Aus dem Julius Wolff Institut
der Medizinischen Fakultät Charité – Universitätsmedizin Berlin

DISSERTATION

Three-dimensional kinematics and kinetics of the knee in posterior cruciate ligament reconstructed patients during daily activities

zur Erlangung des akademischen Grades
Doctor medicinae (Dr. med.)

vorgelegt der Medizinischen Fakultät
Charité – Universitätsmedizin Berlin

von

Yanlin Zhong

aus Shandong, China

Datum der Promotion: 30.05.2015

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DISSERTATION

Dreidimensionale Kinematik und Kinetik des Kniegelenks von hinteren Kreuzband-rekonstruierten Pateinten während Alltagsaktivitäten

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List of Abbreviations

3-D	3-Dimensional
ANOVA	Analysis of Variance
BMI	Body Mass Index
BW*Ht	Bodyweight*Height
CL	Contralateral
Deg	Degree
DoF	Degree of Freedom
EMG	Electromyography
GRF	Ground reaction force
HSS	Hospital for Special Surgery
IKDC	International Knee Documentation Committee
LCL	Lateral Collateral Ligament
MCL	Medial Collateral Ligament
OA	Osteoarthritis
PCL	Posterior Cruciate Ligament
PD	Posterior Drawer
PLC	Posterolateral Corner
PCLR	Posterior Cruciate Ligament Reconstructed
PLS	Posterolateral Structure
ROM	Range of motion

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Abstract:

Introduction:

Injury to the posterior cruciate ligament (PCL) typically occurs as a result of serious high-energy trauma. PCL reconstruction surgery is recognized as an important therapy method for such complex injuries. However, it remains unclear whether the PCL reconstructed (PCLR) patients can return to a normal gait pattern. The objective of this study was to assess the kinematics and kinetics of the knee joint in PCLR patients during activities of daily life, aiming to investigate the effect of the operation on the biomechanics and function of the joint 5-10 years after surgery. We hypothesized that the kinematics and the kinetics are not fully restored compared with the contralateral (CL) side and healthy knee joints.

Methodology:

34 PCLR patients and 10 healthy subjects underwent gait analysis while walking, stairs ascending and descending in the gait lab. The motion (kinematics) was tracked with a set of 10 infrared cameras, while the external loads (ground reaction forces and moments) were recorded by two 6 degree-of-freedom force plates. Skeletal kinematics was tracked using a functional approach to determine joint centres and axes from the motion data. External loads and kinematics served as input to an inverse dynamics model for determining the intersegmental resultant forces and moments at the knee. Statistical analysis was performed to determine functional differences among the PCLR, CL and the healthy group.

Results:

The results showed that the reconstructed sides showed reduced knee flexion moment compared with the CL group, the kinematic and kinetic parameters of PCLR knee joints do not appear to show a significant difference compared to the CL knee joints. However, if we compare the parameters between the patients and the healthy subject group, the PCLR and CL group showed significantly reduced knee flexion angles and external rotation angles, while a difference was also observed in knee flexion and external rotation moments.

Conclusions:

Our results show that although patients exhibit a special gait pattern following PCL reconstruction, the gait pattern is distinctly different to that of healthy controls. The detailed

biomechanical analyses suggested that functional deficits do exist in these patients at a medium-term follow-up. The presented study provides unprecedented, quantitative information about the biomechanical function of PCLR patients which could also help to develop a more comprehensive view of the effect of the PCL reconstruction and the impact of surgical techniques in the future.

Zusammenfassung:

Einleitung:

Eine Verletzung des hinteren Kreuzbandes (HKB) tritt typischerweise als Ergebnis des Einwirkens hoher Kräfte auf. Die HKB-Rekonstruktionsoperation wird als wichtige Therapiemethode solcher komplexer Verletzungen anerkannt. Das Ziel dieser Untersuchung ist es den kinematischen und kinetischen Funktionsstatus des Kniegelenks von HKB-rekonstruierten (HKBR) Patienten während Alltagsaktivitäten zu ermitteln, um klinisch relevante Erkenntnisse zur Taxierung der Operationsmethode bezüglich der detaillierten Biomechanik und Gelenkfunktion 5-10 Jahre post Operation zu erhalten. Es wird die Hypothese aufgestellt, dass die kinematischen und kinetischen Parameter im Vergleich zur kontralateralen Seite und zu Probanden mit beidseitig intakten Kniegelenken nicht völlig wiederhergestellt worden ist.

Methodik:

34 PCL-rekonstruierte Patienten und 10 gesunde Probanden wurden einer Ganganalyse mit Gehen und Treppen auf- und -absteigen im Ganglabor unterzogen. Die Bewegungen (Kinematik) wurden mit 10 Infrarotkameras aufgezeichnet während die externen Kräfte (Bodenreaktionskräfte und momente) durch zwei 6-Freiheitsgrad-Kraftmessplatten aufgenommen wurden. Die Knochen-Kinematik wurde durch einen funktionalen Ansatz zur Bestimmung der Gelenkszentren und Bewegungsachsen erfasst. Externe Kräfte und Kinematik dienten als Eingangsgröße eines inversen Dynamikmodells um die intersegmentalen Reaktionskräfte und momente am Knie zu bestimmen. Statistische Analyse wurde vorgenommen um funktionelle Unterschiede zwischen HKBR-Gruppe, kontralateraler Gruppe (CL) und gesunder Probandengruppe zu ermitteln.

Ergebnisse:

Die rekonstruierte Seite wies ein zur kontralateralen Seite reduziertes Knieflexionsmoment auf, allein die Gruppe mit rekonstruiertem hinteren Kreuzband scheint keine signifikanten Unterschiede der kinematischen und kinetischen Parameter im Vergleich zur kontralateralen Seite aufzuweisen. Hingegen zeigen sich beim Funktionalitätsvergleich zwischen Patienten und gesunden Probanden signifikante Unterschiede der Parameter der HKBR- und CL-Gruppe

hinsichtlich verminderter Knieflexionswinkel und externer Rotationswinkel und gleichzeitigen Unterschieden mit knie Flexions- und externen Rotationsmomenten.

Fazit:

Diese Untersuchungen zeigen, das Patienten ein special Gangbild nach HKB-Rekonstruktion aufweisen, das Gangbild deutlich unterschiedlich zu dem in gesunden Kontrollprobanden ist. Die detaillierte biomechanische Analyse deutet an, dass bei diesen Patienten mittelfristig funktionelle Defizite auftreten. Die vorliegende Studie liefert neuartige, quantitative Ergebnisse zur biomechanischen Kniegelenksfunktionalität von Patienten mit HKB-Rekonstruktion welche dazu beitragen könnten zukünftig eine umfassendere Vorstellung des Einflusses der HKB-Rekonstruktion und der Auswirkung von Operationstechniken zu erlangen.

Chapter 1

INTRODUCTION

The description of knee joint anatomy and function is essential to understand the mechanism of PCL injury and reconstruction. The objective of this chapter is to present the knowledge as a basis of this thesis.

1.1 The PCL and its injury

1.1.1 Knee joint stabilizers

The knee joint is an important and complex joint and its stability is mainly dependent on the cooperation of the active stabilizers and passive stabilizers. While the term “active stabilizers” usually refers to the muscles, such as the quadriceps and hamstring muscle groups, the passive stabilizers mainly contain the soft tissues around the knee joint, such as the ligaments, the capsules, the cartilage and the menisci. The major function of these soft tissues is to constrain the joint’s motion and to absorb forces. With this reason, these soft tissues endure a high risk of rupture and injury resulting from heavy impacts occurring in strenuous sports or car accidents. As important passive stabilizers at the knee joint, the ligaments could be divided into collateral ligaments and cruciate ligaments according to their different functions. The two collateral ligaments are named as the lateral collateral ligament (LCL) and medial collateral ligament (MCL) according to their positions. Furthermore, the two cruciate ligaments are named as anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) since they cross the knee joint from the anterior and posterior direction. In addition, there are also other structures like the posterolateral structure (PLS), which improves the stability of knee joint together with the ligaments (*Fig. 1.1*).

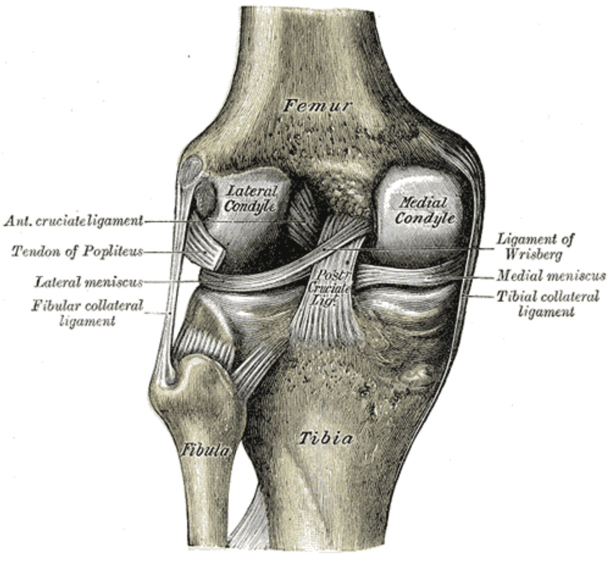

Fig. 1.1: Posterior view of the knee joint which shows the bony structures, the ligaments, menisci and the cartilage [20th U.S. edition of Gray’s Anatomy of Human Body].

The ACL is the primary structure that resists the anterior tibia joint translation, and also works as the secondary rotational stabilizer in the knee joint. This ligament stretches from the medial front of the tibia to the lateral back of the femur. According to the different functions at different flexion angles, the ACL could be further divided into two separate bundles, the anteromedial and posterolateral bundles. It has been previously demonstrated that the posterolateral bundle is tighter at low-flexion angles and the anteromedial bundle acts more at high-flexion angles during the flexion of the knee joint.[1] ACL injuries are common in the sports and daily activities, it is also the most well studied ligament injuries of the knee joint.

The PCL is recognized as the strongest ligament in the knee joint, averages between 32 and 38 mm in length, and inserts approximately 1.0 to 1.5 cm inferior to the posterior rim of the tibia in a depression between the posterior medial and lateral tibial plateaus called the PCL facet.[2] Previous anatomical work showed that the PCL could be further divided into three main portions: the larger anterolateral band, the smaller posteromedial band, and the variable anterior (ligament of Humphrey) and posterior (ligament of Wrisberg) meniscofemoral ligaments.[3] The larger anterolateral bundle has been known as an important posterior stabilizer during flexion, because of the greater tension noticed with increasing flexion angles.[3] As PCL is a strong ligament, the PCL injuries are rare and usually happen in serious injuries like the car accidents.

The MCL is attached to the femur and to the tibia and serves as the dominant ligamentous structure at the medial side. It is a broad, flat, membranous structure and is situated slightly in the posterior on the medial side of the knee joint. It is attached proximally to the medial epicondyle of the femur just below the adductor tubercle, below the medial condyle of the tibia and on the medial surface of its body. The main function of the medial collateral ligament is to stabilize the knee against valgus forces during the movement. Besides, the MCL also functions as the secondary stabilizer at the anterior-posterior direction. It was reported that the long fibers of the superficial medial collateral ligament are the primary stabilizers of the medial side of the knee against valgus and rotatory stress.[4] The LCL is the primary structure at the lateral side to stabilize the knee joint; it supports the knee against pressure from the varus direction.[5] This ligament extends from the lateral epicondyle of the femur above to below the head of the fibula. As the counterpart of the MCL, the LCL is more flexible and less prone to injury.

The posterolateral structure (PLS) has also been recognized as an important stabilizer in the knee joint, which includes the LCL, the popliteofemoral ligament, the popliteofibular ligament and the arcuate ligament complex.[6] The PLS is comprised of three layers of increasing depth. The superficial layer includes the iliotibial tract, the biceps femoris and their extensions. The second layer is composed of the quadriceps retinaculum, the two patella-femoral ligaments and the patellomeniscal ligament. The deepest layer comprises the joint capsule, the popliteal muscle-tendon-ligament complex, the popliteofibular ligament and the lateral collateral, fabellofibular or arcuate ligaments.[7,8] As an important stabilizer in knee joint, PLS usually functions with the PCL and suffer the injuries together.

These ligaments are important structures for sustaining the stability of the knee joint during normal activity. That is the reason why recently various studies have investigated the biomechanical function of ligaments in the last few years.[9-11] However, we noticed that within these studies which concerning knee joint ligaments, the PCL is not quite often studied in spite of its important role in sustaining joint stability. Although the PCL is less prone to injury in daily activities, PCL injuries usually are serious injuries and tend to have a severe impact on joint stability. Our study will focus on the biomechanical function of PCL with a view to obtaining a better understanding of it.

1.1.2 Biomechanical function of the PCL and related structures

The PCL is the primary restraint against the posterior translation of the tibia at the knee joint,[12-14] and it also plays an important role in posterolateral stability of the knee joint.[15,16] Selective ligament sectioning in cadaveric knees has been recognized as an effective method to investigate the biomechanical function of the ligaments. With this method, various studies have been conducted to investigate the function of PCL and its related structures. An early study reported that the PCL is the main structure to prevent posterior translation, while isolated sectioning of the PCL showed no effect on varus or external rotation.[13] Another study by Grood et al.[17] demonstrated that the posterior translation after sectioning of the PCL was greatest at 90 °of knee flexion, and least at 0 °due to the slackening in the posterior capsule. The magnitude of varus angulation and external tibial rotation after PLS sectioning was most noticeable at 30 °of knee flexion, and least at 90 °of knee flexion. This study further showed that when both PCL and PLS were incised, increased posterior translation and external tibial rotation were equally noticeable at both 30 °and 90 °of knee flexion. Veltri et al.[18] reported that combined sectioning of the PCL and PLS led to increased primary posterior translation, primary varus and external rotation, and coupled external rotation at all angles of knee flexion. Based on these findings, examination of the knee at 30 °and 90 °of flexion would be helpful to distinguish an isolated PCL injury from a PCL/PLS combined injury. Measurements of the primary anterior-posterior translation and coupled external rotation may aid in the detection of such combined injuries.

Except for the important role of keeping knee joint stability in the posterior direction, the PCL also plays an important role in knee joint flexion. Von Dommelen and Fowler[19] suggested that the PCL was an important factor in the 'screw-home' mechanism because of the variable region of tautness at different flexion angles. It was shown that when the knee progresses from flexion to extension, the tibia rotates externally relative to the femur. Such movement has been traditionally called the 'screw-home' mechanism of the knee. This mechanism may also consider both the bony anatomy of the knee and the relative lengths of the cruciate ligaments.[20]

The PCL also maintains normal force distribution in the knee joint, which is usually deemed as a potential risk factor for cartilage degeneration. Skyhar et al.[21] reported increased medial compartment pressure when sectioning the PCL, and also increased patellofemoral pressure and quadriceps load while sectioning the PCL and PLS. Kanamori et al.[22] reported that the joint contact force in the medial femoral condyle increased by up to 34% under combined posterior tibial and axial loads in the PCL-deficient knees, while no increase of in situ force was noted in the menisci or lateral articular compartment.

The biomechanical function of the PCL and the PLS highlights the synergistic relationship between them. With this information, it is easier to understand why PLS impairments in combined injury could place the reconstructed PCL graft at a high risk of failure.[23] Furthermore, the importance of recognizing and treating PLS injuries when present in combination with PCL injury has been emphasised, especially since PLS injuries occur in many PCL injuries.

1.2 PCL deficiency and PCL reconstruction

1.2.1 Epidemiology, mechanism and classification of PCL injury

As the main joint supporting the bodyweight in the lower limb, the knee joint is injured quite often in daily life, especially in sports and traffic accidents. From 1999 through 2008, 6.6 million knee injuries were recorded by United States emergency departments.[24] The reported incidence of PCL damage is between 3 and 44% of acute knee injuries. These injuries occur either isolated or combined with other ligament damage depending on the mechanism of injury.[25,26]

Motor vehicle accidents and athletic injuries are reported as the most common causes of PCL injury.[25] Traffic accidents can produce high energy injuries with avulsion stripping and increased associated damage.[27] An investigation from Miyasaka and Daniel[28] reported the PCL incidence to be 3% in general populations, while Fanelli[29] reported the incidence to be 37% in a trauma population. Some studies suspected that the PCL incidence is sport-specific, and it is also apparent from the literature that isolated PCL injuries appear to be more frequent in athletes.[30] Consistent with these observations, Fowler and Messieh[14] also reported on isolated PCL injuries in young patients resulting from various athletic activities. In contrast to the athletic populations, a study from Fanelli and Edson[23] revealed that 95% of PCL injuries seen in emergency department were combined with other ligament injuries. The studies mentioned above show that the incidence and severity of PCL injuries, isolated or combined, may vary greatly depending on the setting in which the patient is evaluated. In general, the isolated PCL injuries usually were results from low-impact trauma which often occurring in sports, while the combined injury usually occurs in high-impact injuries like the car or motorcycle accidents.

