthermore there is evidence that graft type may affect gait parameters (78).

Risberg et al., deny any changes in knee excursion in acute ACLD patients after neuromuscular and strength training (as compared to the CLE). The study, however, shows an improvement in and equalization (in comparison to the CLE) of the lower knee internal extension moment at peak knee flexion (during stance) (59).

Von Porat et al., however, found that neuromuscular training had no effect on chronic ACLD patients 16 years after injury (75). The 12 male subjects that were included in the study had different activity levels, different types of grafts, some were deficient while others reconstructed, some had radiographic osteoarthritis and others did not. Such heterogeneity could have caused the resulting lack of significant results.

Chmielewski et al. further stated that perturbation training improves subject's response to perturbations. The acute potential copers in the study decreased mainly the vastus lateralis – biceps femoris co-contraction (as compared to pre-training values) (12). It is not evident how perturbations on a special platform can be related to real over ground perturbations encountered in daily life.

Coury et al. (16) reported on the effect of eccentric isokinetic training for quadriceps 9 months after a BPTB reconstruction. The study, which included only 5 male subjects, revealed a significant increase in valgus angle (peak, range of motion, velocity) after training in comparison to pre training values. Since post training values were much higher than that of the control (while pre-training values lower), one has to wonder on how useful this type of training really is for the patient. As this study had several limitations, few conclusions can be drawn from it.

Methods of retraining gait itself have been reported only by one study. Decker et al. examined the effect of two different retraining techniques in ACLR (BPTB) subjects from 6 to 12 weeks after surgery (19). The technique that proved to be superior in improving ROM, extension at initial contact, knee extensor moment, knee power generation and absorption was training with the so called FDHO model. This method involved walking with the help of a metronome at an assumed pre-injury stride frequency (calculated by the resonant frequency of a modified force driven harmonic oscillator (FDHO) model). This is a simple formula that requires the input of body weight and lower extremity length. Six weeks after gait training (12 weeks after surgery) the FDHO group had increased range of motion of the knee at midstance as well as increased extension in a direct comparison to a group that trained gait at preferred stride frequency. Authors concluded that the training facilitated quadriceps recovery.

It is difficult to make any conclusions from the above mentioned studies. Training before surgery may later help to improve the range of motion during gait after surgery (32). In ACLD subject training can improve the internal extension moment (59) as well as the function of the quadriceps femoris muscle which is associate with this moment (14). Pertrubation and/neuromuscular training seems post effective in the acute stages of rehabilitation.

4.5.2 Reconstructive Surgery

One of the most debatable issues in the treatment of ACL injured patients is reconstruction surgery. Questions starting from which patients should get the surgical treatment as opposed to conservative, how soon after the injury should the surgery be done, what kind of graft should be used, what kind of surgical technique should be implemented, how much time is needed to recover after the surgery, and so on and so forth. Sever studies (n=9) tried to evaluate the effects of reconstructive repair on gait.

Ferber et al. had one of the most comprehensive studies on the effect reconstruction has on knee kinematics and kinetics (21). The study showed that 3 months after BPTB surgery there was decreased knee internal flexor moment in late stance (as compared to pre-surgical values which were similar to controls), increased hip internal flexor moment (as compared to pre-surgical values which showed a higher extensor moment compared to controls), decreased power absorption in the knee from 80% of stance phase to toe off (as compared to pre-surgical values which were closer to the control values), and an increased power generation from the hip at toe off (compared to pre-surgical values that were lower than that of the controls). No differences were found in joint angles or biceps femoris and vastus lateralis activity (compared to pre-surgical values). From this it is possible to infer that the knee flexor moment decreased after surgery which can be associated with a decrease in hamstrings function which was not seen in this study as only one of the 4 heads was measured and 10 subjects is not enough to disprove lack of difference in EMG signal. The change in hip moments suggests an improvement in the increased iliopsoas activity prior to surgery. Does an increase in power generation in the hip coupled with decreased power absorption in the knee at toe off indicate a possible risk for future pathology (such as osteoarthritis) which could have been avoided without surgery or will this improve as recovery continues?

Although Ferber et al. (21) did not find any change in angles, Favre et al. found an increase in both flexion/extension and rotation mean range of motion one year after BPTB reconstruction using gyroscopes. Although rotations were measured to be higher in the CLE before surgery, after surgery results were quite opposite (20). Considering the difference in measurements and mark limitations (such as only five subjects, use of shoes etc.), it is difficult to compare this to any other study. Georgoulis et al., however, found a decrease (and equalization with control) of previously increased maximum rotation (internal) (28). The deficient and reconstructed subjects were not the same people but two independent groups.

Lewek et al. studied non-copers that underwent surgery, and those that did not, compared to healthy controls (45). The study showed that about one year after surgery individuals with weak quadriceps (less than 80% strength of CLE) had a decreased internal knee moment at peak knee flexion (as compared to healthy controls). Similar findings were shown for the sub-chronic ACLD subjects. The subjects with “strong” quadriceps showed similar values compared to controls. As no direct comparison of the ACLD and ACLR groups were made, it is difficult to conclude that the surgery improved knee kinematics only in subjects that managed to achieve stronger quadriceps.

Knoll et al. in both of their studies examined both acute and chronic patients that underwent surgery with follow-ups 6 weeks, 4, 8 and 12 months after the procedure (39;

40). The authors show that approximately four months after the surgery temporal-spatial parameters, ACL movement parameter (movement of tibia in the direction of the ACL) and the peak knee angles are normalized (in comparison to healthy controls) and at about 8 months the same can be said for muscle activity. Although these parameters are shown (in the same studies) to be faulty pre-surgically, no direct comparison was made between the two groups and thus it is not possible to make any conclusions regarding the effect the surgery had.

Beard et al. also calculated tibial translation (based on the difference in movement between the two lower extremities) in chronic ACLD patients before surgery and then 6 months after reconstruction (4). Results suggest an increase in tibial translation after surgery especially at heal strike. These controversial findings, however, are not significant enough and calculations may have been susceptible to skin movement artefact.

Ferber et al. compared the response of ACLD patients before and 3 months after reconstruction to forward perturbations. The findings revealed an elevated and (longer) sustained internal knee extension moment in the latter half of stance phase (approximately 60% to 75% of stance) in comparison to pre-surgical values that were similar to controls (22). No other differences between the groups were found in the angles, moments, or power. This suggests that subjects rely on increased quadriceps activity to overcome perturbations after surgery. As no EMG was done to confirm these findings, it is difficult to make any firm conclusions. This, however, confirms findings by Knoll et al. (39; 40) in that the recovery post operation may take at least 4 months.

Another very important question that stands unanswered today is which graft to use. The debate is mainly between BPTB graft and hamstring graft (in various forms and preparations). Moraiti et al. found no difference in gait sagittal plane variability (flexion, extension) between BPTB graft and quadrupled semitendinosis-gracilis graft approximately 2 years after the surgery (53).

Webster et al. (78), however, found a decrease in maximum external knee flexion moment (at midstance) in subjects with BPTB graft in comparison to both subjects with hamstrings graft and healthy controls. The same study revealed a decrease in maximum external dorsiflexion and knee extension moment in subjects with hamstrings graft in comparison to controls (which was not observed in BTPB graft subjects) and decreased maximum knee flexion angle in midstance in BTPB subjects in comparison with control (also not found in subjects with hamstring grafts). This suggests that the site of the graft is affected (external flexion moment affected by hamstrings and visa versa). Although both groups of subjects may be considered chronic (more than 3 months after reconstruction), subjects with a hamstring graft had a significantly shorter recovery time. Further evidence for harvest area morbidity (or weakness) may be the decreased varus (adduction) angle in the knee in subjects with a hamstring graft in comparison to those with a BPTB graft and healthy controls found by Webster and Feller (77). There is no EMG data, however, to support these results and one can only stipulate that it is a result of muscle weakness or malfunction.

Not only can the graft type influence recovery, but also the position of the graft. Scanlan et al. found that the more vertical the graft is placed the lower is the peak external flexion moment in the knee suggesting a decrease in quadriceps activity (62).

Owing to the fact that few authors compared variables after reconstruction directly to those before, it is difficult to say exactly how gait is changed by reconstruction. Another obstacle in comparing these studies is that the rehabilitation protocols used before and/or after the surgery are usually poorly described and in some articles not all patients underwent rehabilitation procedures. It is, however, suggested that there is a decrease in flexion moment (probably hamstring function) (21) and an increase in extensor moment (quadriceps function) during response to forward perturbations (22). All evidence also seems to point out that gait is not recovered (even to pre-surgery level) approximately 4 months after surgery. There is rather poor evidence on the long term effect of reconstruction as opposed to conservative treatment.

4.5.3 Bracing

One study investigated the effect of bracing on both ACLD and ACLR patients. Lu et al. (49) found that ACLR patients may benefit more from bracing approximately 10 months after BPTB reconstruction than ACLD patients as they showed an increase in peak knee extension and abduction moments which decreased the difference between the reconstructed and the CLE compared with pre-bracing values. ACLD subjects showed a much smaller improvement and that only in the frontal plane (abduction).

4.5.4 Injury

It is practically imposable to know if the parameters, measured after the injury, were also present before. One case study had the opportunity to compare gait analysis of a lower extremity before and after ACL injury (43). The findings revealed (an almost constant) decreased tibial translation as well as decreased flexion during weight acceptance. A large limitation of these findings is that the CLE had had an ACL injury for 8 weeks prior to the "pre-injury" measurements for investigate extremity. Thus the base measurements were not that of a "healthy" lower extremity as it had to cope with and adapt to the injury of the opposite knee.

4.5.5 No intervention

Most (n=35) of the studies, however, did not investigate the effect of a specific intervention on gait. Most of these studies wanted to pinpoint the parameters that change in ACL patients either in the acute stage, the chronic stage, after reconstruction etc. Each author tried to present, what seemed to them, the gait pattern for the specific group of subjects. The compiled results for these studies are discussed bellow under the appropriate sub-headings.

4.6 ACL Deficient Patients

More than two thirds of the studies examined gait in ACL deficient patients. These can further be subdivided into those that investigated acute or chronic patients and those that had copers or non-copers. Copers are generally understood as ACLD subjects that do not have major problems with their knee, i.e. they continue with their previous level of activity without episodes of giving way. Fitzgard et. al. (24), however, developed a specific protocol for identifying potential copers for conservative treatment. All studies that overlook this difference in ACLD patients may run into the problem of pooled data where the results do not show differences/changes because subjects with different gait strategies were pooled into one group or different studies may show opposite results due to a difference in concentration of copers and non-copers.

Below (table 3) is a summary of effect size (see appendix 1) for sagittal plane moments in ACLD patients adapted from a review by Hart et al. (31). The overall average weighted effect size (compared to healthy controls) was calculated to be -1.00. This shows that ACLD injured limbs show lower moments than healthy control. The largest effect size was from Rudolph et al. A total of 4 out of 7 calculated effect sizes are insignificant (weak) and thus their findings hardly prove the increased or decreased values they found. It is also noteworthy to mention that the two studies that found an increase in the sagittal plane moments in the ACLD subjects had very small effect sizes.

Table 3 Effect sizes for comparison of the sagittal plane moment of ACLD knees (31)

Author (year)	Time since injury	vs.Healthy control	Magnitude	vs.Contralateral limb	Magnitude
Torry et al. (2004)	8.6 years	-0.12	Weak	n/a	
Lewek et al. (2002)	< 6 months	-1.14	Large	n/a	
Rudolph et al. (2001)	Copers, >1 year	-2.71	Large	-0.14	Weak
	Non-copers < 8 months	-3.36	Large	-3.21	Large
Alkjaer et al. (2003)	Copers, 39.1 months	0.16	Weak	n/a	
	Non-copers, 55 months	-0.94	Large	n/a	
Chmielewski et al. (2001)	3.4 weeks	0.17	Weak	1.07	Large

4.6.1 Copers

It has always been a question why is it that some patients seem to have clinical problems after the injury while others cannot continue with their previous lifestyle. Most importantly, is it possible to “teach” this strategy to those that are coping poorly with their injury and if so how? A total of 4 studies evaluated the gait patterns of copers only (12; 13; 47; 68; 71).

Chmielewski et al. (13) found that acute copers (less than 10 weeks post injury) exhibited a decreased peak knee flexion angle during stance phase compared both to the CLE and healthy control from a previous study (61). The support moment was transferred from the knee to the ankle during loading response (first double support phase) in comparison to controls[1]. Although EMG measurements did not accompany, findings suggest greater activity of the muscles around the ankle especially triceps surea which is normally activated mainly after loading response (38; 56). A major flaw of this study is that acute ruptures of grafts were also included. It is my opinion that these subjects cannot be compared together with (in the same group as) ACLD subjects. These reconstructed subjects probably have undergone several stages of rehabilitation

[1] Table 1 of the article indicates a decrease moment at the knee of the CLE compared to control and not the injured extremity as stated in the main text of the article. This will be assumed to be a mistake in the table itself.

and may have developed completely different patterns in comparison to people who previously had no knee injuries.

On the contrary to acute copers, chronic copers are suggested to have no difference in peak flexion angle in the knee or any other temporal, spatial, kinetic or kinematic variables (47). Lindström et al., however, found earlier activation and subsequent longer duration of tibialis anterior as well as earlier activation of the lateral head of gastroclemius in copers as opposed to healthy controls (47). The study also showed differences in temporal-spatial parameters between male and female ACLD participants that were not seen in the controls. Using a different type of equipment (infrared diodes), Houck and Yack did find an increased internal rotation moment about the knee in chronic high functioning ACLD subjects in comparison to healthy controls (34). This suggests a special coping strategy against rotational knee instability.

Torry et al. suggest that chronic ACLD patients have more than one gait pattern. The authors subdivided the subjects into 2 groups: 1 (A) with a biphasic and 2 (B) with an extensor dominant pattern in the external knee moment[2]. The A group was then termed to have a "hip strategy" with increased hip range of motion during stance, increased hip extensor angular impulse, a transfer of support moment from the knee to the hip joint. The second group was said to have a "knee strategy" with lower knee extension and thus decreases range of motion in midstance, similar kinetics to the control and an increase in biceps femoris activity and decreased co-contraction of thigh musculature in the 3rd quartile of stance. All copers exhibited an increase in vastus medialis activity during the 3rd quartile of stance although this muscle is believed to normally end activity after the second quartile of stance (38; 56). This could mean a prolongation of vastus medialis activity beyond its normal activity period which is a rather surprising finding considering that this muscles is known to be inhibited by injuries to the knee (74).

4.6.2 Non-copers

There were only two studies that explicitly stated that they investigated non-copers only (35; 36) with a further two investigating poor functioning individuals (34; 41). Most other studies that investigated the effects

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[2] Authors use the word torque instead of moment which has been substituted here for comparative purposes

Although not explicitly stated, the chronic ACLD patients in the study by Ferber et al. (21) can be classified as non-copes as they had repeated episodes of giving way which lead to them opting for surgical repair. These non-copers exhibited increased internal hip extensor moment throughout stance (with a subsequent decrease in flexor moment), increased hip flexion (0% to 60% of stance), decreased power absorption in the knee at toe off, increased power generation in the hip (during pre-swing) to a point of power generation instead of power absorption (during midstance), increased biceps femoris activity and decreased vastus lateralis activity during loading response. With no difference in knee angles, moments or power (except at toe off), this strategy seems to mimic the “the hip strategy” described by Torry et al. (71).

A different article by Feber et al., however noted only increased average of hip flexion angle with no difference in the average of internal extension moment or power generation around the hip joint (23). The same article does mention increased averaged knee and hip flexion angles, internal knee extensor moment and knee power generation on the CLE in comparison to healthy controls (the two latter variable in comparison to the injured lower extremity as well). A lack of variability of average hip power absorption in non-copers was found in contrast to variability between extremities found in healthy controls (23). Differences in the results may have come up due to averaging of the data. Houck and Yack, however, did find differences concerning the knee itself in low functioning chronic ACLD subjects in comparison to healthy controls. The study showed an increase in knee flexion angle coupled with a decrease in knee flexion moment at 60% of stance (34).

Another study by Houck et al. that examined sub-chronic and chronic non-copers revealed slightly different data. The study showed non-copers to have a lower peak knee flexion angle (0-20% of cycle), decreased peak knee extension moment (10-20%), decreased power absorption during loading response (10-20%) and decreased power generation during midstance (20-50%) in cmparison to healthy controls (35).

Similar to the acute copers (13), acute non-copers were shown to have lower knee excursions during midstance (32) (36) and during weight acceptance after initial contact (36) as compared to the CLE. Hurd and Synder Mackler also found that acute non-copers show signs of increased hamstrings activity, increased hamstrings–quadriceps co-contraction, decreased soleus activity, decreased internal knee moment (at peak knee extension), an increase in the contribution of the ankle to the total support moment in midstance and decreased quadriceps activity, decreased knee and increased hip contribution to support moment during weight acceptance (36).

4.6.3 Copers vs. Non-Copers

A further seven studies directly compared copers to non-copers. In summary non-copers seem to have a lower excursion (and/or peak flexion angle and/or extension) in the knee compared to the CLE[3], healthy controls and copers (7; 11; 31; 32; 34-36; 61)[4] which is perhaps substituted by increased hip flexion (21) although Button et al. suggests also a decrease in hip excursion (11). Although acute copers also seem to have a decreased peak knee flexion angle in comparison to the CLE (12; 13), chronic copers are found to have either similar (7; 34; 47) or increased (1) peak knee flexion values (and /or excursion) in comparison to control and CLE. This could mean that one of the shortcomings of non-copers is their decreased range of motion during gait. Not only is the angle itself lower during peak knee flexion but so is the moment around the knee (1; 34-36; 61). Does this then suggest that the decreased excursion is because of changed muscle activity? Several studies suggest the increased or prolonged activity of the hamstrings especially biceps femoris (21; 36; 61) but this would logically lead to an increase in peak knee flexion and not the decrease noted in most studies. Hurd and Syner-Mackler have suggested that this is due to the increased co-contraction of hamstrings and quadriceps in comparison to the CLE which hampers the development of the normal range of motion during gait (36).

A direct comparison to non-copers, however, reveals that copers have increased activity in semitendinosus compared to non-copers and also exhibit an "additional muscle activity" in the biceps femoris[5] at approximately 15-50% of the stride in comparison to non-copers and controls (7). This type of activity, however, has previously been found in some healthy individuals in the short biceps femoris head (56) (see appendix). As opposed to non-copers who show a decreased vastus lateralis activity (21), copers seem

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[3] One study showed that non-copers differed in excursion with both the injured and the CLE in comparison with the controls (7). As this study used goniometers to measure the angles it is difficult compare it to the other studies that used video analysis. This, however, is further evidence that comparison to the CLE is not a valid one.