Since the PCL could be injured in various activities, understanding the mechanism of injury could be helpful in distinguishing the isolated PCL injury from a PCL combined injury. It is commonly accepted that most of the PCL injuries occur from a posteriorly directed force on the proximal tibia. These injuries usually result from so-called “dashboard” injuries, with the knee in a flexed position, or a fall while the knee is flexed, and the foot is in a plantar-flexed position. For the isolated PCL injury, the most common injury mechanism is forced hyper-flexion of the knee.[14,31] The mechanism of combined PCL and PLS injuries is more complicated，it usually consists of a rotational injury due to a blow to the anteromedial aspect of the flexed knee. This force will first cause injury to the structures in the PLS, then as the rotational force continues, the posterior cruciate ligament is eventually injured.[32] Conflicting opinions were voiced by Wang et al.[6], who suggested that the PCL might be injured first, followed by the PLS, based on observations from surgical findings.

Proper classification and grading of PCL injury could lead to more accurate predictions of outcomes and may aid in setting up treatment protocols. PCL injuries could usually be classified into isolated or combined injuries according to severity, and acute and chronic injuries according to the timing. Both variables will directly affect the treatment and prognosis of PCL injuries. PCL injuries can be graded from I to III based on the degree of posterior tibial translation compared with that of the CL leg. On average, the medial tibial plateau sits 1 cm anterior to the medial femoral condyle. Grade I injuries have 0 to 5 mm of excess posterior translation, but the anterior step-off is maintained. Grade II injuries have 5 to 10 mm of excess translation, which allows the medial tibial plateau to become flush with the medial femoral condyle. Grade III injuries have excess posterior tibial translation greater than 10 mm. Grade I and II injuries represent partial tears of the PCL, whereas grade III injuries represent complete tears and suspicion of associated injuries.[33] A clear classification and grading of acute versus chronic, or isolated versus combined PCL injuries is important for arranging the treatment methods.

1.2.2 Diagnosis and clinical examination of PCL injury

Diagnosis of PCL injury usually starts with determining the patient's previous medical injury history, which includes mode of injury, time since injury, and initial and current symptoms. Patients usually describe the mode of injury as a direct force applied to the proximal tibia, usually occurring when the knee was hyperflexed. Combined injuries can also happen in other knee positions like hyperextension, forced varus or valgus, or dislocation. In high-energy acute injuries, PCL patients may report stiffness, swelling, moderate pain in the back of the knee, or pain with deep knee flexion.[34] Because many patients may not initially have any feelings of disability, such symptoms may only develop with time. Thus, it is important to determine the patients' previous medical history before examining the knee joint.

The main objective of the clinical examination is to evaluate the injury type and to classify the injury level, to determine whether the PCL injury is isolated or combined, and to examine whether the ligament injury is combined with vascular tear or nerve impairment. An examination of the knee usually begins with the assessment of the patient's knee joint alignment and gait. If combined ligament injuries are detected, it is critical for the examiner to check for vascular or nerve impairments around the knee joint. Physical examination is regarded as an effective method to detect the injury, and various physical examination methods have been described in the literature. These methods include the posterior drawer test, the Godfrey test, the quadriceps active test, posterior tibial drop back, decreased tibial step-off, full extension varus and valgus laxity, false-positive anterior drawer test.[33,35] To discriminate isolated from combined PCL injuries, the most effective tests are the posterior drawer test at 30 °and 90 °, posterolateral corner tests, and varus and valgus tests. However, these tests are not as reliable when the knee is swollen; in this case, further diagnostic tests such as an MRI examination are recommended.

The level of PCL injury could be more precisely determined with the help of specialized equipment, such as the KT-1000 knee ligament arthrometer. Imaging tests like MR imaging can provide a direct impression of the PCL injury, and the MRI is the useful equipment not only to assess the PCL injury, but also to check the menisci, articular surfaces or other ligaments for injuries. The last method that should be considered for evaluating a PCL injury is the arthroscopic evaluation under anesthesia, which provides the most detailed examination of the PCL injury, and it is usually applied in cases involving multidirectional instability.

1.2.3 Natural history of isolated PCL deficiency

The natural history of untreated PCL injury is still in debate today. It is generally recognized that the preferred approach in dealing with isolated PCL injuries is conservative treatment. Covey et al.[36] described 3 phases after PCL injury: the first phase is the functional adaptation that takes from 3 to 18 months, the second phase is functional tolerance that takes from 15 to 20 years, and the third phase is osteoarthritic deterioration that usually occurs after 25 years post operation. Torg et al.[37] stated that the natural history and prognosis of PCL injury are correlated with the type and extent of instability, and the functional outcome of PCL injury can be predicted on the basis of the type of instability. Patients with grade III PCL injuries are at risk of recurrent pain and instability, and development of degenerative changes in the knee.

Many authors have reported satisfactory results with isolated PCL injuries that have been treated conservatively. These injuries are usually considered benign in the short term while most of their patients sustained a PCL injury from low-energy trauma including sports injuries.[14,38,39] Cross et al.[40] reported that 47 of 55 sports-related PCL injuries had satisfactory outcomes with conservative treatment. Shelbourne et al.[41] reported that in 133 non-surgical patients with acute isolated PCL injuries, the majority had good subjective results at a 5-year follow-up, while half of the patients were able to return to sports at the same or higher level. Parolie and Bergfeld[42] followed 25 patients with isolated PCL injuries, which resulted from athletic activities, 80%

were satisfied with their knee function, and 68% could return to their previous level of activity after 2 years.

However, there are also different voices regarding the view that the isolated PCL injury could be best treated with conservative methods. Some long-term studies of nonoperatively treated PCL injuries have shown that the pain is going to be a problem and also point towards a high incidence of arthritis.[43,44] Keller and co-workers[43] found that 90% of patients in a cohort of isolated PCL injured patients were complaining of pain after 6 years. Clancy and co-workers[44] found degenerative changes of the articular cartilage at 2 years after PCL injury in 20% of the patellofemoral and 70% of femorotibial joints, with a 48% incidence of degenerative changes in knees with chronic PCL injury. The debate between conservative and operative treatment is not yet settled, however, the extent of injury to the knee is thought to be a key determinant for the choice of treatment. It has been suggested that knees with less than grade III isolated PCL injury from low-energy trauma can be treated conservatively, while knees with grade III isolated PCL injury and combined PCL and posterolateral instabilities should be treated with surgical reconstruction.[45]

1.2.4 Surgical techniques for PCL reconstruction

Arthroscopic PCL reconstruction has currently been recognized as the main method to manage the PCL combined injured knee joint. Various surgical techniques of PCL reconstruction have been described, however, the optimal surgical technique is still being sought. There are two different techniques regarding the type of tibial fixation: the transtibial technique and the tibial inlay technique. A study from McAllister et al.[46] recommend that the tibial inlay technique should be performed using either the arthroscopic or the open surgery technique. Ahn et al.[47] performed a follow-up study with MRI in 42 of 61 patients with a transtibial PCL reconstruction technique, the results showed that there was no graft disruption and no enhancing signal at the tibial insertion site in any patient. Markolf et al.[48] suggested that tibial inlay reconstruction is superior to transtibial reconstruction when subjected to cyclic loading in a cadaveric model. However, clinical studies have failed to show any difference in surgical outcomes regarding transtibial or tibial inlay fixation.[47,49-51]

Although satisfactory results of double-bundle PCL reconstruction were recently reported,[52] the debate between single-bundle and double-bundle PCL reconstruction remains unresolved. Multiple studies have evaluated the biomechanics of PCL reconstructions using either the single-bundle or double-bundle techniques with varying results. Burns et al.[53] recommended the use of single-bundle PCL reconstruction, while Bergfeld et al.[54] claimed that there was no biomechanical advantage in performing a double-bundle reconstruction compared with the single-bundle technique. However, many studies supported the double-bundle techniques, arguing that single-bundle grafts do not completely replicate the intact knee biomechanics.[55,56] Harner et al.[57] found that a double-bundle reconstruction could better accommodate both normal knee laxity and PCL forces during knee flexion. Earlier studies also supported the idea that only the double-bundle graft could restore normal knee laxity across the full range of motion.[55]

There are also studies did not support the superiority of either the single- or double- bundle PCL reconstruction. In 2009, Kohen and Sekiya[58] performed a systematic review comparing single-bundle versus double-bundle reconstructions, they concluded that there is no evidence to show which reconstruction method is much better than the other. Wang et al.[59] compared the outcomes of single-bundle versus double-bundle PCL reconstruction of 35 patients at a 2-year follow-up and concluded that both reconstructions were capable of producing acceptable clinical results with high rates of satisfaction in medium-term follow-up. A study from Hatayama et al.[60] compared single-bundle with double-bundle arthroscopic PCL reconstructions in 20 patients and concluded that there is no significant difference in short-term posterior stability between the two groups using hamstring tendons. In 2011, Kim et al.[61] compared the clinical outcomes of the two surgical techniques, the authors found that the double-bundle PCL reconstruction did not appear to have advantages over single-bundle PCL reconstruction. In the same year, Yoon et al.[62] published their clinical results which compared the effect of these two techniques with a minimum 2-year follow-up. Furthermore, they concluded that it is unclear if the double-bundle reconstruction is notably superior to single-bundle reconstruction.

Conflicting issues also focused on the angle of knee flexion and tunnel placement during graft fixation. Bomberg et al.[63] stated that the PCL graft should be slightly tighter at knee flexion, while Veltri et al.[64] indicated that the best position of the knee for PCL graft tension is full extension. Furthermore, Harner et al.[56] found that graft fixation at full extension may overconstrain the knee and elevate in situ graft forces, whereas fixation with the knee in flexion and under an anterior tibial load could best restore intact knee biomechanics. In addition, biomechanical study showed that the PCL demonstrates non-isometric behaviour over the normal range of motion.[65] Galloway et al.[66] found that a femoral tunnel that was non-isometric by intraoperative measurement most closely reproduced the intact knee's posterior motion limits. Race and Amis[55] found similarly that non-isometric positioning of the graft best corrects abnormal posterior laxity. The use of grafts is also in dispute, there are advantages and disadvantages to both auto- and allografts. However, clinical results showed no significant difference between these two types.[67]

Regardless of the technique used, any reconstruction that attempts to restore knee kinematics through isolated PCL reconstruction without addressing PLS or other ligamentous injuries could easily result in early failure. Therefore, concomitant arthroscopic PCL reconstruction and PLS reconstruction are recommended in knees with combined PCL and PLS injuries.

1.2.5 Clinical results after PCL reconstruction

Until now, various clinical results after PCL reconstruction have been reported by different studies. Garofalo et al.[68] conducted a study to investigate the reconstruction results of 15 isolated chronic PCL injured patients. After 2-year follow-up, subjective International Knee Documentation Committee (IKDC) subjective score improved on average from 36.6 to 66.34. Patients showed improvement on Lysholm, Tegner, and Hospital for Special Surgery (HSS) scales postoperatively. Normalization of posterior drawer (PD) was achieved in 20% of patients. Cooper and Stewart[69] reported a 2- to 10-year follow-up study of 44 PCL reconstructed (PCLR) patients and found that 32 cases have a 1+ or 2+ PD. Fanelli and Edson[70] reported a 2- to 10-year follow-up of 35 PCL reconstruction cases, in which 46% of patients had a normal PD after the operation. Furthermore, Telos stress radiograph showed a mean side-to-side difference of 0 to 3 mm in 52.3% of patients. The mean Lysholm, Tegner, and HSS knee scores after operation were 91.2, 5.3, and 86.8, respectively. Fanelli and Edson[71] reported another 2- to 10- year follow-up of combined PCL and PLS reconstruction in 2004, where normalization of the PD was achieved in 70% of patients, and posterolateral stability was restored to normal in 27% and tighter than normal in 71% of patients. Chen et al.[72] investigated the outcomes of PCL reconstruction using single-bundle quadruple hamstring tendon autografts in a 2-year follow-up: 89% of patients reported good or excellent results, while 29% of patients had posterior translation of 2mm or less, and 56% had 3 to 5 mm posterior translation. Cain and Clancy[73] reported a 2-year follow-up of 32 patients who underwent double-bundle PCL reconstruction, 88% of patients were able to return to their previous participating in athletics, and 73% of patients reported a normal or near normal final IKDC score. Nyland et al.[74] published 2-year follow-up results of 19 patients with PCL injury combined posterolateral instability, the PCL was reconstructed using a double-bundle technique. At final follow-up, PD normalized in 11 of 19 patients, most of patients had a normal or nearly normal IKDC subjective assessment at final follow-up, and most of patients had good results in terms of the final Lysholm knee score. Another study from Noyes and Barber-Westin[75] found that posterior laxity was present during stress radiography in all 19 patients with a mean 5.5 mm compared with the CL knee. Similarly, Hammoud et al.[76] also suggested that according to the long-term studies, normal stability is not restored with current techniques.

It is commonly accepted that PCL reconstruction could help the patients reduce pain and yield satisfactory early clinical results. Higher self-reported knee scores compared with the pre-operation level were found in almost all the PCL reconstruction studies. Although PCLR surgery is an effective method to reduce pain and to help patients gain a better quality of life post injury, the main problem after surgery is the residual laxity after which has been demonstrated by various studies. This residual posterior laxity is difficult to interpret considering the aforementioned large number of patients with excellent self-reported postoperative knee scores. Residual laxity potentially may affect the function in more demanding activities, such as sports participation, and may not be problematic in routine daily activities. Apart from laxity at posterior translation, there are also problems in other directions. Gill et al.[77] evaluated 7 single-bundle PCLR patients during a single-legged lunge both preoperatively and postoperatively. The authors found that there remained an inability to fully restore mediolateral tibial translation as well as patellar rotation and tilt, all of which differed significantly from the healthy knee following PCL reconstruction; the authors thought these subtle changes had implications for the well-documented development of degenerative joint disease of medial compartment and patellofemoral compartment.

1.3 Aims and goals

Despite the numerous studies which investigated the post-surgery outcomes, we noticed that most of the studies focused on comparing the objective knee scores with the self-reported scores, while the objective knee scores seem to lag behind those of subjective scores after surgical reconstructions. The conflicting results of the subjective score and objective clinical assessment indicate that perhaps the knee joint function could not been fully restored by the reconstructive surgery. According to the osteoarthritis incidence after surgery, we concluded that the deficiency of knee joint function may involves not only at the knee joint motion (kinematic), but also at the internal joint loading (kinematic) of structures. However, the clinical methods cannot provide the necessary details to identify more subtle changes in motion/kinematics or the internal loading of the structures. Although more recently advanced techniques to accurately track skeletal motion and assess 3-dimensional kinematics and quantify the kinetics of the knee have been developed, such methods have not yet been widely applied for assessing function after PCL reconstruction surgery.[78-80] In these techniques, the capture of human motion is generally performed in gait analysis by attaching reflective markers to the subject's skin, and the repeatability and reproducibility of these methods were already proved through the earlier study.[81] Based on the computational models of the musculoskeletal system, it is also possible to directly assess the internal loading of knee joints.[78] These advanced techniques may shed some light on the kinematic and kinetic study of PCL reconstructive surgery.

Based on the clinical laxity assessment and the cadaver study from the literature,[68,69,82] it is reasonable to suspect that whether the kinematic and kinetic function of knee joints could be restored through the reconstructive surgery. It is important to clearly understand the kinematic and kinetic functional status of the reconstructed knee joints during daily activities, which can not only provide functional feedback to the clinicians to improve the surgery technique, but also point out the risk factors for knee joint health in the long term. Different from the traditional clinical methods, three-dimensional gait analysis for measuring knee joint kinematics and kinetics can be used to describe the functional gait patterns in PCL reconstructed individuals. Gait analysis is a reliable, non-invasive and safe method of describing lower extremity joint function, providing important information about forces and movements affecting the lower extremity during activities of daily living. Therefore, the objective of our study was to utilize the gait analysis method to explore the kinematic as well as kinetic functional status of the knee joint in PCLR 5-10 year post-operative patients during walking, ascending and descending stairs. To achieve the goal of our study, it was essential to check whether the function of reconstructed side is restored compared with the CL side in PCLR patients, and with the knee joint in healthy subjects. In this case, a cohort of healthy subjects was also included in our study for comparison. In our study, we could apply the gait analysis and inverse dynamic technique to detect the kinematics and kinetics of knee joint during daily activities. The inverse dynamic is so called because we work back from the kinematics to acquire the kinetics which is responsible for the motion.