[4] One study found no difference in peak knee flexion angle between copers and healthy controls (1), one study found an increase in knee flexion angle at 60% stance in low functioning ACLD subjects in comparison to high functioning subjects and healthy controls (34)

[5] This activity was not statistically different.

to have either a prolonged activity of vastus medialis (71) or a earlier peak of activity of vastus lateralis (61). Although the decreased knee contribution to the support moment in non-copers (36; 61) confirms a change in the way the extensor mechanism (mainly quadriceps femoris) may work, this does not confirm quadriceps avoidance (see appropriate section) as there is little EMG proof. This deficit in the support moment is substituted by the increase of the ankle's contribution during midstance (36) and the hip's contribution during weight acceptance (36; 61). The increase in the contribution to the support moment by the hip seems quite logical since in this phase the hip is already the largest contributor to the total support moment and there is an increase in hamstring activity (previously mentioned) which is a hip extensor, as well as direct evidence of increased hip extensor moment (21). Does this however, mean that there is an increase in gluteus maximus activity as well? Few studies ever measure gluteus maximus activity, but this is one of the muscles that act against the ACL even though it is not directly connected with the knee (44). A second muscle that affects the knee joint without being directly associated with it is the soleus. The soleus, contrary to the gluteus maximus, assists the ACL in the control of anterior translation of the tibia (44) and has been found to have decreased activity in acute non-copers during weight acceptance and midstance (36)[6]. These two muscles maybe the key answer as to why non-copers have episodes of "giving way", while copers have no such problems. Previously this was explained by the decrease in internal knee extensor moment (34) and an assumption that there was decreased quadriceps activity but there is little evidence suggesting that there is true decrease in quadriceps activity in comparison to healthy controls (see section on quadriceps avoidance gait).

4.6.4 Adapters

One study by Courtney et al. described a third group of ACLD patients termed adapters. These subjects altered their activities so as to not have any episodes of giving way. In the above mentioned study adapters were found to have an earlier activation of gastrocnemius in comparison to healthy controls (15).

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[6] Soleus activity has been found to be higher during weight acceptance in sub-chronic non-copers in comparison to copers and healthy controls (61)

4.6.5 Acute

As one may have already noticed there are certain differences between acute and chronic patients. Many studies, however, either poorly specify when the injury occurred (49) or include both acute and chronic subjects in one group (2; 15; 20; 35; 42; 55; 64; 68) . For instance the study by Rudolph et al. specifies that the non-copers are less than 8 months after injury (61). Six or more month after injury could be considered at least sub-chronic if not chronic, while injuries up to 3 months before examination, such as in the study by Hurd and Synders-Mackler (36), can truly be called acute. Rudolph et al., however, in the discussion mention that the non-copers were “recently injured”. Does this suggest acute? Patel et al. had ACLD subjects ranging from 1 to 124 month. Considering that the mean was 21 months can it be stipulated that most of the subjects were acute or sub-chronic?

One thing on which almost everyone agrees on is that acute patients have decreased knee excursion (and/or decreased peak knee flexion angle) when compared to CLE as well as healthy controls (12; 13; 26; 39; 40; 59). One study suggested that this decreased knee angle is due to an increased co-contraction of the vastus lateralis and biceps femoris muscles compared to healthy controls (12). Other studies show a decrease in knee moment at peak knee flexion in comparison to the CLE (45; 59) and suggest no activity in the vasti for the first half of the gait cycle (39)[7].

At least one study (28) did not confirm a decrease in sagittal plane angles weather during toe off, loading response or swing phase in comparison to healthy controls. The same study, however, did suggest an increased internal maximal rotation which occurred in early swing. This was explained by the assumption that during this phase of gait there is an increase in quadriceps and gastorcnemius activity coupled with a decrease in hamstring activity resulting in an increased load on the ACL and the resulting rotational instability.

4.6.6 Chronic

Do ACLD patients change their movement stereotype with time? In addition to the already previously discussed articles in the copers and non-copers section, 17 other

[7] The significance for EMG differences is not reported in the study. One is left to judge the result according to presented graphs.

studies were conducted on chronic (mean time after injury) ACLD patients. Two of these studies discussed the flexion–extension variability, calculated with Lyapunov exponent and an additional one calculated by approximate entropy. While Stregius et al. found an increased variability as opposed to the CLE (67), two other studies found decreased variability in comparison to controls or CLE (27; 52).

Although Patel et al. found no difference in peak knee external flexor moment, the study did find a decrease in peak knee external extension moment and an increase in knee excursion in late stance with a correlation between the two (55). This study, however, had both acute and chronic patients with the range post injury being 1 to 124 months as well as several patients with knee instability (thus both copers and non-copers were included). On the other hand, this is the study with the largest number of subjects who were compared to healthy controls[8]. Zhang et al. also found a decrease in flexion angle in chronic ACLD patients in comparison to healthy controls, although this finding was between 85% and 93%% of the gait cycle (81). The study also found an increase in abduction right before and during heel strike (93% - 2% of cycle) which was not found by Favre et al. (20). Rather opposite were the findings of Fuentes et al. and Gao and Zheng with ACLD subjects illustrating a decrease in peak extension angle (25; 26), increased flexion angle (37-46% of cycle) (25) and an increase in adduction (most evident in the first half of stance) (26). Although Andriacchi and Dyrby found a decrease in anterior translation in late swing (2), Zhang et al. found an increase in this variable for most part of the swing phase (60% - 83% of cycle) as well as some instances of the stance phase (15%, 24%, 57% - 60% of the cycle) (81). A study by von Porat et al., however, found absolutely no differences in chronic ACLD patients in comparison to healthy controls (76). The study included measurements of knee angles and moments at peak knee flexion as well as knee power absorption but only in the sagittal plane.

Similarly to acute ACLD patients (28), chronic and subchronic subjects were found to have a decrease in maximal external rotation angle (during extension before heel strike) and an internal rotation offset (for the entire gait cycle) in comparison to healthy control (2; 26), as well as decreased mean range of motion for rotation in comparison to the

[8] Study with the largest number of subjects compared to control examined only termporo-spacial parameters (10)

CLE (20). These findings were interpreted as a problem in the screw home mechanism preceding heel strike and a possible cause of increased medial compartment stress increasing the risk of osteoarthritis. Rather opposite finding were reported by Zhang et al., however. The study interpreted an increase in external rotation for almost the entire (9%-83% and 94%-98% of) gait cycle as a compensatory mechanism to avoid instability (internal rotation) and suggested that there should be an increase in biceps femors, medial gastrocnemius and vastus lateralis activity coupled with a decrease in semitendinosis activity (81). Recent EMG studies, however, have not proved or disproved these suggestions. A reason for such discrepancies could be the use of different instrumentation such as goniometers by Zhang et al., gyroscopes by Favre et al. and optoelectronic equipment by the remaining authors. Another reason could be the presence or absence of copers/non-copers in the groups as well as the sample size with only three studies (26; 28; 81) having more than 10 subjects in the ACLD group.

From the above, and previously mentioned data, it is difficult to compile any given gait pattern for chronic ACLD patients as a whole. All the studies measured different variables and had different results.

4.7 ACL Reconstruction

After an ACL reconstruction is done, some of the most important questions are: what kind of rehabilitation plan is best for the individual, what criteria should be used to progress to the next stage of rehabilitation, do the clinical parameters (easily measured by each clinician) reflect the functional state of the person, when can the individual start sport specific training especially if he/she is an athlete, and so on and so forth.

Table 4 Effect sizes for comparison of the sagittal plane moment of ACLR knees (31)

<table>
<tr><th>Author (year)</th><th colspan="2">Time since injury, graft type</th><th>vs.Healthy control</th><th>Magnitude</th></tr>
<tr><td rowspan="2">Hooper et al. (2002)</td><td colspan="2">6 months, BPTB</td><td>-0.4</td><td>Small</td></tr>
<tr><td colspan="2">12 months, BPTB</td><td>-0.49</td><td>Small</td></tr>
<tr><td rowspan="2">Webster (2005)</td><td colspan="2">11 months, BPTB</td><td>-1.27</td><td>Large</td></tr>
<tr><td colspan="2">9.3 months, Hamstrings</td><td>-0.09</td><td>Weak</td></tr>
<tr><td rowspan="2">Lewek et al. (2002)</td><td>14.3 w. (‘strong’)</td><td rowspan="2">Allograft or Hamstrings</td><td>-1.02</td><td>Large</td></tr>
<tr><td>20.8 w. (‘weak’)</td><td>-1.77</td><td>Large</td></tr>
</table>

A summary of effect size (appendix 1) for sagittal plane moments in ACLR patients adapted from a review by Hart et al. (31) can be found in table 4. Out of the six calculated effect sizes only three were significantly large. All studies showed a decrease in the sagittal plane moments of the ACLR subjects when compared to healthy controls.

One difficulty in comparing studies on reconstructed patients is that there are quite a few variables that may affect the outcome, and are usually different one study from another. As already mentioned, studies have different approaches to rehabilitation, with some using bracing, others starting the rehabilitation much later, others use neuromuscular training in addition to strength training. There are also articles that do not see it fit to describe the kind of rehabilitation that took place making the comparison between articles even more difficult as one does not know if the outcome is due to the surgery, the type of graft, the type or length of rehabilitation, or time. A total of 25 articles discussed the gait patterns in ACLR patients at different times after surgery and are discussed below in chronological order.