According to the early study about the PCLR patients, it was found that there was a high incidence rate of degenerative changes in these patients.[6] It could be hypothesised that the PCL reconstruction cannot fully restore the knee joint function, and the post-surgery patients may have a high risk of knee joint osteoarthritis (OA). To assess the risk of OA incidence in post-surgery patients, the most convincing method is to apply a long-term follow-up in a large number of patients, with X-ray based assessment of cartilage health. However, before this time- and effort-consuming follow-up study, it is logical to obtain more evidence of OA incidence in patients using a much easier method. Consistent with the advantage of gait analysis we described above, more and more studies have reported that the gait analysis results are correlated with the knee joint OA,[83-86] which makes it possible to use the gait analysis method to assess the risk of OA in the PCLR patients. Therefore, the other objective of this study was to evaluate whether the PCLR patients are at a risk of OA after surgery.

Gait analysis has been used to clarify the kinematics and kinetics of OA knees in many studies. It has indicated that the OA patients walk slower, with reduced stride length and lower single-limb support compared with healthy subjects, and the severity of knee OA severity could be classified by the spatiotemporal parameters from the gait analysis.[87] Besides, the OA patients showed decreased excursion in sagittal and axial tibial rotation during gait.[86] The kinetic function of OA patients was also different from the healthy subjects. The adduction moment has been shown to be directly associated with the distribution of load and progression as well as severity of OA.[83-86] Furthermore, greater internal rotation moment was found in knees with OA compared to asymptomatic knees in the gait analysis.[88] In our study, we also wanted to know if the functional performance of our PCLR patients would be similar to that of the OA patients.

The read-out parameters in this study would be: spatiotemporal parameters (walking speed, stride length, single-limb support time), kinematic parameters (flexion-extension angle, adduction-abduction angle, internal-external rotation angle), kinetic parameters (flexion-extension moment, adduction-abduction moment, internal-external rotation moment). Vertical ground reaction force (GRF) of the patients was recorded in order to check if the patients shifted their body weight unconsciously when performing the daily activities. The mid-thigh circumference of the limbs in the patients was recorded to check the gross morphology changes. Although the subjective score is not the focus of our study, we still wanted to know if the scores of our patients would be similar to the excellent scores reported in the literature.

Therefore, in this study, we would like to figure out:

1. If the PCLR patients could report the good subjective score 5-10 years after surgery.
2. If the kinematics and kinetics of PCLR patients are back to the normal status compared with the healthy subjects.
3. If the patients could show normal spatiotemporal parameters during walking compared with the healthy subjects.

In this study, we hypothesized that:

1. Our PCL patients could get an acceptable IKDC subjective score.
2. The three-dimensional kinematics and kinetics of the PCLR joint will not be fully restored 5-10 years after surgery compared with the healthy knee joints.
3. We expected that our PCLR patients would show slower walking speed, reduced stride length and single-limb supporting time during gait, with decreased knee excursion at the sagittal and axial tibial rotation, and also higher adduction moment and greater internal rotation moment at the coronal plane compared with the healthy subjects.

Chapter 2

Methodology

The aim of this chapter is to provide the overview of our measurements. The participating subjects, measuring equipment and processing techniques in our study will be described in this chapter. Furthermore, the surgical procedure, as well as the principle of gait analysis will be introduced.

2.1 Gait analysis

Three dimensional gait analysis is a specialized medical method to investigate the gait pattern in subjects. Gait analysis can be used in sports biomechanics to help athletes to raise sports efficiently or to identify posture or movement related problems, and can also be used in the clinical field to assess the injury and recovery status of patients. The equipments used for gait analysis are high-speed video cameras and retro-reflective markers, and a sports lab which is capacious enough to allow subjects to perform different movements and engage in various activities (*Fig. 2.1*). Two kinds of data can be recorded in gait trials: kinematic data (data of motion) and the kinetic data (data of force). Several cameras should be used in order to record trajectories with high quality. The number of cameras is dependent on the entire space in which the measurement takes place. The cameras should be arranged carefully to make sure that each marker is visible at least to two cameras during the activities. In order to record kinetic data, force plates which can record the force component in different directions are needed. The recording of the kinematic and kinetic data should be synchronized so that the motion and force can be recorded at the same time.

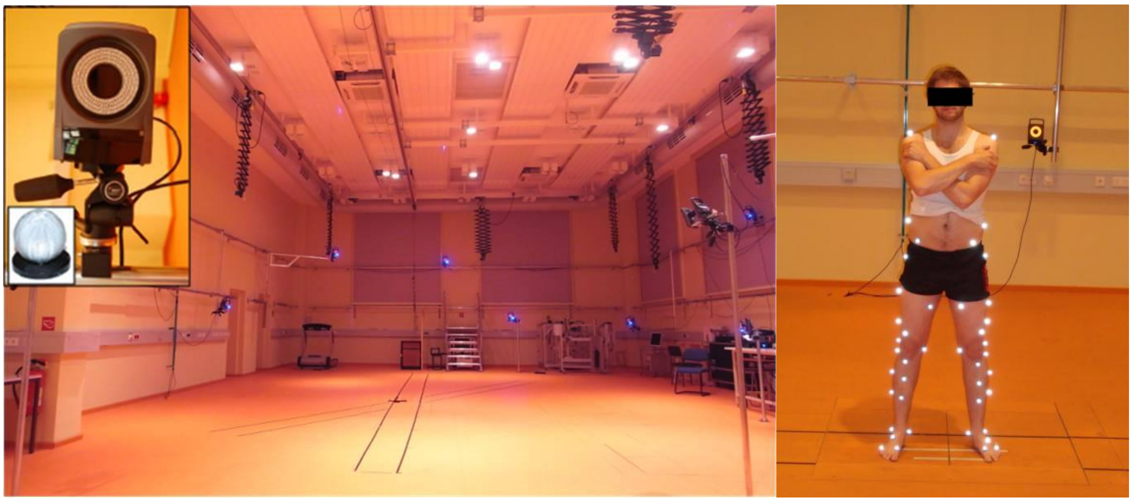

Fig. 2.1: Left picture shows the infrared video camera and a retro-reflective marker used in the gait lab. Central picture shows the gait laboratory, equipped with ten infrared cameras. Ten cameras were set in the gait lab shown here. Right picture shows one subject standing on the force plates. The light is reflected by the retro-reflective markers attached to the subject's skin.

Before performing 3-D measurements, the camera system needs to be calibrated with the help of a wand, which is equipped with markers with a predefined distance between them. The wand is randomly waved around in the space which is to be calibrated. After that, the wand is placed at the center of the space being measured, and the wand serves as a reference object to define the origin of the global co-ordinate system, using the x-, y- and z-axes. During data acquisition, the 3-D positions of the markers are recorded for each frame while the subject performs various movements in the measurement space (*Fig. 2.1*). The synchronized force data is collected from the force plates, which make it possible to process the kinetic data with the inverse dynamic technique. The GRF is the force exerted by the ground on a body in contact with it, and could be measured by the force plates in biomechanical study.

In this study, we used the inverse dynamic technique to computer the kinetics which was responsible for the motion in the lower limb, while the moment of the knee joint was emphasized in our research. The inverse dynamic technique is a method to computing forces and moments in the biomechanical study, which was based on the kinematics of a body and the body's inertial properties. This method was so-called because it works back from the kinematics to the kinetic that drive the motions. In this method, the link-segment models were usually used to represent the mechanical behaviour of interconnected segments. It is represented that when there is contact of the lower-limb with the ground, the forces between the limb and the ground can be measured with the help of force plates. The forces collected by the force plates can be used as the input data for the link-segment models to calculate the kinetic of joints in the lower-limb. Combining with the gait analysis and inverse technique, we can not only monitor the kinematics of the lower-limb, but also understand the kinetics that drives the motions.

Gait analysis and inverse dynamic technique are powerful tools for measuring the kinematic and kinetic function of subjects in biomechanical study. With the help of inverse dynamic technique, the gait analysis of various subjects can provide important information to clinical workers and sports scientists. In our study, the three-dimensional gait analysis was applied on the patients and healthy subjects to investigate the kinematic and kinetic knee joint function during walking, stairs ascending and descending. The spatiotemporal parameters, kinematic and kinetic parameters were processed and analysed in our research.

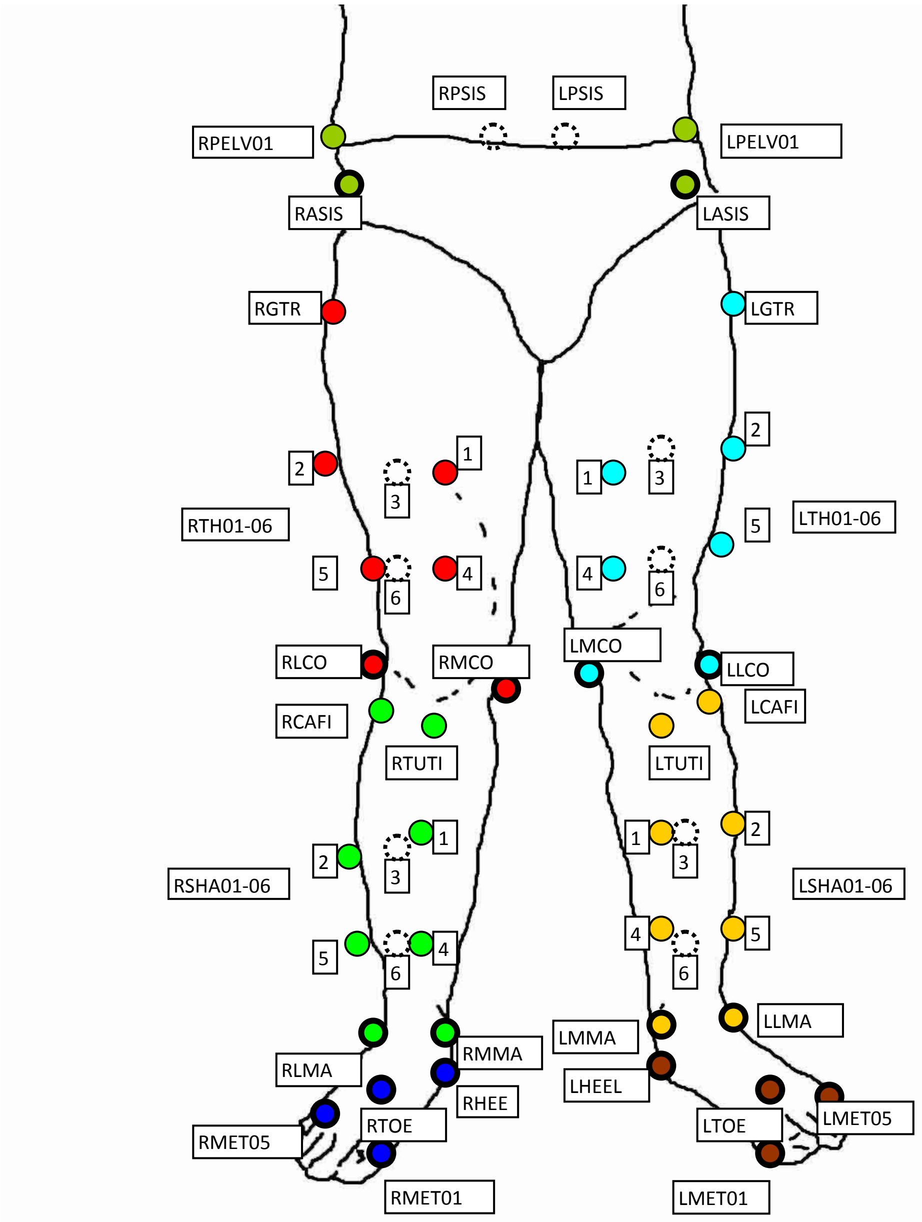

Fig. 2.2: The figure showed the marker set protocol which include 52 marks, with different colour markers representing different parts of the lower limb: hip, left thigh, right thigh, left shank, right shank, left foot, right foot (6 on the pelvis, 18 on the thigh, 20 on the calf, 8 on the foot). The important indicators of the bone position such as the greater trochanter, medial/lateral epicondyle, medial/lateral malleolus, anterior/posterior superior iliac spine are marked in this figure.

2.2 Subjects

2.2.1 Demographics

34 PCLR patients (24 men and 10 women, mean age 35.9 ±10.3 years, mean weight 86.9 ±13.3kg, and mean height 176.8 ±8.1cm, Body Mass Index (BMI): 27.8 ±3.4kg/m^2) and 10 healthy control subjects (7 men and 3 women, mean age 30.4 ±4.1 years, mean weight 67.4 ±9.5kg, mean height 169.3 ±10.2cm, BMI: 23.5 ±2.1 Kg/m^2) were recruited to participate in this study which took place from 2012 to 2013. The patients had either isolated or combined PCL injuries incurred in motorcycle accidents or sports, and underwent PCL reconstruction surgery at the Centre for Musculoskeletal Surgery between 5 and 10 years ago. Of the 34 PCLR patients, 5 patients had isolated PCL injuries, 16 patients had combined PCL-PLS injuries, while in a further 13 patients all the cruciate ligaments and collateral ligaments were injured. Exclusion criteria were a history of lower limb injury at the CL side, serious injuries of the joints of the ipsilateral hip and ankle, and obvious discomfort at the involved knee joint like knee joint pain or swelling.

The study was approved by the ethics committee of the Charité – Universitätsmedizin Berlin (EA2/071/10; EA2/055/10). All subjects were informed about the measuring procedure and provided informed consent prior to the start of the measurements. All the patients filled the IKDC subjective knee evaluation form before the gait analysis.

2.2.2 Surgical procedure

Surgery was carried out by three different surgeons who used identical surgical techniques for all patients, while the senior author performed more than 90% of the procedures. A single-bundle (anterolateral) arthroscopically assisted PCL reconstruction was performed using the conventional tibial tunnel technique and femoral single-incision technique with biodegradable interference fit fixation. At the tibial site, a hybrid fixation with suture backup was used. The surgeons used maximum manual pretension in approximately 60-80 °of flexion according to the clinical routine. A device to create maximum pretension as described by Fanelli and Edson was not used in the surgery.[71] Surgeons further have pretreated all cases with a PTS Splint (Fa. Medi, Bayreuth, Germany) to minimize the risk of a fixed posterior subluxation. The primary graft choice was a 5-fold semitendinosusgracilis tendon autograft from the ipsilateral knee.

Posterolateral corner (PLC) stabilization was done with a modified Larson technique through two miniincisions by use of a CL semitendinosus tendon. In selected cases (e.g., refusal of CL graft harvest and depending on availability), fresh frozen allograft tissue was primarily used. If necessary, ACL reconstruction was done using an arthroscopic single-incision technique, with biodegradable interference screw fixation of 4-fold CL gracilis tendon autograft or allograft tissue. Postoperative care consisted of immobilization of the knees for 6 weeks in a straight posterior tibial support splint (PTS Splint), allowing gradual passive mobilization into flexion with the patient in the prone position. Crutches were used as tolerated for 3 to 6 weeks. Mobilization beyond 90 º was allowed after the sixth week. Active hamstring contraction exercises were prohibited for 3 months.[89]

2.3 Measurement protocol

All subjects were asked to walk at a self-selected pace on a 10-meter walkway and stair ascent and descent (step height 20 cm) at a normal self-selected speed until at least three successful trials had been recorded for each activity. Reflective markers were placed bilaterally on the subject's pelvis, thigh, shank and foot. Individual markers on the greater trochanter, medial/lateral epicondyle, medial/lateral malleolus, anterior/posterior superior iliac spine were important indicators of the bone position and were identified while standing motionless. (*Fig. 2.2*) Knee kinematic data were measured using a real-time motion capture system (10-camera motion capture system, Vicon, Oxford, UK) at 120 Hz. Knee kinetic data were calculated using an inverse dynamics technique with the help of two 6 degrees of freedom (DoF) force plates (AMTI, Watertown, MA). To increase the accuracy of the measurements, we kept the subjects from knowing when data were actually being recorded and where the force plates were. Patients performed at least three successful level walking and stairs ascending as well as descending trials in the gait lab for both sides. (*Fig. 2.3*) Those walking trials were considered successful where the patients could hit each force plate with one foot, and only one foot on each force plate. During stairs climbing, the patients stood on the first force plate with feet, the second force plate would record the force data during climbing when one of the feet hit it clearly. At least three valid trails were conducted separately for both sides during ascending and descending stairs.

The mid-thigh circumference was also evaluated as the structural parameter in the affected and unaffected limbs of the PCLR patients. The data from the motion capture system and the force plates were collected, and the markers on the patients were labelled so that they could be recognized by the software for further processing. (*Fig. 2.4*) Vertical GRF of the patients were recorded in order to check if the patients shifted their bodyweight unconsciously when performing the everyday activities. All the patients were asked to complete the IKDC subjective knee evaluation forms before the measurement.

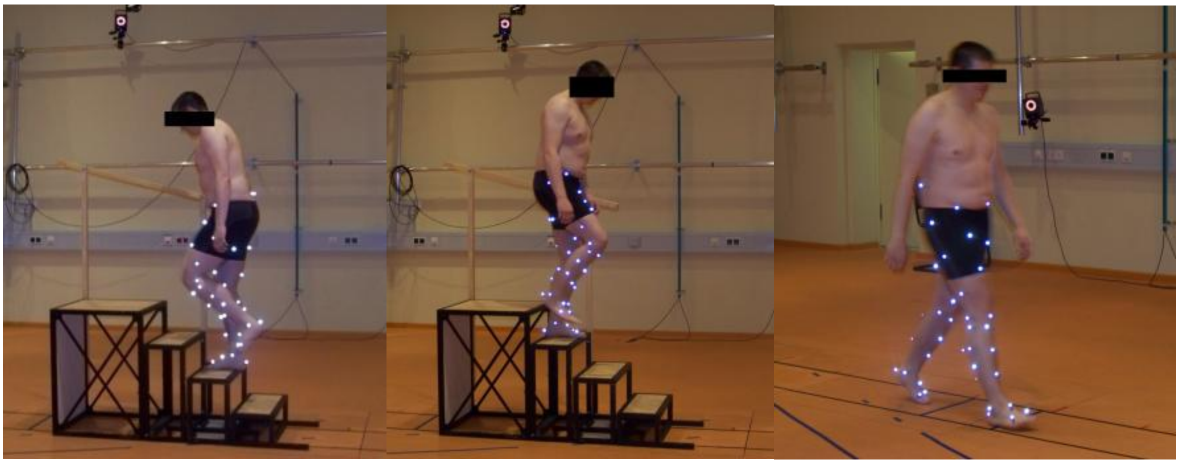

Fig. 2.3: A patient engaged in daily activities in the gait lab, such as level walking, stairs ascending and descending.

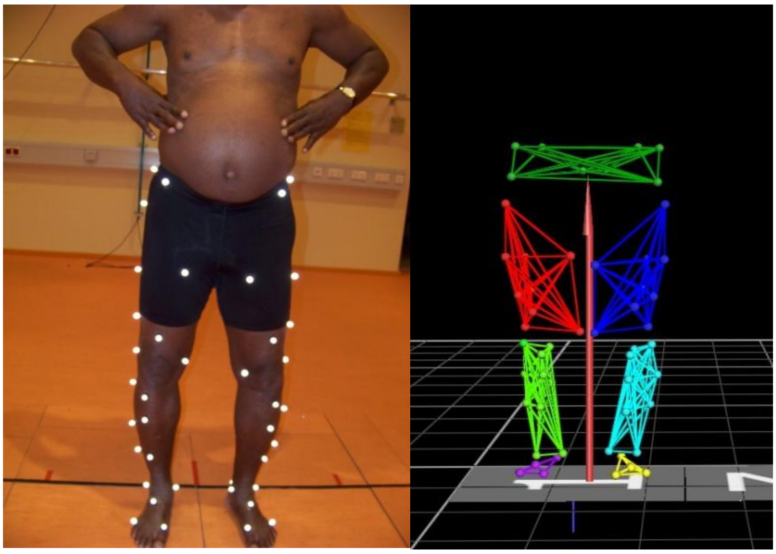

Fig. 2.4: The markers on the patients were labelled and recognized by the software of motion capture system (Vicon, Oxford, UK).

2.4 Data processing and statistical methods

With the method reported by Trepczynski et al.,[78] patient-specific musculoskeletal models of each subject's lower limb bones and muscles were derived from the patient's medical record, together with a reference model based on the Visible Human dataset. These models included bones, 3-D muscle paths, and anatomical landmarks. The landmarks were used to describe bone geometry and define local coordinate systems. Segment circumferences were collected at multiple locations to determine the inertial parameters of segments, based on relative segment masses and approximating the segments' mass distributions using simple geometric relationships. Segment masses were computed using reference tissue density parameters.

The position of joint centers and joint axes were calculated from the relative motions of the marker clusters from neighboring segments during specific reference motions, which could provide the range of motion to functionally determine the kinematic parameters.[90,91] To derive joint kinematics from motion data, a model of the lower limb kinematics was defined, which contained joint centers and axes, local coordinate systems, and DoFs for each joint. The hip and ankle were modelled as 3 DoF ball joints, and the knee joint was modelled based on the geometry of the femoral component, which defined the 6 DoF relative transformations between the femoral and tibial segments.[92] This model was then fitted to the segment motion for each time step where the model joint centers were aligned with the functional joint centers, the model landmarks were best fitted with respective marker positions, and the model joint axes were oriented onto the functional joint axes.

Based on the segment and joint kinematics, the position of muscle attachment and via points of the muscle paths were determined for every frame, which allowed the calculation of muscle lever arms at the joints.[93] Segment and joint kinematics, GRFs, and inertial parameters were all used as inputs to an inverse dynamics approach to yield the inter-segmental resultant moments and forces at the ankle, knee, and hip.[94,95] The inverse dynamic approach could be explained that when there is contact of the limb with the ground, the forces between the limb and ground in this close-chain could be measured with the help of equipment. In our study, we used two force plates to measure the GRF during walking, stairs ascending and descending.

The parameters we assessed pertain to the kinematic and kinetic results from the patients and comparisons with the healthy controls. The kinematic and kinetic variables examined in this study were knee flexion/adduction/rotation angles during the whole gait cycle and knee flexion/adduction/rotation moment during the loading phase. In order to assess the difference between patients and healthy subjects at different time point during gait cycle, for each kinematic and kinetic variable, one hundred and one discrete points according to 0-100% gait cycle at 1% intervals were extracted using one-dimensional interpolation for statistical analysis.

To assess the repeatability of the approach, the interpatient and the intrapatient reproducibility to assess the flexion angle over the entire gait cycle between repetitions was tested using the intraclass correlation coefficient (ICC). Univariate analysis of variance (ANOVA) was used to test for main effects in these three different groups and statistical analysis was performed with the SPSS software package (IBM SPSS Statistics, Chicago, Illinois). The significance level for these tests was set at 5%. The one-way ANOVAs were also used to detect the differences within the spatiotemporal parameters, as well as the knee excursions. Additionally, group average curves were calculated for the knee flexion-extension angle and moment, adduction-abduction angle and moment, internal-external angle and moment, the average curves of all the participants in a group were averaged to obtain the group average curves.

Chapter 3

Results

This chapter examines the results of the knee joint functional parameters in patients and healthy subjects while walking, stairs ascending and descending. Several figures and tables are attached in this chapter in order to help understand these results.

3.1 IKDC score and gross morphology

According to the IKDC score, 15 of all 34 patients reported the knee joint function to be 'normal' (IKDC score = A) or 'nearly normal' (IKDC score=B), while 19 of all patients reported C and D IKDC scores (*Table 3.1)*. Within the patients who reported an IKDC score of A or B, there were 2 patients with isolated PCL injury, 8 PCL&PLS injured patients, and 5 patients with all the cruciate and collateral ligaments injured. Within the group of patients who reported IKDC scores of C and D, 3 patients had isolated PCL injuries, 8 patients had PCL&PLS injuries, and in other 8 patients all the cruciate and collateral ligaments were injured.

Furthermore, a significantly reduced mid-thigh circumference was detected in the PCLR limb (53.1 ±4.2 cm) compared with the CL side (54.2 ±4.4cm), P= 0.001.

3.2 Spatiotemporal parameters

The spatiotemporal parameters are shown in *Table 3.2*. No significant difference was found in duration of gait cycle, step length, speed and cadence within PCLR, CL and healthy knee joints.

3.3 Vertical GRF in PCLR patients

The vertical GRF of walking is shown in *Fig. 3.1*. No significant difference was found between the PCLR and CL knee joints. The vertical GRF of stairs ascending is shown in *Fig. 3.2*. Significant differences were found at 27-30% and 76-84% of the gait cycle. The vertical GRF of stairs descending was shown in *Fig. 3.3*. Significant differences were found at 7-10% and 71-90% of gait cycle.

Patients	Injury type	IKDC rank
PCL_01	ALL	D
PCL_02	PCL	A
PCL_03	PCL+PLS	D
PCL_04	ALL	C
PCL_05	PCL+PLS	B
PCL_06	PCL+PLS	B
PCL_07	PCL	B
PCL_08	PCL+PLS	B
PCL_09	ALL	D
PCL_10	ALL	C
PCL_11	ALL	D
PCL_12	PCL+PLS	A
PCL_13	PCL+PLS	D
PCL_14	PCL+PLS	A
PCL_15	PCL+PLS	B
PCL_16	PCL+PLS	D
PCL_17	PCL+PLS	B
PCL_18	PCL	D
PCL_19	PCL	D
PCL_20	PCL+PLS	C
PCL_21	PCL+PLS	D
PCL_22	ALL	D
PCL_23	PCL+PLS	D
PCL_24	ALL	B
PCL_25	ALL	C
PCL_26	ALL	B
PCL_27	PCL+PLS	C
PCL_28	PCL+PLS	A
PCL_29	PCL	D
PCL_30	ALL	D
PCL_31	ALL	B
PCL_32	PCL+PLS	D
PCL_33	ALL	B
PCL_34	ALL	A

Table 3.1 This table represents the injury type of the patients and the IKDC score in the questionnaire. In the injury type column, PCL means isolated PCL injury, PCL+PLS means both PCL and PLS are injured, ALL means all the cruciate and collateral ligaments including the PLS are injured.

	Single-limb support (s)	Stride length (cm)	Speed (m/s)
PCLR	*0.68 ±0.07*	*134.46±9.78*	*1.24±0.14*
CL	*0.69 ±0.07*	*134.65±10.0*	*1.24±0.14*
Healthy	*0.65 ±0.05*	*134.49±10.53*	*1.29±0.15*

Table 3.2 This table represents spatiotemporal parameters of the patients and of the healthy subjects during walking, which including the single-limb support time, stride length and speed.

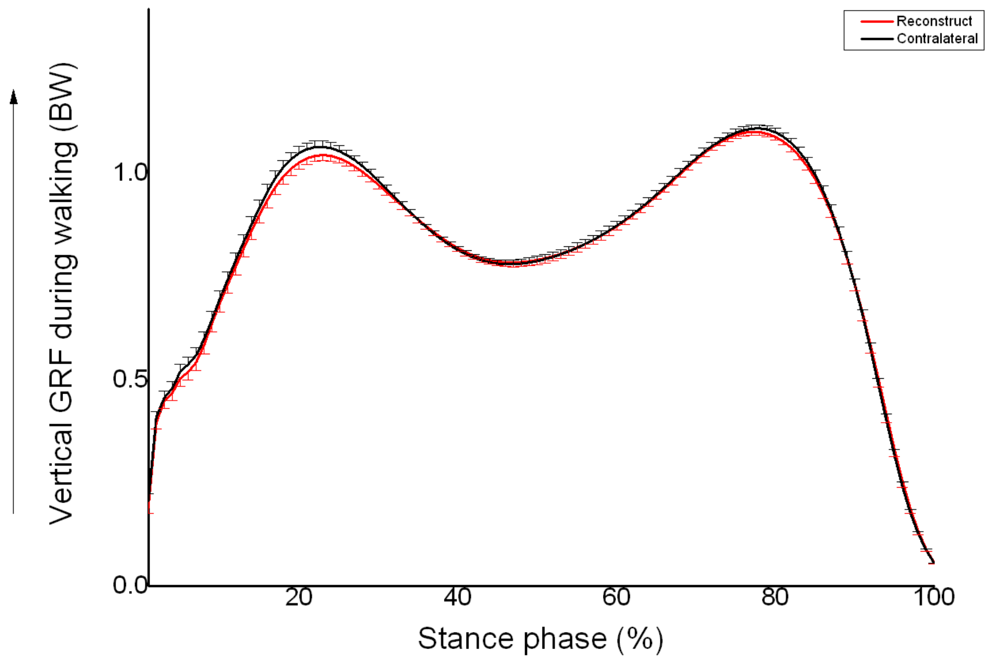

Fig. 3.1 Vertical GRF during walking in the PCLR patients. No significant difference was found between the PCLR sides and the CL sides.

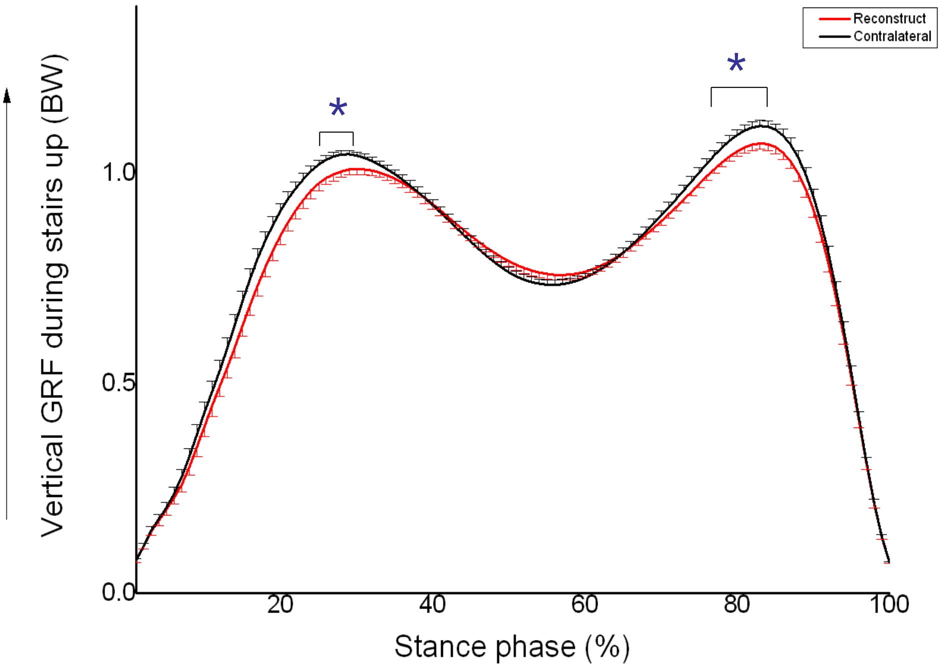

*Fig. 3.2 Vertical GRF during stairs ascending in the PCLR patients. * represents significant difference between the PCLR sides and the CL sides.*

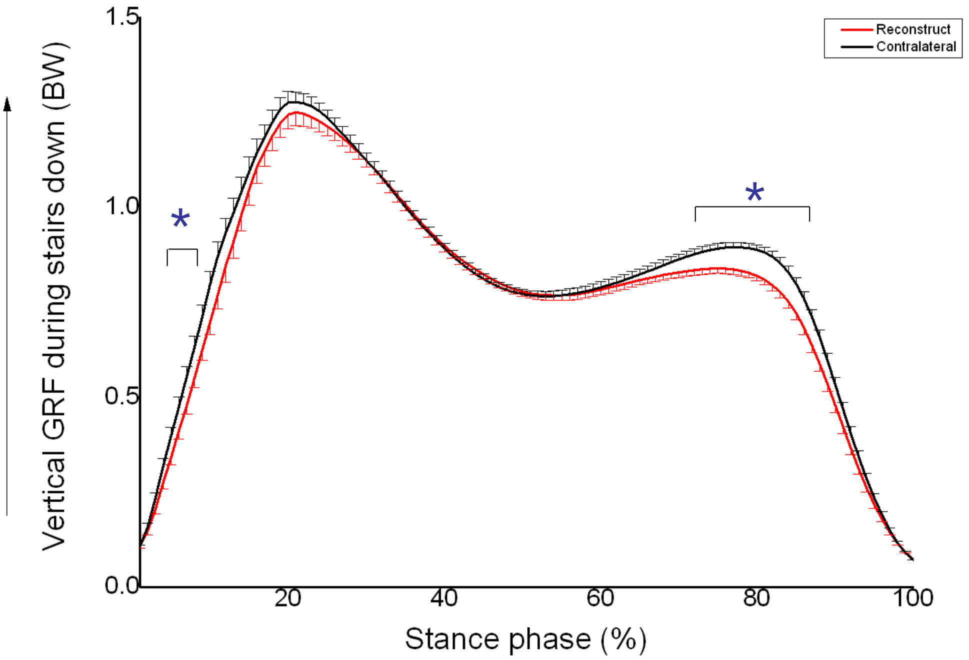

*Fig. 3.3 Vertical GRF during stairs descending in the PCLR patients. * represents significant difference between the PCLR group and the CL group.*

3.4 Biomechanical indicators of knee function

Excellent intrasubject reproducibility was observed for the assessment of knee flexion angles (ICC=0.99) and moments (ICC=0.99) between repetitions in subjects, and also the intersubject reproducibility with knee flexion angles (ICC=0.99) and moments (ICC=0.98).