Six weeks after BTPB reconstruction, there is a decrease in peak knee extension, ROM (weight acceptance and midstance), flexion angles and power absorption and generation at the knee as well as changed temporal-special parameters (19; 39; 40). Knoll et al also suggest that there is no activity of vastus medialis and lateralis in the first half of the cycle in patients that were acute before surgery[9] (39; 40).

Three months after BTPB reconstruction the lower extremity does not exhibit normal gait in comparison to healthy controls as shown by Ferber et al. The study suggests the following differences: increased knee internal extensor moment in the first half of midstance followed by a decrease in the knee flexor moment in late stance, increased hip extensor moment in early stance and again in the second half of midstance, increased flexion angle for the knee in late stance and for the hip in early stance and first half of midstance, decreased power absorption in the knee in late, power generation in the hip instead of power absorption in midstance, increased biceps femoris activity during loading response and decreased vastus lateralis activity at initial loading (21). This means that during the first 20% of stance phase there is an increased hip extensor moment with increased biceps femoris activity but also increased hip flexion (which does not quite fit the picture). The next 20% is dominated by an increase in knee

[9] The significance for EMG differences is not reported in the study. One is left to judge the result according to presented graphs.

extensor moment with increased knee flexion angle and still present increased hip flexion. The increased extensor moment is quite interesting as it suggests an increase in quadriceps activity but no increase was actually found in vastus lateralis, in fact, there was a decrease in the activity in the first 20% of the phase. This could of course mean that the other heads of the muscle were more active but no proof is given. Terminal stance is dominated by a decrease in power absorption by both the knee and hip. Does this signal the possibility for future degenerative pathology in both joints? Power absorption is associated with eccentric muscle activity (38). Would eccentric exercises for these muscles help to change this fault in the subject's gait?

Four months after surgery Knoll et al. found no differences in kinetics and kinematics in comparison to healthy controls (39; 40). The studies did find a decrease in the vastus lateralis et medialis activity in the first half of the gait cycle, which was an improvement to the EMG taken at 6 weeks[10].

Six month after reconstruction with a patellar graft, contrary to the lack of finding by the previously mentioned studies by Knoll et al., several authors found significant changes in several parameters. Bacchini et al. found a decreased knee flexion angle as well as a decreased external knee flexor moment during terminal stance suggesting a decrease in quadriceps activity (3). Hopper et al. also found a decrease in knee flexion angle during heal strike. The study also revealed a general decrease in knee excursion in the midstance phase but no differences were found in knee moments (33). This study however, included two different surgical methodologies and subjects with complicated injuries who were excluded from most of the other studies. Subjects of this study also underwent different length and type of rehabilitation post surgery. Both studies compared the reconstructed knee with the CLE. Georgoulis et al., however, found no difference in angles in all planes throughout the whole gait cycle between reconstructed subjects and healthy controls on average of seven months after BPTB reconstruction (28).

Although Knoll et al. found no differences between ACLR and healthy controls twelve months after surgery (39; 40), Hooper et al. found several differences with the CLE (33). The study shows that the decrease in knee excursion persists and that there is a

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[10]T he significance for EMG differences is not reported in the study. One is left to judge the result according to presented graphs

decreased knee flexion angle during the toe off which is consistent with the findings by Bacchini et al. at 6 months (3). Gao and Zhen, however, found an increase in knee flexion angle during the second half of the stance face in sub-chronic (3 to 12 months after surgery) ACLR subjects in comparison to healthy control (26). The above mentioned studies may have concluded different results because they use completely different technology for data collection.

Chronic, more than a year after surgery, patients also seem to show some differences in their gait pattern. Bush-Joseph et al. found a decrease in peak external knee flexor moment during midstance (8) which coincides with the decrease of internal knee moment at peak knee flexion found in “weak” quadriceps subjects by Lewek et al. (45). Although Bush-Joseph et al. found an increase in the terminal knee extension angle (8) and Lewek et al. found a decreased peak knee flexion angle in the “weak” group (45), Butler et al. did not find any difference in comparison to healthy controls (9). The study did find an increase in peak knee abduction moment compared with healthy controls which was also found by another study (3). The authors suggest that this implicates future osteoarthritis. The above mentioned studies used different types of grafts (table 4)

Although Georgoulis et al. found no rotational differences in sub-chronic ACL reconstructed patients (28); two studies found an external rotation offset (decreased internal rotation) during stance phase in ACL reconstructed subjects more than 6 months after reconstruction (with varying graft types) in comparison to healthy controls and the CLE (63; 77) and one study found an internal rotation offset (26). This could imply incorrect loading of the knee and a risk of osteoarthritis in the future.

Lastly Moraiti et al. (53) suggest that there is increased flexion extension variability in gait in comparison to healthy controls as well as an increased variability of the CLE in comparison to the ACLR lower extremity. Thus further evidence to support bilateral accommodations of the lower extremities in the chronic ALCR patient. The study, however, did not find any difference in variability between a BPTB and a semitendinosis/gracilis graft.

According to the above summarized articles it is not very easy to answer the questions mentioned in the beginning of this section. It is possible to assume however, that 3 months may be too early to load (in the sense of going back to high level/risk activities) the knee as there are marked faults in the gait which need further rehabilitation with perhaps special emphasis on eccentric muscle contractions. Six months after surgery there might be decreased quadriceps activity that has not been proven with an EMG study but the main problem seems to be a decreased in the range of motion used during gait. Thus rehabilitation methods should take greater care in increasing the functional range of motion that the patients use. Even several years after surgery, certain differences are found in comparison to the healthy population. On the one hand, this may signify a special gait adaptation the ACLR patients use; on the other hand, this adaptation may be due to incomplete or incorrect rehabilitation and may be detrimental to the future health of the patient such as early onset of osteoarthritis.

4.8 Gait Strategies

4.8.1 Quadriceps Avoidance

Quadriceps avoidance gait was first described by Berchuck et al. (6). It is thought to be a decrease in the knee flexion angle, the knee internal extensor moment or a constant knee internal flexor moment all of which assume a decrease in the activity of the quadriceps muscle itself. This strategy suggests that ACL patient reduce the activity of the quadriceps to intern reduce the anterior translation which is not passively restricted in ACLD patients. Others argue that in the absence of EMG data to confirm the quadriceps deficiency, moments alone cannot indicate that there is a decrease in the muscle activity. As the moment is depended on both flexors and extensors, a decrease in extensor moment may be due to an increase in flexor activity and not due to a decrease in extensor activity (7). On the other hand, it is especially difficult to prove anything with EMG collected from just a handful of subjects which is true for most studies included in this thesis. Thus instead of “avoidance” this gait strategy should be described as s change in the communication between the hamstring and quadriceps muscles. Although this was an often finding in earlier literature, few recent studies mention finding quadriceps avoidance gait in their subject.

Out of all the articles that considered this strategy only 3 claimed to find quadriceps avoidance gait in some of the subjects (8; 39; 40), and one implicitly suggested of such a strategy (78), while the rest said that this strategy was not found in their subjects (1; 7; 21; 33; 36; 55; 61; 71; 81) (table 5). Bush-Joseph et al stated that 2 of the ACLR patients and one healthy control subject showed signs of quadriceps avoidance gait without further specifications (8). Knoll et al. concluded that the acute ACLD subjects in their study exhibited this strategy shortly before surgery and 6 weeks after. This conclusion was based on increased knee extension during stance and reduced flexion during the swing phase as well as the decreased activity of vastus medialis et lateralis (39; 40). Webster et al. suggested that a strategy that decreases the amount of knee flexion and external knee flexion moment was used by BPTB reconstructed subjects explaining this as pain avoidance (78). Although most studies exclude patients with swelling, others may have not paid as much attention to this important variable which may not be obvious at first glance. Swelling has been shown to produce quadriceps avoidance gait (72) and could affect the results of studies that fail to these exclude subjects.

Table 5 Summary of Studies investigating moments

First author year	Group, time post injury/surg.	Analysis vs.	Results	Quadriceps avoidance gait
Alkjaer 20003 (1)	Copers 39 months Non-copers 55 months	control	↓ moment, NSD quadriceps	NO
Boerboom 2001 (7)	Copers 39 months Non-copers 22 months	control	NSD quadriceps	NO
Bush-Joseph 2001 (8)	ACLR 22 months	control	not related	2 ACL, 1 control
Ferber 2002 (21)	ACLD 5.7 years, ACLR 3 months	control	NSD moments	NO
Hooper 2002 (33)	ACLR 6, 12 months	CLE	NSD moments	NO
Houck 2003 (34)	Non-copers, 64 month	copers	↓ moment	
Hurd 2007 (36)	Non-copers 11 weeks	CLE	NSD quadriceps	NO
Knoll 2004(39; 40)	acute ACLD 12 days	control	↓ quadriceps activity, ↓ E	YES pre and 6 weeks post surgery
	chronic ACLD 28 months	control	NSD	NO
Patel 2003 (55)	ACLD 21 months	control	NSD	NO
Rudolph 2001 (61)	copers ≥ 1 year, non-cop ≤ 8 months	control	↓ moment, NSD quadriceps	NO
Shin 2007 (64)	ACLD 2 – 432 months	CLE	↓ moment	YES
Torry 2004 (71)	ACLD 8.9 years	control		NO
Webster 2005 (78)	ACLR BPTB 11 months	control	↓ moment, ↓ F	(YES)
Zhang 2003 (81)	ACLD 5 years	control	↓ F,	NO

NSD – no significant difference, joint angles: E – extension, F – flexion, quadriceps – muscle EMG activity

Shin et al. suggests that quadriceps avoidance may be a question of anatomy (64). The authors found that the greater the patellar ligament insertion angle (PLIA) in ACLD patients, the lower is the peak external knee flexion moment and thus the great chance of quadriceps avoidance. The correlation between the difference (in comparison to the CLE) in the peak moment and the PLIA was most evident in the large PLIA group (from a minimum angle of approximately 20 degrees). The study, however, included both acute and chronic patients and did not distinguish between copers and non-copers.