3.4.1 Sagittal plane

The knee flexion angles and moments were determined for PCLR knee joints as well as for their healthy CL knee joints during walking, stairs ascending and descending (*Fig. 3.4-3.6*), whereupon statistical differences were obtained during the activity of ascending and descending stairs. The angles and moments are indicated in degrees (Deg) and bodyweight*height (BW*Ht). *Fig. 3.4* shows the knee flexion angles and flexion moments during walking between PCLR group and CL group. No significant difference was found between them. *Fig. 3.5* shows the differences during the stairs ascending, with a significant difference observed at 18-26% of stance phase, and the CL group showing greater flexion angles at 76-81% of gait cycle. In *Fig. 3.6*, during stairs descending, the PCLR group showed reduced knee flexion moment compared the CL group, while no difference was found at the flexion angles. *Fig. 3.4-3.6* illustrates that there was no significant difference between the PCLR group and CL group during all these activities, and the reduced knee flexion moment at the PCLR group could be found during both stairs ascending and descending.

The kinematic and kinetic parameters of the patients were further compared to those of a bilateral healthy cohort (*Fig. 3.7-3.9*), where both the PCLR group and CL group were compared with the healthy cohort. As shown in *Fig. 3.7*, the PCLR and CL group showed reduced knee flexion angles at 68-94% of the gait cycle during walking. In *Fig. 3.8* during stairs ascending, reduced knee flexion angles were shown at 0-18%, 47-55% and 71-83% of the gait cycle in the patients. In *Fig. 3.9* during stairs ascending, reduced knee flexion angles are shown at 69-75% of the gait cycle in patients. It should be noticed that there were differences not only between the PCLR group and healthy group, but also between the CL group and the healthy group, which means the CL knee joints also showed significantly reduced flexion angles when compared with the healthy subjects.

Moreover, as shown in *Fig. 3.7*, there was no significant difference between patients and healthy subjects at the flexion moment during walking. However, in *Fig. 3.8* during stairs ascending, the PCLR group demonstrated a reduced knee flexion moment compared to the healthy group at 19-29% and 63-82% of the stance phase, whereas during stair descending shown in *Fig. 3.9*, the significance was found at 80-94% of the stance phase. However, at 36-51% of the stance phase, an increased knee flexion moment could be obtained in the PCLR group during stair descending.

As regards the excursion of flexion and extension at the sagittal plane, there were significant difference between the patients and healthy subjects. The PCLR group showed significant reduced flexion-excursion during walking, stairs ascending and descending compared with the healthy group, P=0.001, 0.02, 0.001, respectively. The CL group showed significantly reduced flexion-extension during walking and stairs descending, P=0.001 and 0.04, respectively. However, no significant difference was found between the PCLR group and the CL group. The flexion-extension excursion values are shown in *Table 3.3*.

	PCLR	*CL*	*Healthy*
Walking	*59.29±4.35 º**	*60.25±4.62 º*Δ	*66.07±6.11 º*
Stairs ascending	*88.86±7.54 º**	*91.05±6.0 º*	*93.68±6.0 º*
Stairs descending	*90.17±5.62 º**	*92.13±6.51 º*Δ	*96.03±6.47 º*

Table 3.3 The comparison of flexion-extension excursions within the patients and healthy subjects when performing daily activities. In the table, ***** *represents significant differences (p<0.05) between the PCLR and healthy group,* Δ *represents significant differences (p<0.05) between the CL and healthy cohort.*

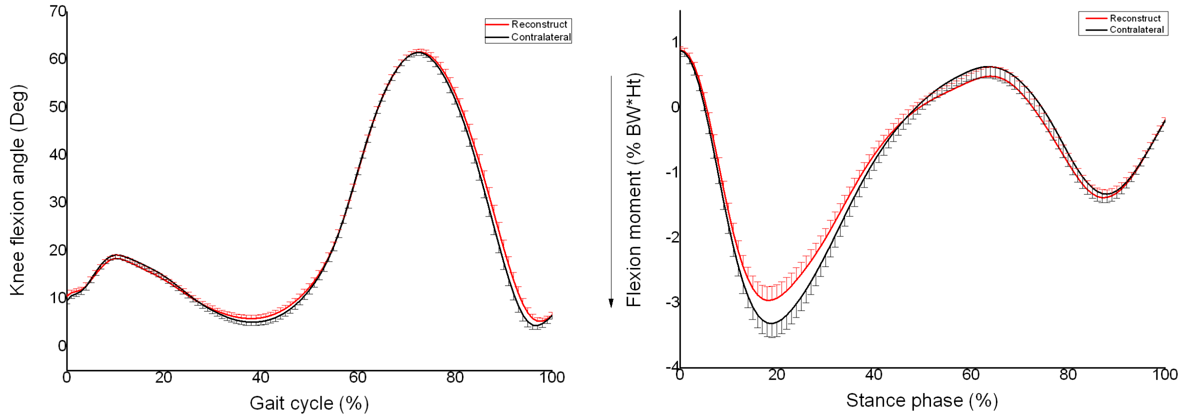

Fig. 3.4 Knee flexion angles and flexion moments during walking in patients, the red line stands for the PCLR group, while the black line stands for the CL group.

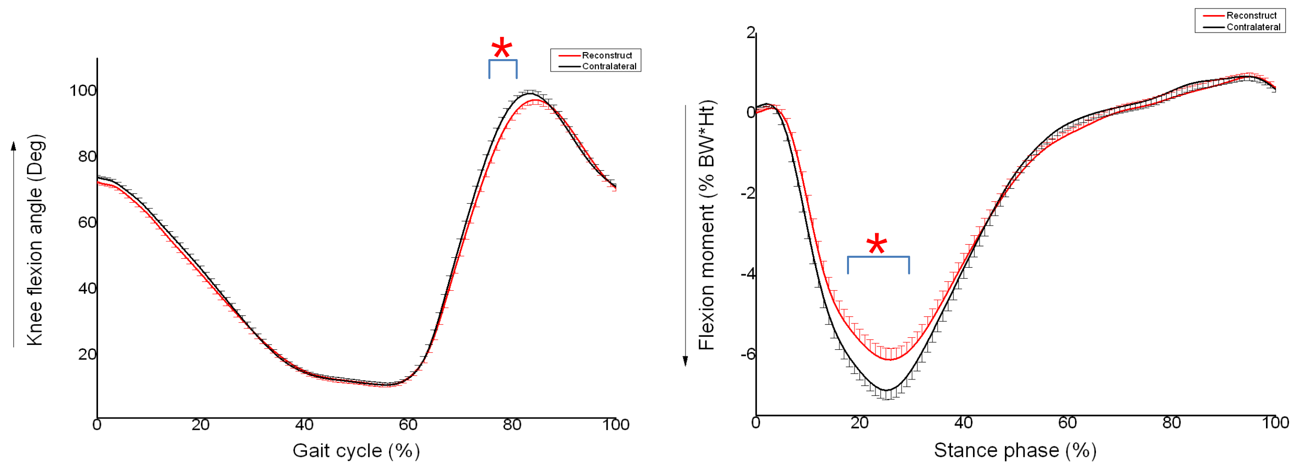

Fig. 3.5 Knee flexion angles and flexion moments during stairs ascending within patients, the red line stands for the PCLR group, while the black line stands for the CL group. * *represents significant difference between the PCLR group and the CL group.*

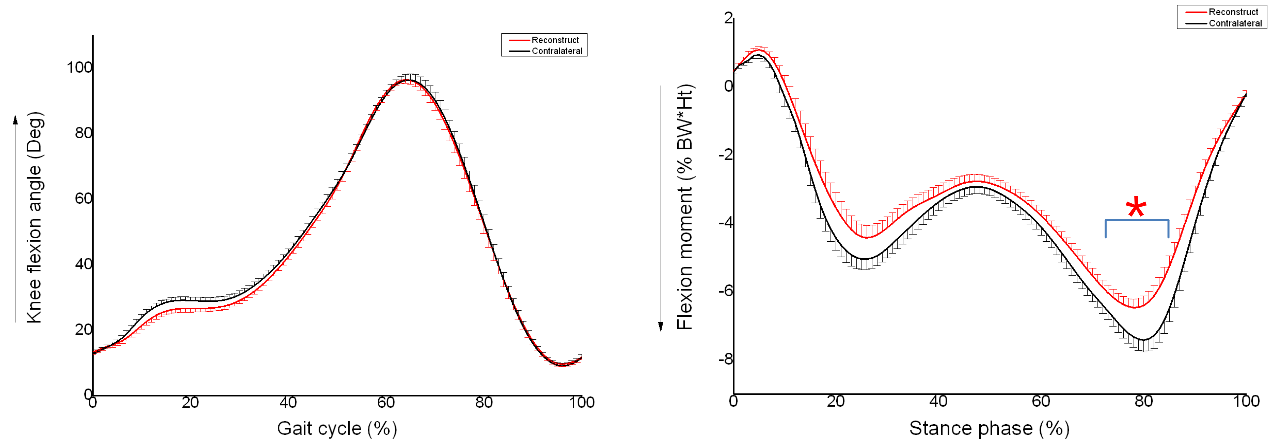

*Fig. 3.6 Knee flexion angles and flexion moments during stairs descending within patients, the red line stands for the PCLR group, while the black line stands for the CL group. * represents significant difference between the PCLR group and the CL group.*

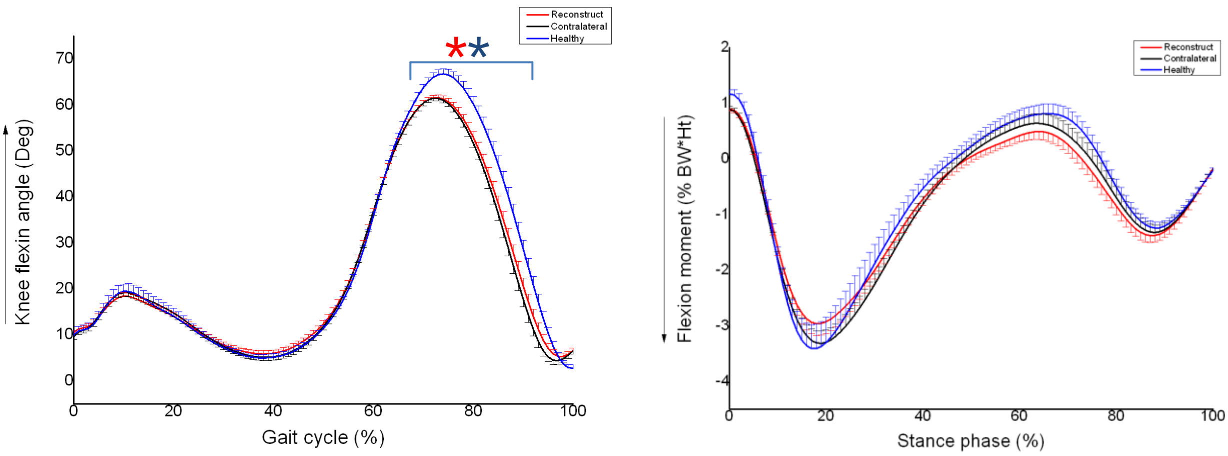

*Fig. 3.7 Comparison of knee flexion angles and flexion moments during walking between patients and healthy subjects, the blue line represents the healthy subjects, the red line stands for the PCLR group while the black line for the CL group. * represents significant difference between the PCLR group and the healthy group. * represents significant difference between the CL group and the healthy group.*

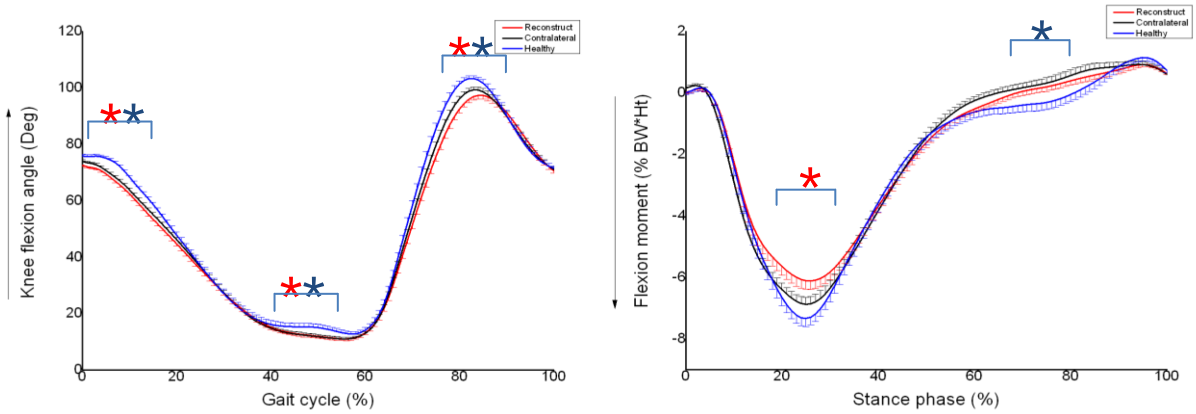

*Fig. 3.8 Comparison of knee flexion angles and flexion moments during stairs ascending between patients and healthy subjects, the blue line represents the healthy group, the red line stands for the PCLR group, while the black line stands for the CL group. * represents significant difference between the PCLR group and the healthy group. * represents significant difference between the CL group and the healthy group.*

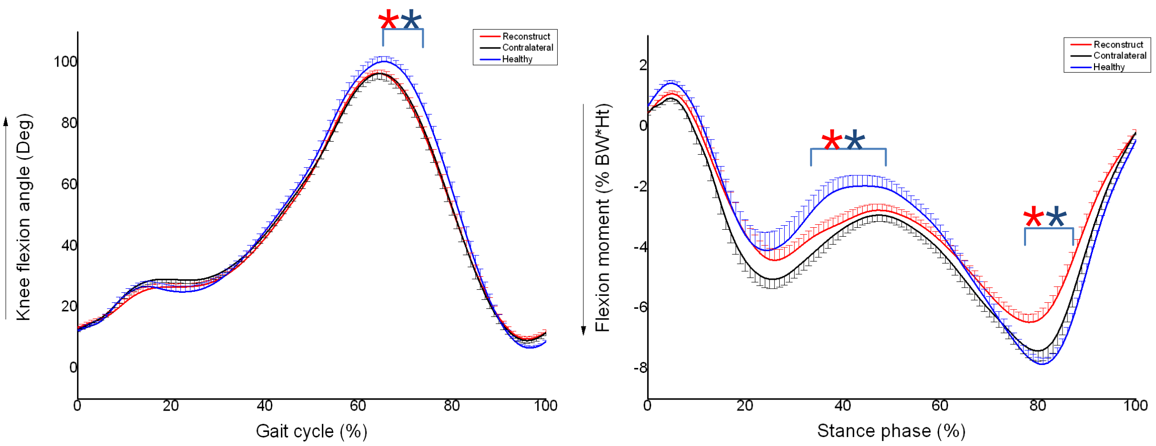

*Fig. 3.9 Comparison of knee flexion angles and flexion moments during stairs descending between patients and healthy subjects, the blue line represents the healthy subjects, the red line stands for the PCLR group, while the black line stands for the CL group. * represents significant difference between the PCLR group and the healthy group. * represents significant difference between the CL group and the healthy group.*

3.4.2 Coronal plane

When comparing the PCLR group with the CL group at the coronal plane, it was found that there was no significant difference during walking (*Fig. 3.10*), stairs ascending (*Fig. 3.11*) or descending (*Fig. 3.12*), with regard to either kinematic, nor kinetic parameters. When comparing the patients with the healthy subjects, it was also found that there were few significant differences with regard to the kinematic parameters during different activities. The only difference was found at 62-69% of gait cycle at stairs descending when compared with the healthy subjects (*Fig. 3.13- Fig. 3.15*). During most daily activities, there were no significant differences between the patients and the healthy subjects at the kinetic parameters. The only difference was found at the walking trials, where there was significant difference between the CL group and the healthy group at 72-76% of stance phase, and differences between the PCLR group and healthy group at 27-38% of stance phase (*Fig. 3.13*). Other than that, we could only detect a difference between the mean value at the adduction angle and moments, although the difference was not significant.

When comparing the adduction-abduction excursion at the coronal plane, the PCLR group and CL group showed significantly reduced excursion compared with the healthy group during stairs descending (P=0.004, 0.001). However, no significant difference was found between the patients and healthy subjects during walking and stairs ascending. No significant difference was found between the PCLR group and CL group during these three activities. The adduction-abduction excursion values are shown in *Table 3.4*.

	PCLR	*CL*	*Healthy*
Walking	*7.83±2.97 º*	*8.22±2.8 º*	*8.72±4.39 º*
Stairs ascending	*8.39±2.55 º*	*8.04±2.2 º*	*9.26±3.39 º*
Stairs descending	*6.23±1.77 º***	*6.07±1.49 º*Δ	*8.35±3.29 º*

Table 3.4 The comparison of adduction-abduction excursions within the patients and healthy subjects when performing daily activities. * *represents significant differences (p<0.05) between the PCLR and healthy group,* Δ *represents significant differences (p<0.05) between the CL and healthy cohort.*

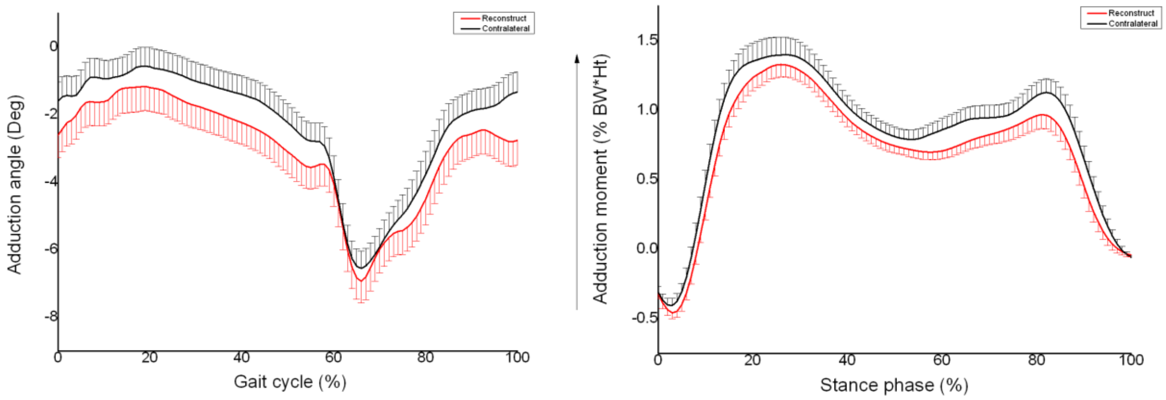

Fig. 3.10 Knee adduction angles and adduction moments during walking within patients, the red line stands for the PCLR group, while the black line stands for the CL group.

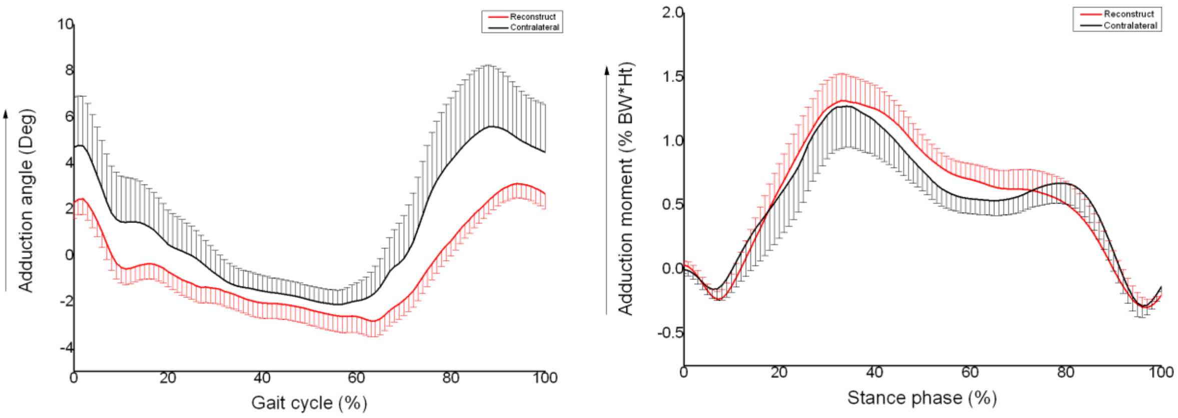

Fig. 3.11 Knee adduction angles and adduction moments during stairs ascending within patients, the red line stands for the PCLR group, while the black line stands for the CL group.

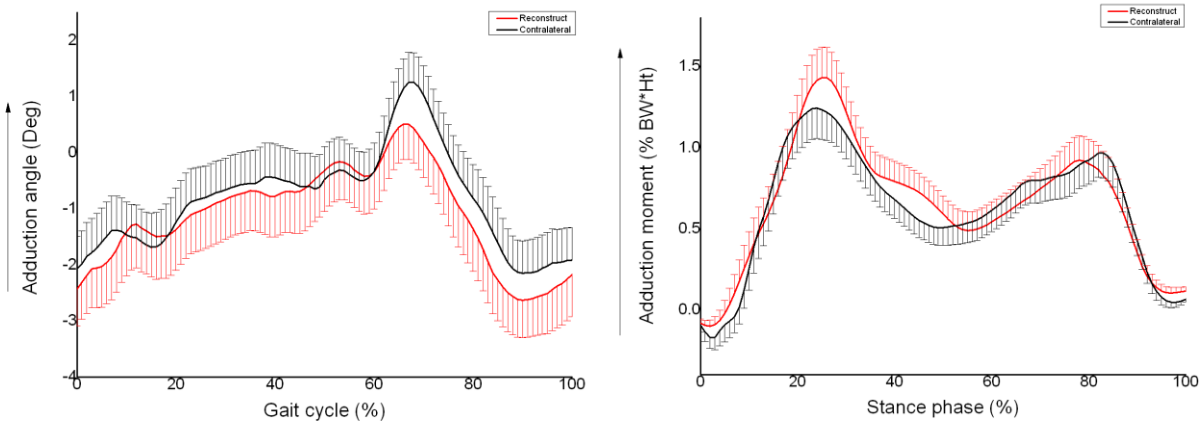

Fig. 3.12 Knee adduction angles and adduction moments during stairs descending within patients, the red line stands for the PCLR group, while the black line stands for the CL group.

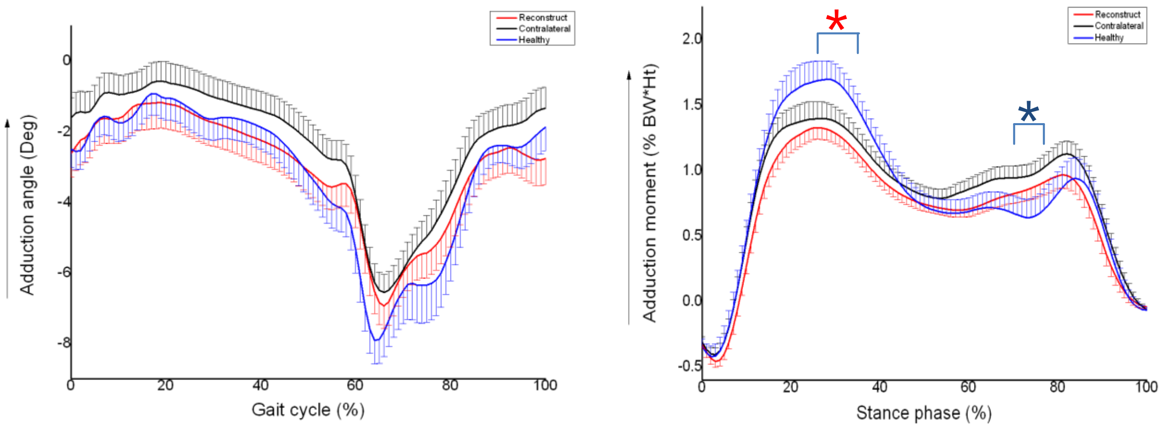

*Fig. 3.13 Comparison of knee adduction angles and adduction moments during walking between patients and healthy subjects, the blue line represents the healthy subjects, the red line stands for the PCLR group while the black line stands for the CL group. * represents significant difference between the PCLR group and the healthy group. * represents significant difference between the CL group and the healthy group.*

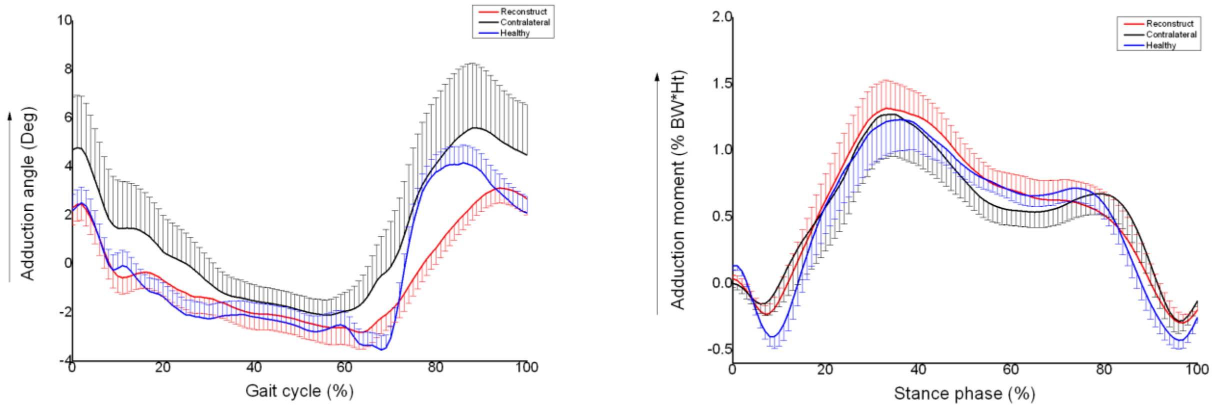

Fig. 3.14 Comparison of knee adduction angles and adduction moments during stairs ascending between patients and healthy subjects, the blue line represents the healthy group, the red line stands for the PCLR group, while the black line stands for the CL group.

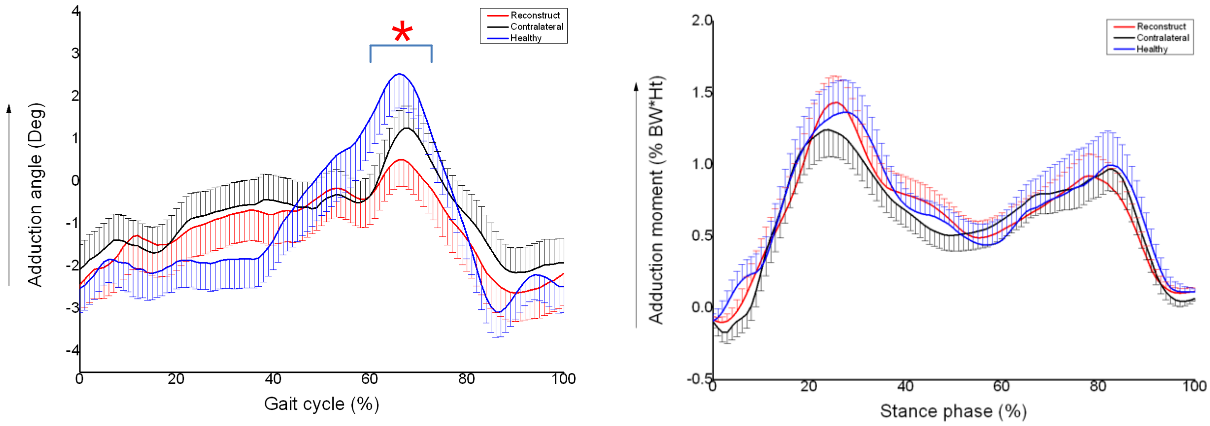

*Fig. 3.15 Comparison of knee adduction angles and adduction moments during stairs descending between patients and healthy group, the blue line represents the healthy group, the red line stands for the PCLR group, while the black line stands for the CL group. * represents significant difference between the PCLR group and the healthy group.*

3.4.3 Transverse plane

At the transverse plane, there was no significant difference between the PCLR group and the CL group during daily activities like walking (*Fig. 3.16*), stairs ascending (*Fig. 3.17*) and stairs descending (*Fig. 3.18*). We did not find a significant difference in the kinematic and kinetic parameters when we compared the PCLR group with the CL group. However, when we compared the PCLR group with the healthy group, the patients showed significantly reduced knee flexion angles in all three activities, they were 1-5%, 15-28% and 77-90% of gait cycle during walking as shown in *Fig. 3.19*; 0-15%, 70-77% and 86-99% of gait cycle during stairs ascending in *Fig. 3.20*; and 6-10%, 44-57% and 69-78% of gait cycle during stairs descending in *Fig. 3.21*. It should also be noted that not only the PCLR group but also the CL group showed reduced knee rotation angles compared with healthy group.

When compared with the healthy group, patients also showed significant differences in the kinetic parameters, but the differences are not consistent with the kinematic parameters. As shown in *Fig. 3.19*, during walking there was a significant difference between the PCLR group and the healthy group at 49-71% of stance phase. During stairs ascending shown in *Fig. 3.20*, there was no significant difference compared with the CL group or the healthy group. During stairs descending shown in *Fig. 3.21*, significant differences were observed at 3-8%, 33-37% and 92-99% of stance phase, and the difference could be found not only between the PCLR group and healthy group, but also between the CL group and healthy group.

As regards the excursion of tibial rotation, the PCLR group showed significantly reduced internal-external rotation excursion during walking, stairs ascending, the P values were 0.028, 0.003. The CL group also showed reduced rotation excursion during walking, stairs ascending and stairs descending, the P values are 0.003, 0.014 and 0.012, separately. However, no significant difference was found between PCLR group and CL group during any of the three activities. The rotation excursion values were shown in *Table 3.5*.

	PCLR	*CL*	*Healthy*
Walking	*12.45 ±4.26 °**	*11.53 ±2.8 °Δ*	*14.93 ±4.93 °*
Stairs ascending	*10.83 ±4.4 °**	*11.44 ±3.27 °Δ*	*14.11 ±3.14 °*
Stairs descending	*10.6 ±3.76 °*	*9.73 ±2.91 °Δ*	*12.18 ±3.33 °*

*Table 3.5 The comparison of internal-external rotation excursions within the patients and healthy subjects when performing daily activities. * represents significant differences ($p<0.05$) between the PCLR and healthy group, $^{\Delta}$ represents significant differences ($p<0.05$) between the CL and healthy cohort.*

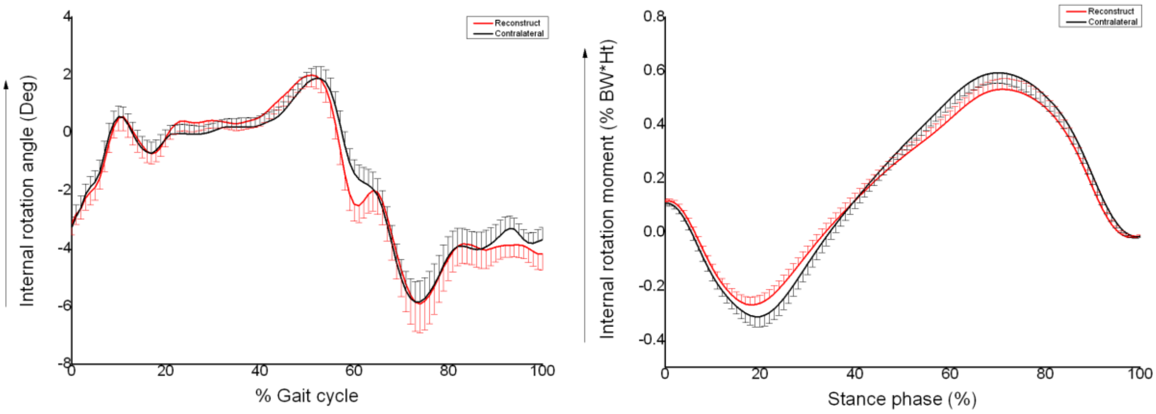

Fig. 3.16 Knee rotation angles and rotation moments during walking within patients, the red line stands for the PCLR group, while the black line stands for the CL group.

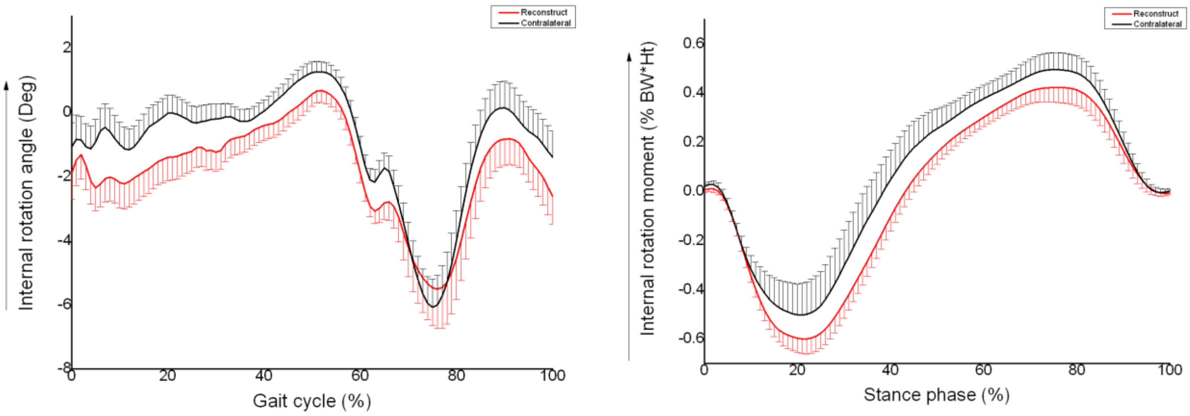

Fig. 3.17 Knee rotation angles and rotation moments during stairs ascending within patients, the red line stands for the PCLR group, while the black line stands for the CL group.