4.8.2 Knee Stiffening

Another gait strategy that is gaining more support in recent publications on gait in ACL patients is knee stiffening. This is when the knee has decreased knee motion (angles) due to an increase in muscular co-contractions especially that of the quadriceps and hamstrings, or a decrease in their activity. Since most subjects included in gait studies have full knee range of motion the decrease in its use during gait is considered to be of muscular origin. In addition this strategy is considered primitive and if used often may affect the integrity of the joint in the long run (46).

Hurd and Snyder-Mackler found both decreased knee excursion and increased co-contraction of the quadriceps and hamstring muscles during weight acceptance and midstance in acute non-copers (36). These findings, however, were in comparison to the CLE. Although other studies found decreased knee excursion/peak knee flexion angle in non-copers, no increase in co-contractions were found in comparison to healthy controls (7; 61). In contrast Alkjaer et al. found an increase in peak knee flexion angle in copers and significantly no difference between non-copers and healthy controls (1). The study also did not find any difference in co-contractions between any of the groups. The lack of co-contraction findings may be explained by the small number of subjects in the studies that is reflected in low significance in EMG findings. At least one study (68) found a decrease co-contraction of both lower extremities in functional ACLD patients in comparison to controls. This was explained by a change in the gamma-muscle-spindle system. The study, however, has very high variability in the results of the control group.

Ferber et al. investigated the response of ACLR subjects, three months after surgery, to frontal perturbation during gait (22). Although no decreased knee excursions were found (in comparison to healthy controls), the authors suggest that the near zero net moment found in early stance is an indication of a stiffening strategy. Similar response to perturbation during gait was investigated by Chmielewski et al. in potential copers (12). Although a decrease in peak knee flexion was found only when there was no perturbation, co-contraction of lateral quadriceps and hamstrings were increased in the locked (no perturbation) position and during lateral and anterior perturbation in the preparatory phase (100ms before heal strike) and weight acceptance. T. Fonseca et al., on the other hand, found either a decrease (in the CLE) or no difference in the injured extremity (probably due to a low number of subjects) right after medio-lateral perturbation in functional ACLD subjects in comparison to healthy controls (68).

Thus the stiffening strategy seems to be used more by non-copers during gait (although the evidence is quite poor). All other patients, both ACLR and ACLD may use this strategy only during gait perturbations.

4.8.3 Pivot Shift Avoidance

The most recently proposed gait strategy is the pivot shift avoidance gait presented by Fuentes et al. in the beginning of the this year (25). This strategy includes increased knee flexion angle and decreased maximal knee extension angle which is similar to the stiff knee strategy described previously. The inclusion of parameters in the transverse plane is the new addition to the strategy. The author found a decrease in the external moment of internal rotation in chronic ACLD[11] subject between 40% and 49% of gait cycle coupled with a reduced maximal internal rotation moment in comparison to healthy controls (25). The author interprets this as a compensatory strategy that avoids rotational instability and suggests an increased activity of biceps femoris muscle towards the end of stance phase when there is an increased extension on the ACLD extremity just before second double support phase.

The increase in knee flexion angle (or decreased knee extension angle or ROM) in terminal stance has also been found by several other authors in acute as well as chronic ACLD (also directly in non-copers) in comparison to the CLE and healthy controls (26; 34; 36). Similar findings in other phases of gait were also found by numerous studies (7;

[11] The author specifies that ACLD subjects are awaiting reconstruction thus it is possible to conclude that these are non-copers or non-functional ACLD patients

11; 20; 42; 59). At least four studies, however, found no difference in relation to knee flexion angle (21; 23; 28; 41; 42).

The decrease in internal rotation moment is similar to the finding of external rotation angle offset by Zhang et al. (81). Three EMG studies confirm an increase in biceps femoris (or hamstrings) in acute and chronic ACLD (both copers and non-copers) subjects in comparison to the CLE and healthy controls during the terminal stance phase (7; 31; 39; 40). Similar findings in other phases of gait were also reported (12; 21; 61). Rather opposite findings were reported by several authors finding an internal rotation offset (or increase (decreased) internal (external) rotation) in acute as well as chronic ACLD patients. These authors suggest that ACLD patients thus undergo episodes of giving way. This is supported by the decreased hamstring activity coupled with increase in vastus medialis during terminal stance in chronic ACLD patients (42; 71).

4.9 Other Findings

Several articles have found little change in gait in ACL patients but show that there are much greater differences between these patients and healthy controls during more strenuous activities such as running, cutting, stepping and jumping (13; 34; 42; 45; 59; 61; 75). The discussion of these activities is beyond the scope of this thesis. Several other issues pertaining to gait are discussed bellow.

4.9.1 How Quadriceps Strength Affects Gait

Quadriceps strength is often associated with quadriceps activity but this may not be true as the isolated isometric strength of a muscle says little as to how the muscle functions during gait. Does a decrease in the strength, however, hamper the proper functionality of the muscle during gait? Several studies have shown that there is no correlation between quadriceps strength and sagittal plane knee moments in ACLR (8) and ACLD (55) patients as well as other gait parameters (30). None of the three mentioned studies, however, subdivided their subjects into functional groups, and thus may not have found any correlations. Lewek et al. (45) examined ACLR patients which were subdivided into a strong quadriceps group (80% or more strength in comparison to CLE) and a weak group (less than 80% of CLE). The strong group had gait similar to the healthy controls while the weak group had different angles and moments around the knee in comparison to the control group and more similar to that of the ACLD patients. Rudolph et al. suggested that quadriceps strength is correlated with knee flexion angle and external knee flexion moment in non-copers but not in copers (61). From the above mentioned conflicting data it is very difficult to say whether or not quadriceps strength affect gait but there is a suggestion that it may affect angles and moments in the weaker patient or patients that poorly cope with the injury.

4.9.2 How Laxity Affects Gait

Passive knee laxity does not seem to correlate with various gait parameters whether in acute reconstructed patients or in chronic ACLD patients (30; 55; 61). Beard et al., however, suggest that tibial translation against femur increases after surgery, as opposed to being normal before surgery (4). These findings are rather questionable as skin markers were used to calculate the subtle difference in tibial translation between extremities. It can however, be concluded that measurement of passive knee laxity, a standard clinical examination, cannot predict the functional parameters of gait.

5 Practical Application

As previously mentioned, there have been several reviews summarizing data from various studies about gait analysis and what it reveals about the ACL patient. There are also quite a few books that have been published on the topic of gait analysis that try to put the voluminous amount of information into practical advice. Few of these sources, however, mention the exact application to rehabilitation of ACL patients. Below I have tried to put forward my own advice from the knowledge I have gained researching for this thesis as well as advice given by Kirtley et al. (38).

5.1 Minimal Requirements

The most basic requirement for gait analysis is a walkway. Minimal area can be a 6m by 3m walkway but largely depends on the complexity (and/or amount) of equipment being used. Simple mobile equipment (not 3D video analysis) can be used in any place including a physiotherapy gym, corridor of a clinic etc. Another way to solve limited area is to use a treadmill instead of an over-ground walkway. Although, as previously mentioned, treadmill gait may not represent the way the patient walks on the ground it can be used for comparative purposes over time with the same patient.

Simple temporo-spatial may be measured with the use of a stopwatch and or camcorder.

Kinematic data can be measured with the use of as simple technologies as goniometers, gyroscopes or arthrometers. In my opinion, gyroscopes are good investment as it is possible to derive angles in all three planes and their use is neither limited to the lower extremity nor to gait analysis. More complicated (and perhaps more accurate) measurements may be obtained from 3D video analysis. This requires at least 3 cameras and 4 markers (lateral side of the greater trochanter, lateral femoral epicondyle, lateral malleolus, and head of the fifth metatars) for unilateral analysis. Certainly accuracy increases with the increased number of cameras.

Forces beneath the feet may be obtained with the use of a footswitch or one to two force plates embedded into the floor or treadmill. Although the moments may tell a great deal about the forces about the knee as well as other joints, the use of EMG may give direct answers as to the activation of certain muscles. A great limitation of surface EMG, however, is that it is impossible to measure deep muscles and there is danger of cross-talk.

When it comes to time required for the examination, it varies a great deal depending on the equipment used. As few as one trial per extremity can be used but it better to perform approximately 5 trials to avoid the error of unrepresentative gait on one hand, and not too much data for processing, on the other hand. Gait analysis on a treadmill requires a further 5 to 10 minutes familiarization time. The more complex the system the more time that has to be invested into training of the staff, calibration of the equipment, attachment of the equipment on the patient, processing the data etc.