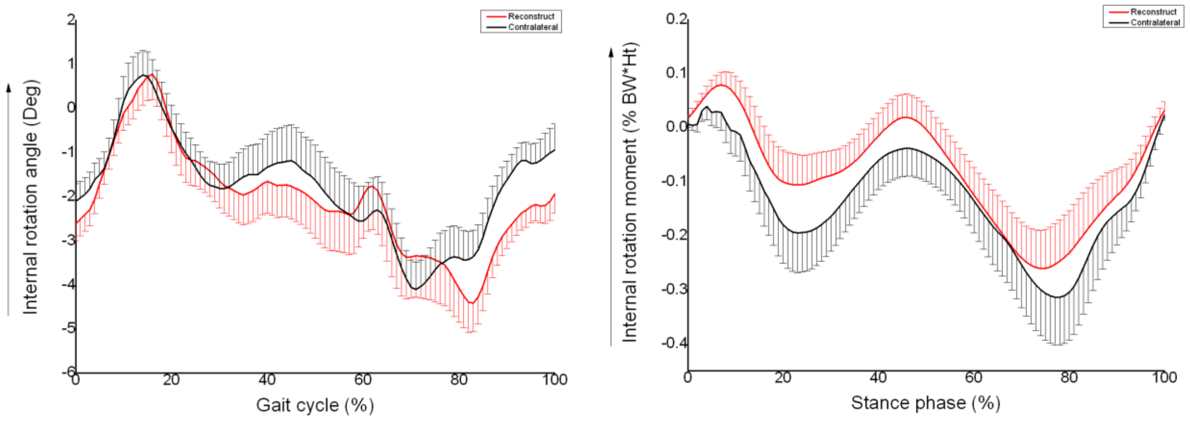

Fig. 3.18 Knee rotation angles and rotation moments during stairs descending within patients, the red line stands for the PCLR group, while the black line stands for the CL group.

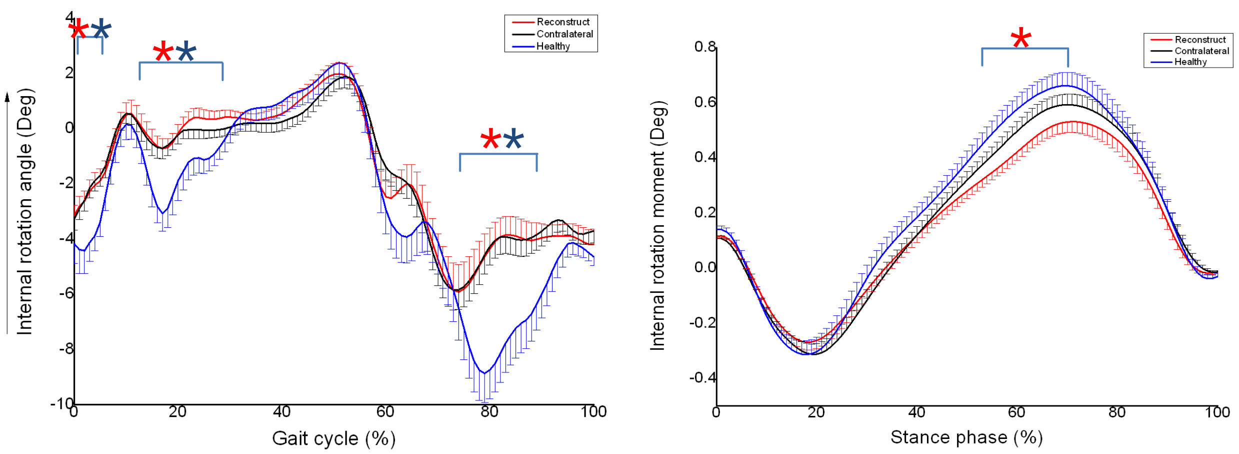

*Fig. 3.19 Comparison of knee rotation angles and rotation moments during walking between patients and healthy subjects, the blue line represents the healthy group, the red line stands for the PCLR group, while the black line stands for the CL group. * represents significant difference between the PCLR group and the healthy group. * represents significant difference between the CL group and the healthy group.*

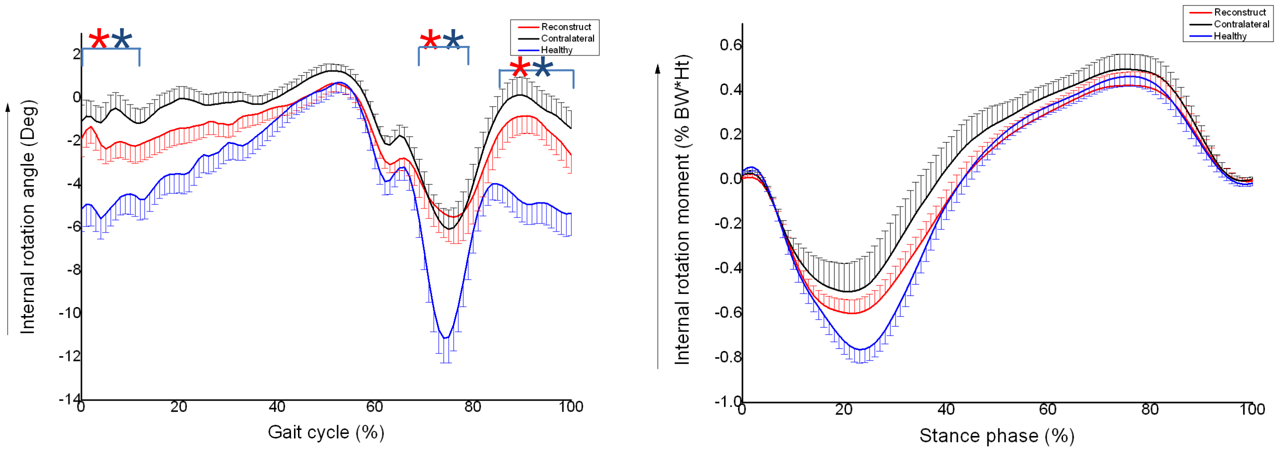

*Fig. 3.20 Comparison of knee rotation angles and rotation moments during stairs ascending between patients and healthy subjects, the blue line represents the healthy group, the red line stands for the PCLR group, while the black line stands for the CL group. * represents significant difference between the PCLR group and the healthy group. * represents significant difference between the CL group and the healthy group.*

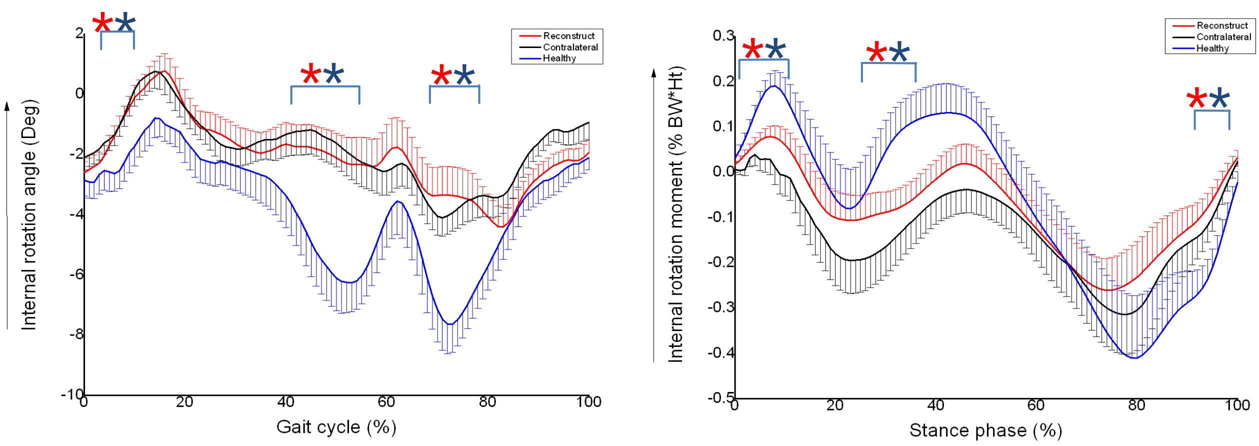

*Fig. 3.21 Comparison of knee rotation angles and rotation moments during stairs descending between patients and healthy subjects, the blue line represents the healthy group, the red line stands for the PCLR group, while the black line stands for the CL group. * represents significant difference between the PCLR group and the healthy group. * represents significant difference between the CL group and the healthy group.*

Chapter 4

Discussion

This chapter discusses the knee joint functional results in PCLR patients at the sagittal, coronal and transverse planes. This chapter will elucidate which kind of problems still exist after the surgery, what the possible reasons are and how we should proceed in the future.

The incidence of PCL injuries was reported between 4 to 44% in acute knee injuries, most of the injuries are caused by high-energy trauma like motor vehicle accidents.[25,26] It is recommended that PCL reconstruction surgery could repair the ruptured ligaments and restore the function of knee joints. Indeed, reports of clinicians indicate that patients could get a good subjective score on the questionnaire after surgery.[96,97] However, it is still unclear if the kinematics and kinetics of the knee joint could be fully restored after the operation. The objective of this study was to examine the effect of PCL reconstruction surgery on the kinematic and kinetic function of the knee joint during walking and stair using in the long term after surgery. We hypothesised that the PCL reconstruction cannot fully restore the kinematic and kinetic function of the knee joints, and the PCLR knee joints would be at a high risk of OA after surgery. The results of this study partially supported our ideas and demonstrated that, even the satisfied clinical results could be got after the reconstruction surgery, the patients still exhibited different kinematic and kinetic joint functional performance compared with the healthy subjects during daily activities.

4.1 IKDC and spatiotemporal parameters of the patients

In our study, we hypothesised that our patients would report acceptable IKDC results. According to the results, almost half of the patients reported a ‘normal’ or ‘nearly normal’ IKDC score. Considering most of our patients had suffered serious combined injuries, these subjective results are acceptable and also in accordance with our hypothesis about the subjective assessment. Ahn et al.[47] reported that by IKDC scoring, all 61 of their patients achieved normal or near-normal knees. Jackson et al.[96] reported that 24 of 26 patients rated their knees as normal or near-normal in his research and the study indicated that excellent subjective results can be maintained with long-term follow-up. Compared with the reported subjective score, the reported IKDC score from the patients in our study is not so positive, with about half of our patients reporting fine results. Considering that most of our patients had suffered combined injuries before the surgery at the knee joint (within all the 34 PCLR patients, 16 patients had combined PCL/PLS injuries, 13 patients had all the cruciate and collateral ligaments crushed), we can conclude that the surgery did improve the life quality of the patients, and the clinical results of the surgery were acceptable from the patients’ viewpoint. However, when we checked the injury level of the patients in details, we found out that the patients who gave the marks A and B in the study did not suffer less severe injury than the patients who gave the marks C and D, which implied that the subjective score after the surgery could not full predicated by the pre-surgery injury level.

There are many other factors that may affect the IKDC score after surgery, for example, the surgical technique that developed during surgery, the individual rehabilitation program that developed after the surgery, and so on.

It should be noticed that the subjective knee joint score, like the IKDC, could not represent the objective knee joint function after the surgery. Voos et al.[97] concluded that the objective knee scores seem to lag behind subjective self-reported scores after surgical reconstruction, and it is still unclear so far which factors would affect the subjective assessment score and help the patients gain the self-satisfactory results after the surgery. Although the objective assessment of knee joint scores was not included in our study, we do found that the objective results of the kinematics and kinetics in the PCLR knee joint were not as well as that represent by the IKDC score. This finding revealed that the commonly utilized subjective knee assessment score, like the IKDC, may not be able to fully represent the recovery situations after the surgery. To gain a better understanding of recovery situations in the PCLR patients, the objective clinical assessment or functional test should be utilized, combining with the subjective self-reported knee joint score.

For the spatiotemporal parameters, we hypothesised in our study that the patients would walk slower with less single-limb support time and reduced stride length compared with the healthy subjects. The reason we set this hypothesis is based on the study from Elbaz A et al.[87] who indicated that the spatiotemporal parameters could act as good indicators for age-related knee OA severity, and the OA patients would walk slower, with reduced stride length and lower single-limb support time compared with healthy subjects. Study from Mills K et al.[98] supported the idea that spatiotemporal gait analysis objectively classifies patients with knee OA according to disease severity. However, the results we got in our study did not quite support our hypothesis. It is found that although the patients walk more slowly and have a shorter stride length, the difference was not significant between the patients and healthy subjects with respect to the spatiotemporal parameters. Although recent studies indicated that the spatiotemporal parameters could work as the indicators for the age-related knee OA severity,[98] these parameters might not be sensitive enough to detect the onset of injury-based OA in our study. The reason could be that the PCL injuries are usually serious and combined injuries during violent studies, great damage will be applied not only on the ligaments but also on the cartilage of the knee joints. The cartilage damage levels can be classified by the clinical methods, like the arthroscopy, but not indicated by the spatiotemporal parameters.

In our study we cannot simply conclude the OA level of the PCLR patients only based on the spatiotemporal results. However, from our study, it is found that there was no significant difference at the spatiotemporal parameters between the patients and the healthy subjects during walking, which means that through operation, the PCL injured patients would gain a walking function that close to the healthy subjects. This finding support the superiority of the PCL reconstruction surgery and can also partly explain that why the PCLR patients usually give high subjective knee scores after the operation.

4.2 Kinematic and kinetic performance of daily activities

4.2.1 Kinematic function in PCLR patients

Our hypothesis concerning the kinematic function was supported by the results in our study that the PCLR patients showed reduced knee excursion compared with the healthy subjects, especially at the sagittal and transverse plane. At the sagittal plane, the patients showed significantly reduced knee flexion angles during all three activities, significant differences were noticed especially during the swing phase, not only at the reconstructed knee joints but also at the CL joints. At the transverse plane, the patients showed significantly reduced external rotation angles compared with the healthy knee joints. It is noticed that the significant reduced knee excursions was found at the sagittal and transverse planes of the knee joints in the PCLR patients, not only during walking but also in stairs ascending and descending.

Many studies which examined the patients with OA knees reported reduced knee excursions at the sagittal and transverse planes,[86,99,100] our results revealed that the PCLR patients have a kinematic performance that similar to that of the OA patients when performing daily activities. Besides, earlier studies noted a similar reduced knee excursion during walking in the patients with knee ligament deficiency and assumed the reason of this phenomenon as the subconscious reprogramming of body during locomotive process in order to protect the knee joint from excessive translation.[101,102] There was a earlier study concluded this phenomenon as a ‘stiff-knee’ gait pattern and explained it as the pathological action of the muscles counteracting the knee flexion.[17] An investigation of OA patients reported that the patients may motivate muscle co-activation around the knee joint and increase the stiffness in order to improve the joint stability.[103] Based on the fact that PCLR patients usually exhibit residual laxity at the knee joints after surgery, especially at the sagittal and transverse plane, it is highly possible that the patients may motivate muscle activations in order to improve the stability of the knee joint during daily walking, stairs ascending and descending. To verify this conjecture, further study should apply electromyography (EMG) investigation to further understand the role of muscle activities around the knee joint, and the joint stability should also be detected to check the consistency with the muscle activities.

However, apart from the advantage of maintaining the stability of the knee joints, this mechanism could also have a disadvantage toward the knee joint. It is easy to understand that in order to keep the stability in a lax joint, the muscles around the knee joint need to be more activated than that in the case of a normal joint. The knee joint will show improved knee joint stability during daily activities because of the muscle activation, on the other side, the more activated muscle activation may generate higher contact force at the knee joint, which is believed to be harmful to the cartilage health in the long term. Besides, it is still unclear if the PCL reconstruction could well relocate the contact area of cartilage at the knee joint. Based on the OA study, it is reported that the altered contact mechanics in the newly loaded regions could produce local degenerative changes to the cartilage of joints.[104] In other words, although the body may adopt this strategy to maintain the stability of the knee joints, this strategy may place the knee joint in a higher risk of OA in the long term. Therefore, further study should investigate the contact positions in the PCLR patients as well as the muscle activation compared with the healthy subjects in order to obtain a better understanding of the effect of this strategy. Although the underlying reasons are still unknown, knee stiffness in PCLR patients could support our hypothesis that the kinematics of the reconstructed knee joints are not back to normal and these joints may be at a high risk of OA in the long term after surgery.