5.2 Transferring Data into Person Specific Rehabilitation

The most important aspect of clinical gait analysis is its transfer into useful rehabilitation. Most researchers try to find the trends in various ACL populations (as reported in this thesis) so as to compile a universal rehabilitation plan that will suit one or the other group of patients. Many of these studies, however, concentrate on highly active, young men. This may not be the case of the clinical population of ACL patients. The point of performing gait analysis on patients in the clinical setting is to plan and evaluate patient specific rehabilitation according to the findings of the analysis.

A major problem in diagnosis occurs when deal with patients in a clinical setting as the CLE is not "control". The best way to overcome this problem is to compare the values derived with normal values. Although normative values are included in the appendix of this work, they very much depend on the equipment (or combination thereof), population and normalization used. Thus the optimal solution would be for each laboratory to compile its own "normal" population with the equipment that would be used for analysis of the patients. If possible this normal population should be further subdivided into professional sportswo/men, active and non-active individuals.

So how does a clinician actually interpret the acquired data? One has to keep in mind that the measurements are done in a dynamic activity. This means that rehabilitation measures for increasing range of motion in a joint statically (for example stretching) may not be helpful if decreased range of motion during stance phase is found. In this the increase in range of motion has to be attained through direct training of gait or other activities of daily living as well as neuromuscular training.

Increased force (moments) around a joint may damage the joint especially if they are distributed differently to the "norm". It may also indicate the over activity of muscles compensating for the weakness or inhibition of other muscles. Decreased moments and

EMG values may indicate the inactivity of muscles but not necessary their weakness. If a muscle is strong (which is initself a subjective measure) but shows decreased activity, neuromuscular training may be attempted included some types that have not been to date investigate such as post neuromuscular facilitation.

Decreased power generation may require concentric muscle training while decreased power absorption may require eccentric muscle training.

As there is no formula or proof –tested method, the clinician has to evaluate the progress of rehabilitation on a regular basis. For the evaluation it is best to select one or several parameters most characteristic (different from the "norm" or CLE) to the patient so that there are concrete goals as well as easy analysis.

5.6 Further reading

The following is a list of books (in alphabetical order) for inspiration as well as technical guidelines. As most texts have several editions, only the newest ones are sited.

Clinical gait analysis : theory and practice (38)

Dynamics of human gait (73)

Gait analysis : an introduction (79)

Gait analysis: methodologies and clinical applications (29)

Gait analysis: normal and pathological function (57)

Gait analysis: theory and application (17)

Human walking (60)

Joint structure and function: a comprehensive analysis (44)

Measurement of human locomotion (51)

6 Conclusion

This review focused on gait analysis in the ACL patient. The most up to date research seems to focus on dividing ACL deficient subjects into groups according to their functional ability and if they experience episodes or not. The most common division is into copers and non-copers. Another factor that plays a great importance in the type of gait exhibited is the time that has elapsed since the injury/operation. The improvements with time are quite evident especially in the reconstructed patients. Although there is controversial evidence, recovery after reconstruction takes more than 6 months and may depend on anatomy and type of surgical intervention with only several studies investigating the latter.

Three main gait strategies were identified in literature. The first, quadriceps avoidance gait, is rather an old outdated hypothesis which has not been confirmed by EMG studies in any recent studies. The knee stiffening strategy is most likely present in non-copers during normal gait and in all other ACL patients during perturbations. The most recent gait strategy is pivot-shift avoidance which hypothesis that ACL patients avoid any position of the knee that would result in an episode of giving-way.

As neither quadriceps strength nor knee laxity do reflect the actual state of improvement of gait itself, an important daily activity, instrumental gait analysis should be used in the clinical setting if possible. The amount of time and finances spent on the analysis reflects the desired precision in the measurements and subsequently the detail of the rehabilitation plan.

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Appendix

Appendix 1 – Effect Size

Effect size can be calculated with the use of the following formula (31):

$$\text{Cohen's d} = \frac{(\text{Mean}_{\text{injured}} - \text{Mean}_{\text{control}})}{\text{SD}_{\text{pooled}}}$$

This may be calculated with the help of a free downloadable spreadsheet from http://stat-help.com/. It is necessary to input the following data into the spreadsheet: mean, standard deviation (SD) and number of subjects for each group (for example the ACL group and the control group).

The greater the effect size (above or below zero) the more powerful is the finding of the researcher. Magnitude can be applied for easy interpretation of effect size with 0.2 as small, 0.5 as medium, and 0.8 as large.

Appendix 2 – Sagittal Plane Normative Values

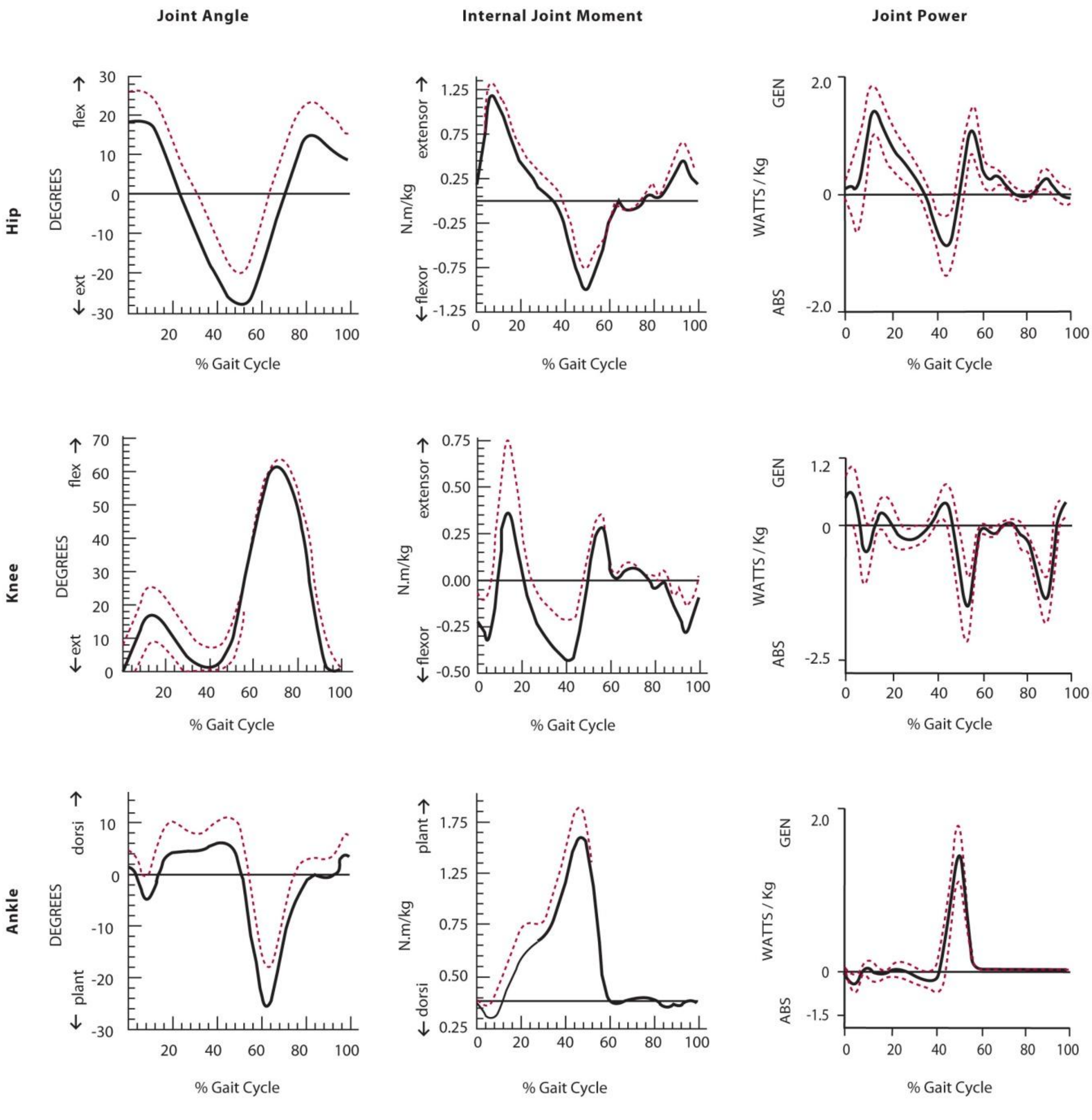

Figure I Angles, moments and powers in the hip, knee and ankle in the sagittal plane. Dark line represents the mean while the dotted line represents the standard deviation. Adopted from *Joint structure and function: a comprehensive analysis* (44).