Besides, in our study, the CL group showed similar kinematic functional performance compared with the PCLR group during all the daily activities, and the CL group also showed reduced knee excursions compared with the healthy subjects. This phenomenon revealed that the PCLR patients could apply a well adapted gait pattern during daily activities after operation, with the performance of CL sides function close to that of the PCLR sides. This finding could partially explain why the patients usually reported the acceptable subjective knee joint score after the surgery. Despite the difference of kinematics with the healthy subjects, the patients would not exhibit quite different kinematics between the PCLR and CL sides when performing daily activities. This adaptation strategy can make the patients get the impression that the injured knee joints are already back to normal when compared with the CL sides, and this kind of impression will help the patients reported a high subjective score after surgery. In this way, the healthy status of the PCLR knee joints should rely not only on the subjective scores, but also on the objective assessments, and that is also the motive why we check the kinematics and kinetics in the PCLR patients.

4.2.2 Kinetic function in PCLR patients

In our study, we hypothesised that the main difference concerning the kinetic function would be reflected on the coronal plane, with a significant higher adduction moment at the PCLR group. However, the kinetic results we obtained in our study did not quite support our hypothesis, we did not find a higher adduction moment at the reconstructed knee joints, and no significant difference was found at the coronal plane in the patients compared with the healthy subjects. However, there are significant differences of knee kinetics at the sagittal plane. In our study, it was found that the PCLR knee joints showed reduced flexion moments compared with the CL and healthy subjects, which we did not expect before our study.

Reduced knee flexion moment at the knee joints was usually found in ACL related injuries, the same finding was present in the ACL reconstructed patients from the study conducted by Zabala et al.,[11] which investigated the three-dimensional knee moments of ACL reconstructed and control subjects during gait, stair ascending and descending. Our study is the first investigation so far to report the kinetic changes in the PCLR patients during daily activities, and the PCLR patients showed reduced knee flexion moment compared with the healthy subjects. There could be many possible reasons which accounted for the reduced knee flexion moments in the PCLR knee joints, the main reasons would be the muscle weakness in the reconstructed sides, or the patients shift their body weights to avoid using the PCLR sides.

Firstly, these results could be explained by the muscle weakness in PCLR patients. Muscle weakness, especially the quadriceps weakness, was usually reported in patients after the knee surgery.[105] The significantly smaller mid-thigh circumference measured in our study could also support the idea that PCLR patients may still suffer muscle weakness in the reconstructed knee joint in a long term after the surgery. Similar result was found in a study of patients with multiple reconstructed ligaments conducted by Hart et al.[106], which showed that the knee joints with reconstructed ligaments exhibited significantly reduced knee flexion moment during walking and stair ascending and descending. The author also concluded the reason of reduced flexion moment into muscle weakness, especially the weakness of quadriceps muscles. Therefore, the patients are encouraged to do quadriceps strengthening exercises after the PCL surgery, and the individual rehabilitation program should be developed based on the injury level and clinical performance of the patient.

The reduced knee flexion moment could also be explained by the shifting body weight in the patients, and this idea was also supported by our results about the vertical GRF, which showed that during daily activities, the patients showed significantly reduced vertical GRF at the PCLR knee joints, suggesting that the patients shifted their body weight to the CL side during different activities. GRF is a clear and important parameter to reflect the force that the human body applied on the ground. As the external flexion moment was processed based on the GRF value, the bodyweight shifting would be a factor that affect the kinetic performance in the PCLR joints of patients. Besides, the bodyweight shifting strategy could also contribute to the muscle weakness around the PCLR joints. According to the literature, it should be noted that there was some links between muscle weakness and cartilage degeneration in human and animal models,[107,108] this information could help the clinicians to gain a better understanding of OA risk in the PCLR patients after operation.

In our study, the kinetics of the PCLR knee joints is quite different from our hypothesis. Comparing with the CL group and the healthy group, the PCLR knee joints did not show any significant difference of kinetic function at the coronal plane during walking, stairs ascending and descending. It is known that in OA patients, the adduction moment could be linked to the progression and severity of osteoarthritis, while higher adduction moments are usually related to higher contact forces at the medial compartment.[109] Concerning the high OA incidence at the PCLR patients after the surgery, we hypothesised that in our study the PCLR group would show higher adduction moment compared with the CL and healthy group, with the purpose to revel the high OA risk at the knees after PCL reconstruction. However, we didn’t find a significantly higher adduction moment in the PCLR patients compared with the healthy controls. Similar results were also obtained in a study concerning ACL-reconstructed patients who are at a risk of OA, the ACL reconstructed patients even experience a lower adduction moment compared with the healthy controls.[11] The possible reason would be that the ligament-injury based patients may show a special gait pattern and loading mechanism different from patients suffering from age-related conditions. The adduction moment is usually the factor affecting the progression and severity of OA, its role in the initiation of OA is still not well investigated in injury-based patients. Besides, the changes in magnitude of loads on the knee joint cannot be only determined by the moment data. The knee moment is a net joint moment calculation that does not account for the muscles and its antagonistic muscles separately. No significant changes of adduction moment was found in our study cannot directly draw the conclusion that the amount of load at the knee joint is not changed, because the co-contraction of the muscles can alter the contact force in the knee joint and with little changes at the knee moment. In order to gain a better understanding of moment and forces at the knee joint, further study should apply the EMG measurement to collect the data of muscle activities in the PCLR patients.

4.3 OA risk in PCLR patients

The PCL injury is usually caused by the traffic accident and is a kind of serious injury in the daily life. The PCL injured patients usually suffer pain, instability in the knee, with the knee OA risk after the injury. It is reported that even the patients could tolerant the pain and instability at the knee joint, however, the knee OA would also be a problem in the long term.[44] The PCL reconstruction surgery is a method which is capable to help the patients reduce the pain and gain a better life quality in the long term. According to the literature, most of patients are satisfied with the surgery, with most of the patients could return to their previous participating in athletics.[73,74] However, it was found that the reconstruction surgery may not fully restored the joint stability in all the patients, and the incidence of degenerative changes was still prevalent in the PCLR patients, which revealed that the significance of PCL injury has been over simplified, and the functional disability of knees with PCL injury underestimated.[6] In other words, the PCL reconstruction surgery can improve the life quality of PCL injured patients, however, it is still unknown if the knee joint function was fully restored in the PCLR patients, and if the OA risk was successfully prevented by the surgery.

There are several reasons to account for the knee OA risk of PCL patients after the reconstruction surgery. Firstly, as the PCL injuries are usually violent, it is highly possible that many of the PCL injured patients suffered the cartilage injury at the same time. The cartilage injury may start and accelerate the degeneration process, and the PCL reconstruction surgery cannot be quite positive towards it. Secondly, there are several reconstruction technique concerning the PCL injury, it is still unknown if these methods can relocate the physiological contact position of cartilage at the knee joint. As we discussed before, the altered contact mechanics in the newly loaded regions may produce local degenerative changes to the cartilage of joints.[104] The prevalent residual laxity after surgery also pointed out that the PCL reconstruction surgery we adopted currently may not be able to arrange the joint laxity properly.[68, 75, 76] It is high possible that the PCLR patients utilize a strategy to motive the muscle activities to overcome the instability of the knee joint during daily activities, which would apply the higher contact force in the knee at the same time and be harmful for the cartilage health. Besides, the rehabilitation program is also import for the recovery of PCLR patients, a proper rehabilitation will be quite helpful to prevent the OA at the knee joint.

Considering so many factors that may affect the OA risk in PCL patients, it is difficult to tell the possibility of OA incidence just from a cross-sectional research like our study. To assess the cartilage health and OA risk in PCLR patients after operation, a study should be designed with X-ray test of cartilage status during pre-, post-operation, and with a long time follow-up after the surgery. As the low incidence of PCL injuries during daily life, this kind of study would be a quite time consuming work. However, we can compare the kinematics and kinetics of PCLR patients with the healthy subjects to investigate if the PCL reconstruction surgery could fully restore the knee joint function during daily activities, and we could conclude the OA risk in the PCLR patients based on the joint function status that we got.

In our study, we found that there were several kinematic and kinematic differences in the patients when compared with the healthy subjects. Although no significant difference was found at the adduction moment, we do found there are reduced knee excursions, reduced knee flexion moments that may be associated with the OA incidence and progress. According to the literature, biomechanical changes may play roles in the initiation and progression of OA in the knee.[110] Based on our findings in this study, it is reasonable to conclude that the PCL reconstruction surgery can not completely prevent the tendency of OA progress in the PCLR patients. Although the surgery could help the patient reduce the pain and improve the joint stability, the PCLR patients may still endure a high risk of OA incidence even in a long term after the ligament reconstruction surgery.

4.4 Conclusions

4.4.1 Summary

PCL injury and reconstruction are attracting more and more attentions nowadays, while the effect of PCL reconstruction is commonly assessed by the questionnaire score or the clinical test. However, it is still unknown the status of the kinematic and kinetic functions of knee joints in these PCLR patients so far, and it is also unknown if the reconstruction could successfully block the post-surgery joint degeneration in the long term. In our study, we investigated the kinematic and kinetic function of the knee joint in PCLR patients and hypothesised that the knee joint function could not be properly restored after surgery and that the patients may still endure the risk of OA after operation. The results supported our hypothesis and showed that there are significant differences of knee joint function between the patients and the healthy subjects, which proved that the PCLR patients did not obtain the normal knee kinematics and kinetics after surgery. Our study is the first investigation so far concerning the three-dimensional kinematic and kinetic function of PCLR knee joints. The results revealed that the PCLR patients still exhibited an abnormal gait pattern compared with the healthy subjects even during a long time after surgery. Moreover, the abnormality was not only in the reconstructed knee joint, but also in the CL side. Besides, the abnormal parameters we found in our study, for example the stiff gait pattern that the PCLR patients acquired in our research, may suggest the PCLR patients are still endure the risk of OA even after the operation.

The PCL reconstruction technique utilized currently could definitely improve the knee joint function of PCL injured patients, especially for the patients who have PCL combined injuries at the knee joint. However, our study pointed out that the knee joint kinematics and kinetics of the PCLR patients were not fully restored after the ligament reconstruction surgery, and the PCLR patients may still endure a high risk of OA at the knee joint even after the ligament reconstruction surgery.

4.4.2 Limitations

There are some limitations in our study. As PCL injuries are usually the result of serious violent accidents and the patients usually suffer damage to other knee structures except for the PCL, the patients may have the operation with different injury levels and operation methods. In this way, the variety of injury mechanisms and reconstruction methods may potentially affect the gait patterns of our patients. This inconsistency of the injury levels and reconstruction methods will affect the reliability of the study. For example, the isolated PCL injured patients and PCL combined injured patients may have different kinematics and kinetics at the knee joint, and the different reconstruction method would certainly exhibit these difference after the surgery. Further study should investigate the knee joint function with the similar injury level, in order to reduce the effect that different reconstruction methods may bring. However, as the PCL injuries are rare traumas in the daily life, it would be a time-consuming work to collect enough numbers of these patients. With a big number of participants, further study should also consider the effect of other factors such as the gender, BMI or the dominant leg.

Besides, our study did not include the clinical performance of the PCLR patients after operation. The PCLR patients may have different clinical performance after the surgery, for example, the residual laxity was recognized as the common complication at the knee joint. The different clinical performance of the patients may suggest that the patients would apply different walking strategies during daily life, which would affect the kinematics and kinetics of the knee joints in PCLR patients. Other clinical performance such as the pain level may also affect the kinematics and kinetics of knee potentially. Further study could include the clinical performance of the PCLR patients with some specialized questionnaire to assess the pain level and the medical equipments such as the X-ray test to check the joint laxity.

Another limitation is that our study is a cross-sectional study, it is still unknown that which kind of gait patterns the patients may adapt before the injury, early after the operation and long-term after the operation. To investigate the effect of surgery on a group of patients, the optimal method is to compare the functional performance of the patients before and after the surgery. However, as a cross-sectional study, it is quite difficult to understand the kinematic and kinetic performance of knee joints at different time points. We can only compare the patients with the healthy subjects to see if the knee joint function back to normal, however, it is unable to tell the effect of reconstruction surgery from our study with this method. To have a better understanding of the effect of PCL reconstruction surgery on the patients, further study should apply a long time follow up before and after the surgery in order to check the gait pattern changes of the patients at different time points.

4.4.3 Outlook

In our study, we found the functional differences between the PCLR patients and healthy subjects, which indicated that the reconstruction technique of PCL so far cannot fully restore the knee joint kinematics and kinetics. Besides, the post-surgery patients adapted a gait pattern that with the risk of OA at the knee joints. Our study pointed out that the PCL injured patients may still suffer the risk of cartilage degeneration even after the reconstruction surgery. However, out research results were gained only based on the functional factors, but without the research to the structure changes, such as cartilage morphology and muscle activities. These kinds of information would help us gain a better understanding of the relationship between the PCL-based structure changes and OA risks after the operation. Further study should apply a long-term follow-up study, and focus on investigating the PCL-based structure changes and the underlying reasons with the help of EMG and X-ray detection methods. A thorough investigation of the relationship between the structure changes and the knee joint function will provide information to help the patients gain a normal gait pattern after the surgery and could also help the patients prevent the cartilage degeneration in the long term.

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Affidavit

“I, [Yanlin Zhong] certify under penalty of perjury by my own signature that I have submitted the thesis on the topic [Three-dimensional kinematics and kinetics of the knee in posterior cruciate ligament reconstructed patients during daily activities] I wrote this thesis independently and without assistance from third parties, I used no other aids than the listed sources and resources.

All points based literally or in spirit on publications or presentations of other authors are, as such, in proper citations (see "uniform requirements for manuscripts (URM)" the ICMJE www.icmje.org) indicated. The sections on methodology (in particular practical work, laboratory requirements, statistical processing) and results (in particular images, graphics and tables) correspond to the URM (s.o) and are answered by me. My interest in any publications to this dissertation correspond to those that are specified in the following joint declaration with the responsible person and supervisor. All publications resulting from this thesis and which I am author correspond to the URM (see above) and I am solely responsible.

The importance of this affidavit and the criminal consequences of a false affidavit (section 156,161 of the Criminal Code) are known to me and I understand the rights and responsibilities stated therein.

Signature ______________________________

Date ______________________________

Curriculum vitae

Mein Lebenslauf wird aus datenschutzrechtlichen Gründen in der elektronischen Version meiner Arbeit nicht veröffentlicht.

List of publications

Publications in scientific journals

Moewis P, Boeth H, Heller MO, Yntema C, Jung T, Doyscher R, Ehrig RM, **Zhong Y**, Taylor WR. Towards understanding knee joint laxity: Errors in non-invasive assessment of joint rotation can be corrected. Med Eng Phys, 2014, 36(7): 889-95.

International Congresses

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Acknowledgement

I would like to thank the China Scholarship Council for financing my study in Germany. The study life in Berlin is really a great experience for me, I learned a lot not only at the academy, but also at the society of Germany. The financial support could help me focus on my studies and give me the chance to obtain an international view. Great thanks for the staff working in the embassy of China, they kindly helped me a lot during my stay in Berlin.

Thanks to the Julius Wolff Institute, which provided me the great opportunity to get in touch with the advanced technique in my study field. In our Institute, I learned a lot from designing the experiment to finally finishing this dissertation. It is really my honor to join our institute as a MD student, I am so glad that I could be one member of JWI in the past few years.

Thanks to the patients and participants that volunteered in my measurements, I could not have finished the measurements without the help of you. I really appreciate for your kindness and cooperation during the measurements.

Thanks to Prof. Georg N. Duda who invited me into the Julius Wolff Institute and helped me a lot with my study, especially at the last year when I was processing my data, he provided quite a lot of support to help me. Thank you so much for your kind encouragement.

Thanks to Prof. Markus O. Heller for helping with everything since I first came to Germany, he helped me a lot when I was still new to our institute. He provided me with a lot of good ideas and taught me how to do the measurements. Wish him everything good in England.

Thanks to Dr. Heide Boeth, who helped a lot with my measurements, especially the kindness help in the last years of my study. She helped me finally finished my project, and provided a lot of help with the paper and thesis writing. I could not have finished this dissertation without her help.

Thanks to Dr. Tobias Jung, who recruited the patients from the hospital and provided many clinical materials to help me finish this dissertation. Thanks to his students Julia and Teresa, the project could not finish so soon without their work. Thanks to Prof. Andreas Weiler, thanks for the kind support to this project.

Thanks to Prof. William Taylor, Dr. Alexey Sharenkov, Dr. Navrag Singh, Shuyang Han, Philippe Moewis, Alison Agres, Mark Heyland, Adam Trepczynski…and so on, it is my honor to work with you and to have spent these years together. Thanks for the great help not only in the work but also in the daily life. I feel so lucky to join our group and work with you.

Finally, I am most grateful to my family. Thanks to my parents, they are always supporting me and helping me get through the tough times. Their encouragement and understanding helped me go aboard and study in Germany. Thanks to my wife, Xiaofei, the time we spent in Germany would be the best memory in our life. I will keep on progressing with the love of my family.