Appendix 3 – Frontal Plane Normative Values

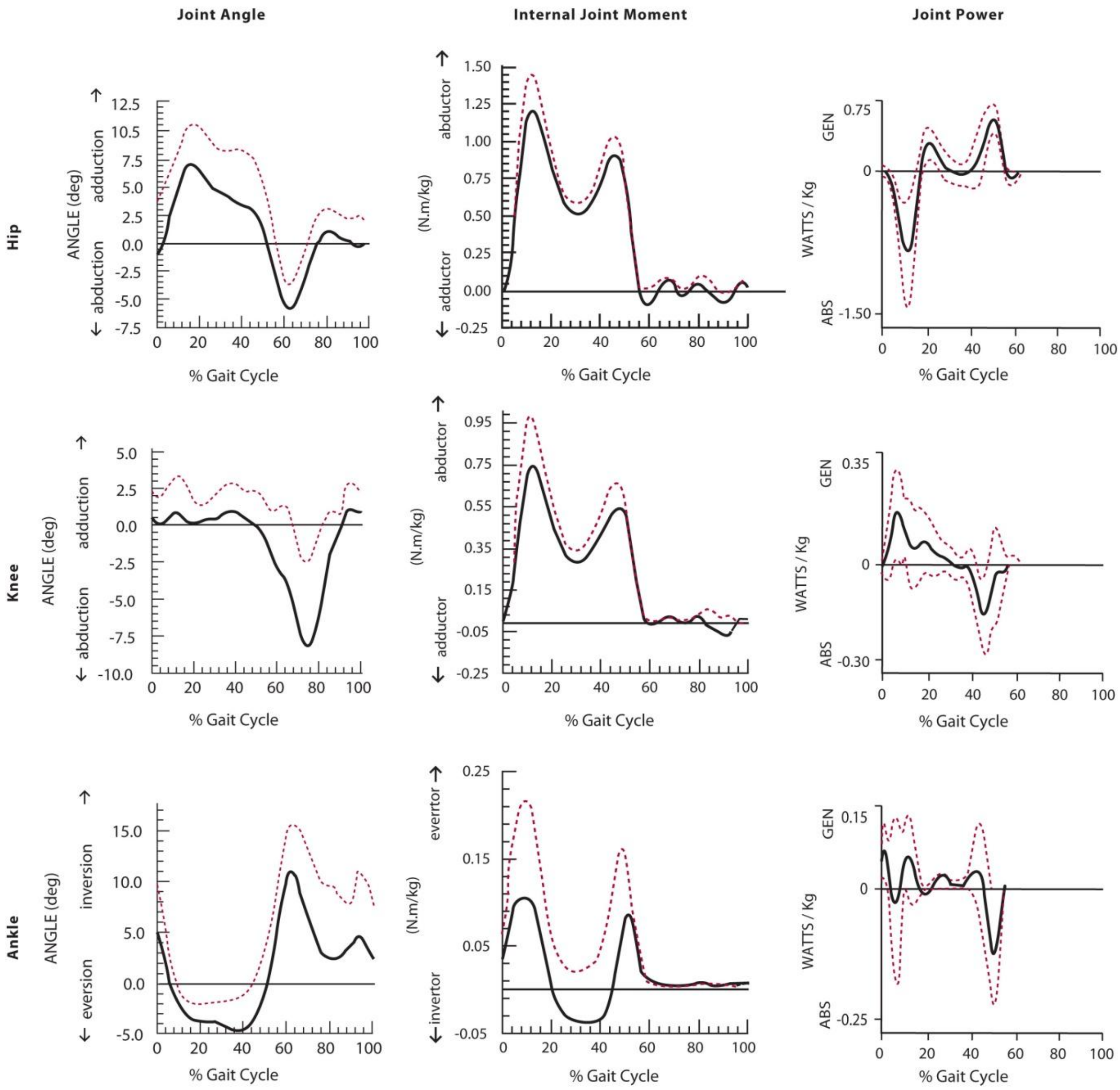

Figure II Angles, moments and powers in the hip, knee and ankle in the frontal plane. Dark line represents the mean while the dotted line represents the standard deviation. Adopted from *Joint structure and function: a comprehensive analysis* (44).

Appendix 4 – Transverse Plane Normative Values

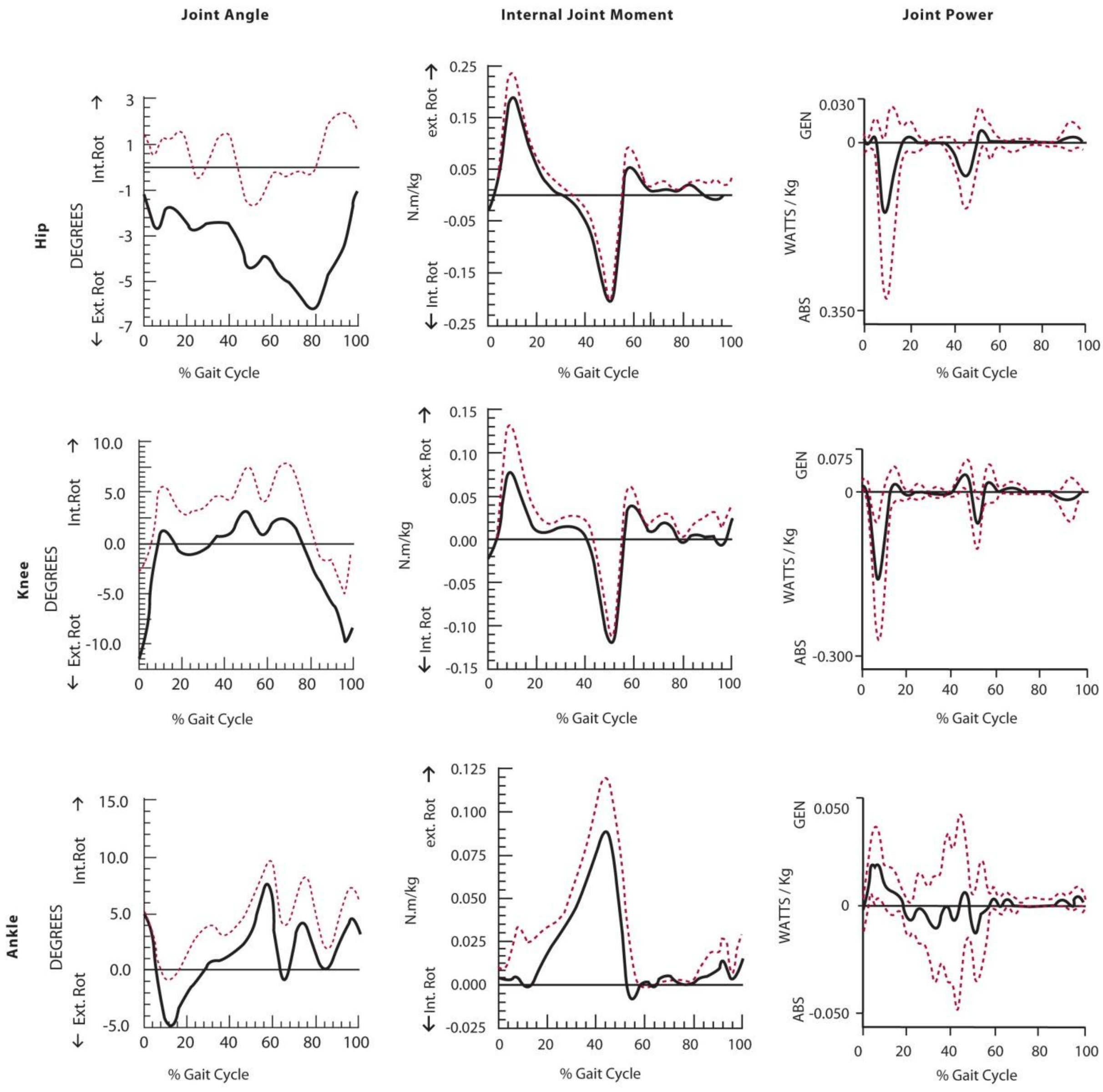

Figure III Angles, moments and powers in the hip, knee and ankle in the transverse plane. Dark line represents the mean while the dotted line represents the standard deviation. Adopted from *Joint structure and function: a comprehensive analysis* (44).

Appendix 5 – Summary of Normative Values for the Knee Joint

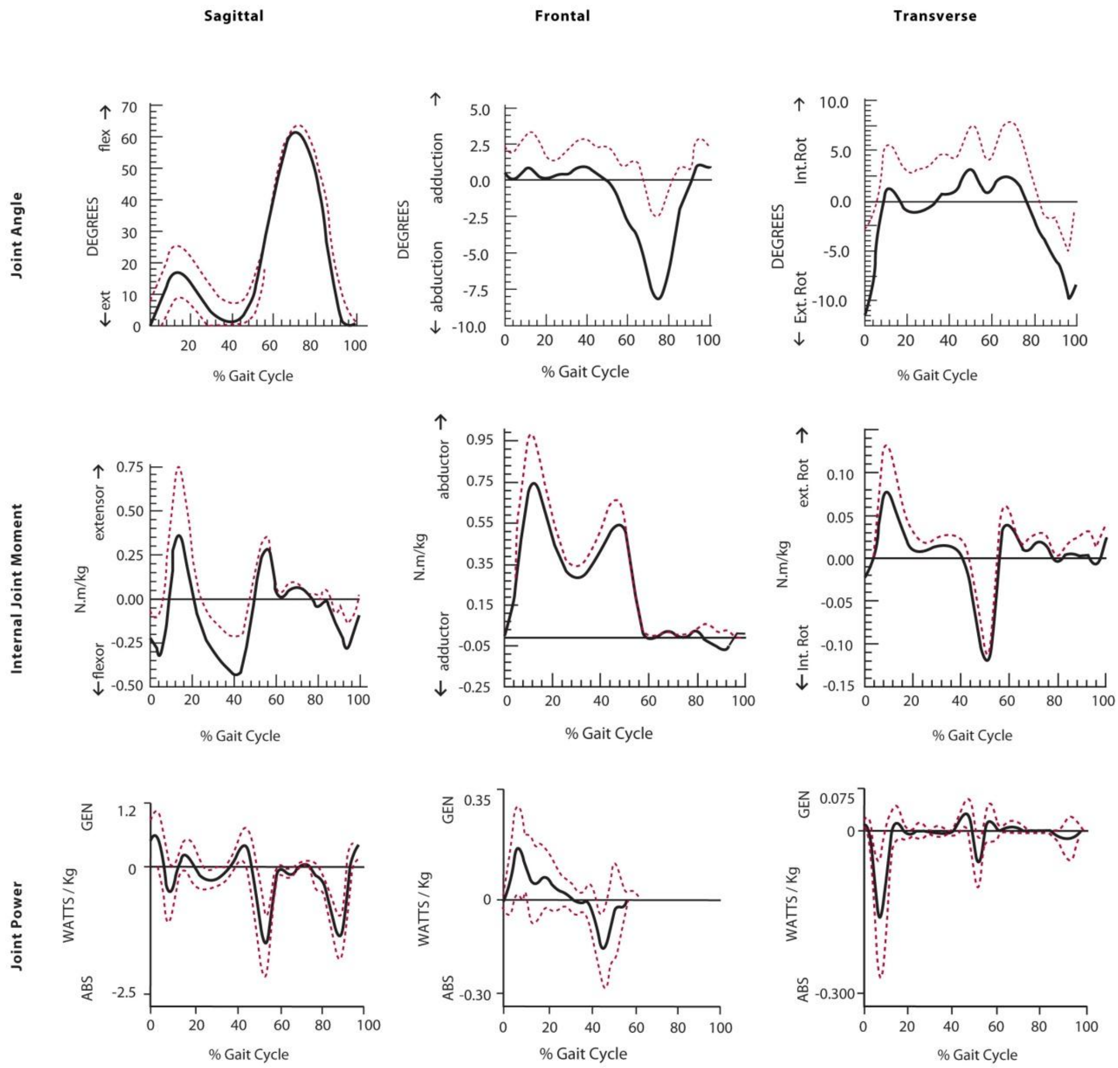

Figure IV Knee angles, moments and powers in the sagittal, frontal and transverse plane. Dark line represents the mean while the dotted line represents the standard deviation. Adopted from *Joint structure and function: a comprehensive analysis* (44).

Appendix 6 – EMG Normative Values

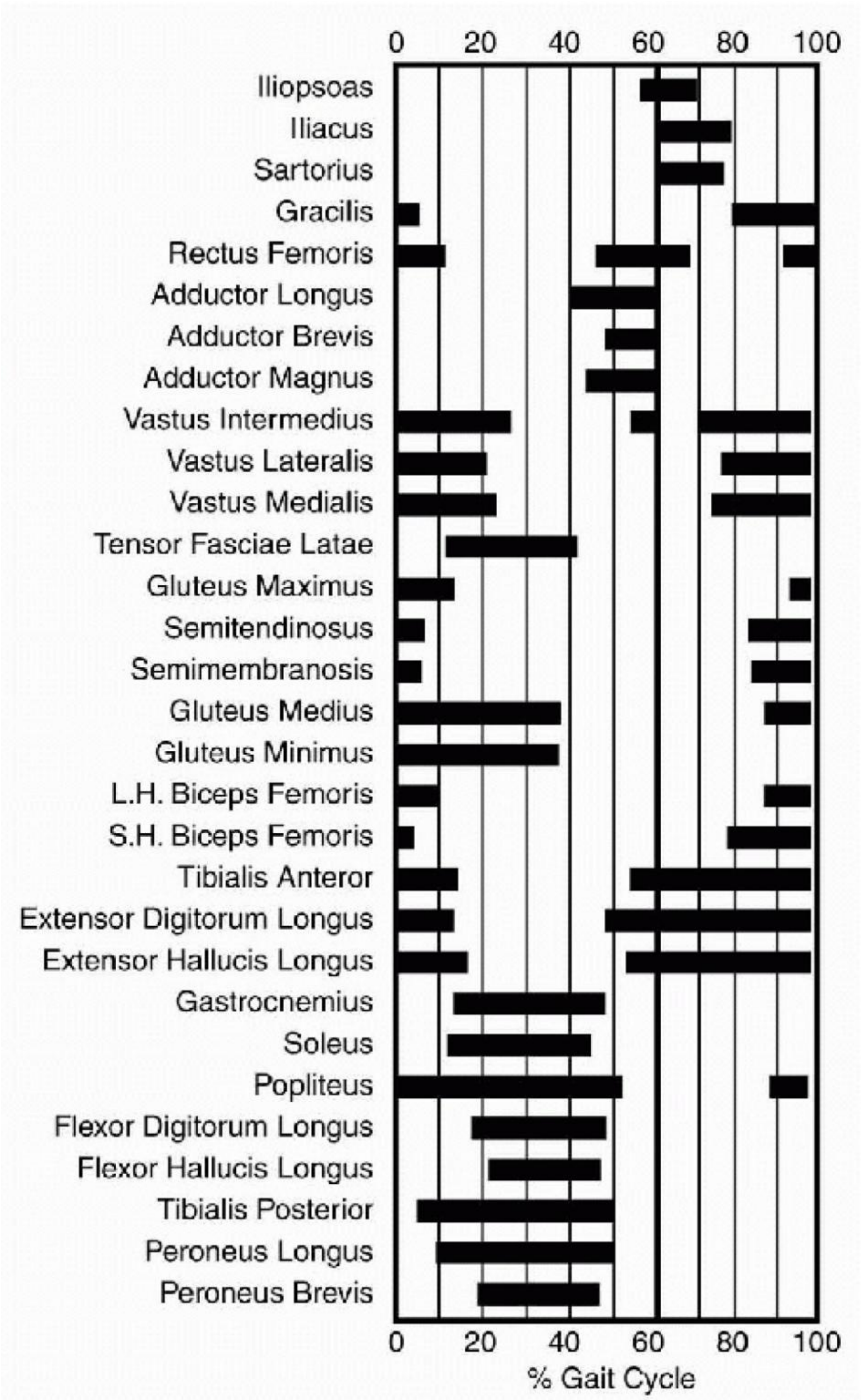

Figure V Normal timing (on-off) of muscles on the lower extremity (60)

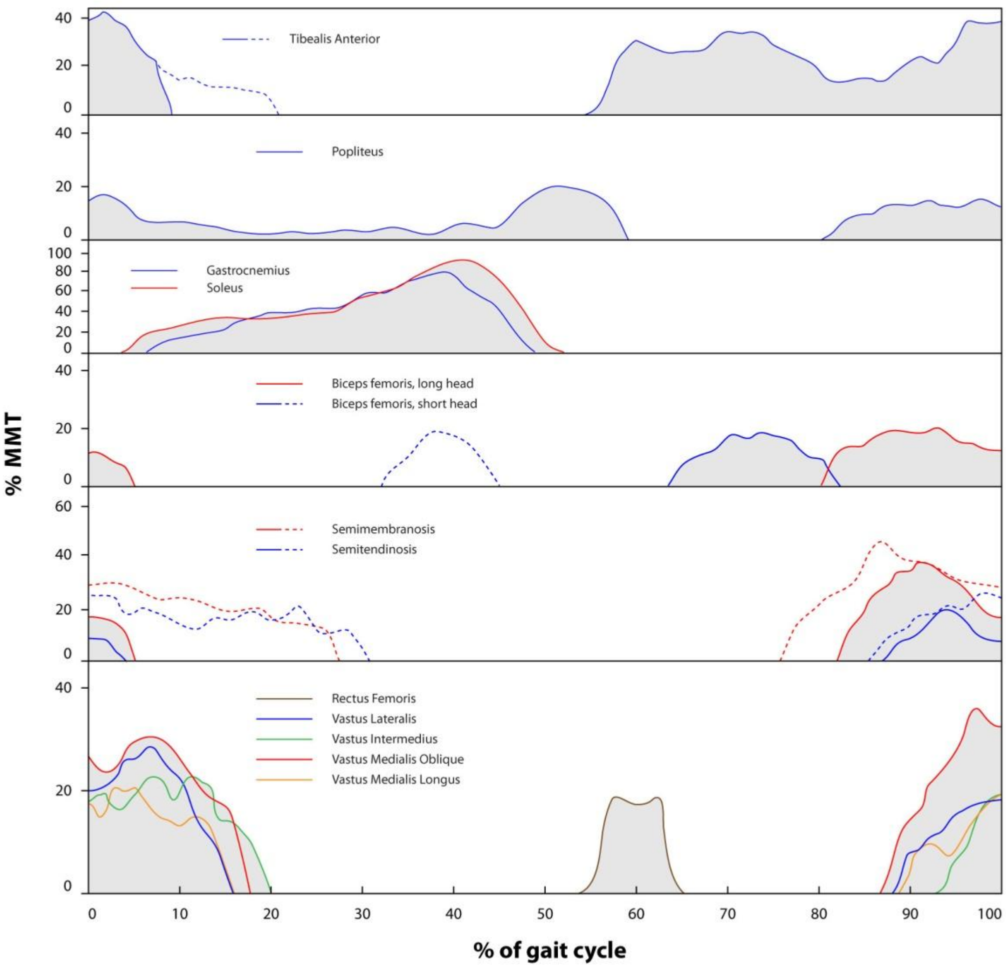

Figure VI Activity of selected muscles around the knee. Thick lines represent results for the majority of the population while doted lines represent possible activity in a minority of the population. Shaded grey area represents the cumulative activity for a given muscle group. MMT – manual muscle test. Modified from *Gait analysis: normal and pathological function* (56)