Comprehensive Assessment and Investigation of Knee Joint Functionality in ACL Reconstructed Subjects

Course of performance capacities from Pre- to Six Months Post-ACL Reconstruction

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„Arbeit dehnt sich in genau dem Maß aus, wie Zeit für ihre Erledigung zur Verfügung steht“
(Cyril Northcote Parkinson, 1909-1993)

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Summary

The anterior cruciate ligament (ACL) has an important function for the knee joint stability. Therefore, tearing of the ACL leads to a severe impairment of the human locomotor system, including a reduction of knee joint stability and knee joint functionality. Accompanied by a potentially long-lasting reduction of the activity level in locomotion tasks of daily life and sports. The incidence of ACL tears reached 42 per 100,000 inhabitants in German hospitals in 2016. Furthermore, an increasing amount of ACL tears was determined in recreational athletes in recent decades.

In the ACL tearing scenario further biological structures of the knee joint (i.e. menisci, collateral ligaments, and joint cartilage) can get concomitantly injured. Therefore, tears of the ACL can negatively impair the knee joint homeostasis to a high extent. This impaired joint homeostasis shall get restored by the surgical reconstruction of the ACL and the subsequent rehabilitation program. Although reconstruction techniques improved in recent years, there is no guarantee that the injured and reconstructed individuals achieve a symptom-free daily life and the pre-injury sports level. Additionally, the earlier onset of degenerative joint diseases (i.e. knee osteoarthritis) in ACL reconstructed individuals represents a challenging field for the prospective quality of life and activity level.

ACL injured and reconstructed individuals receive a post-surgical rehabilitation program, which aims to recover the knee joint stability and functionality. Current criteria for return-to-sports recommendations represent the time-period since the reconstruction of the ACL and the knee joint functionality in clinical physical examination (i.e. Lachman test). However, these criteria bear the risk that knee joint functionality is not determined comprehensively enough, as hardly any information about knee joint functionality in locomotion tasks of daily life and sports are detected.

The necessity of activity-specific functional tests as well as the combination of various functional tests to determine knee joint functionality was widely described and discussed. Accordingly, for assessment of dynamic functionality one-legged jumps for distance have established since the 1980s. However, these tests are not applied standardized in the clinical and rehabilitative field. Although one-legged jumps for distance represent a high-demanding locomotion task, it seems not sufficient to rely on the results of these tests alone, to give an adequate rating of functionality for the return to pre-injury sports. Knee joint stability and functionality is determined by numerous factors in a complex framework. Furthermore, the locomotor system has various strategies of functional adaptations, depending on the musculoskeletal impairments. To meet these requirements in functional testing, a test battery should have the claim of a comprehensive approach and should be applied repetitively over the rehabilitation cycle. Singular measurement of the knee joint functionality at the time point of potential return-to-sports seems not to be adequate. By repetitive comprehensive functional testing, important data can be collected, which provide a broader picture of the state of the knee joint functionality. According to the detected functional deficiencies, the rehabilitation program can be specifically adapted. This could benefit to counteract the early manifestation of musculoskeletal imbalances and to better prepare the individuals for the return to sports.

The whole thesis comprises eight main chapters. In Chapter 1 the preface and the outline of the thesis are depicted. In Chapter 2 the entire theoretical background of the thesis is described by the elaboration of the state of research, including all anatomical fundamentals and the wide range of consequences that can occur due to ACL tears. Furthermore, the current state of functional testing and common return-to-sports concepts after ACL reconstructions are briefly described. Out of the deduced research gaps, the purpose of the thesis is motivated and specifically depicted in Chapter 3. Therein, the main research questions of this thesis are embedded in the synthesis of the theoretical findings of Chapter 2. Chapter 3 is finalized by the summarized illustration of the conducted studies, which were conducted to reach the purpose of the thesis, which was to analyze the knee joint functionality in ACL reconstructed subjects comprehensively over the rehabilitation cycle.

The following Chapter 4 contains the general methodology of the main study. In this main study, a comprehensive test battery was applied to ACL injured and reconstructed subjects at four test sessions. T1 was before the reconstruction; T2 seven weeks, T3 three months, and T4 four months after the ACL reconstruction. To meet the requirement of a comprehensive approach, knee joint functionality was assessed and analyzed in functional clinical tests (passive range of motion in knee flexion and knee extension, leg circumference measurements), in activities of daily living (straight gait over flat ground, straight gait over uneven ground, walking up and downstairs, and walking turns), and in sport-specific functional performance tests (unilateral and bilateral jumping tests, isometric force tests). Besides kinematic and kinetic parameters, special attention lied on the side-to-side relationship of the legs (leg symmetry index) in the examination of the knee joint functionality. Additionally, standardized questionnaires/scores were applied (Knee Injury and Osteoarthritis Outcome Score and Tegner Activity Score), to determine self-evaluated knee joint functionality and psychometric properties, as the influence of the knee joint injury on the quality of life, and the current activity level. After data acquisition, knee joint functionality was analyzed intra-individually over the investigation period up to six months after ACL reconstruction. Furthermore, the results of the ACL reconstructed subjects at T4 were compared to anthropometrically-matched healthy control subjects.

Because the reproducibility of turning gait locomotion was recently not described in literature, this topic was examined in a methodological pre-study, which is also part of this thesis (Chapter 5). Therein, in relation to the parameters general locomotion strategy, ground contact times, medio-lateral, and vertical ground reaction forces, it could get shown that turning locomotion was performed reproducible at different testing times at different days. Due to these findings, turning tasks were determined valid for inclusion into the main study as additional daily locomotion task.

Selected results of the main study, which were included in this thesis, are depicted in Chapter 6 and 7.

Chapter 6 comprises the analyses of the functional clinical tests, the sport-specific functional performance tests, and the results of the questionnaires/scores. Therein, a general pattern of the knee joint functionality over the investigation period was found in the majority of the analyzed parameters. Initially, a strong reduction of the functionality was found from T1, before the reconstruction, up to T2, seven weeks after the reconstruction. Afterwards the functionality increased in the majority of the parameters up to six months after ACL reconstruction. However, in average, the level of functionality of the healthy control group could not get reached. This course of functionality emerged as well in the functional clinical tests, the self-evaluated knee joint functionality and the activity level. Out of this results and findings, it was concluded that the ACL injured and reconstructed subjects of this study did not reach the level of the matched control group and, thus, did not achieve their pre-injury activity level. Additionally, strong variances of the results were found. This gave indication for a very individual healing and rehabilitation process.

The results, findings, and conclusions of the analyses of these functional tests were supported by the descriptive analyses of the turning gait locomotion (Chapter 7). Therein, in the half of all analyzed turning locomotion conditions tendencies of kinematic and kinetic adaptations were detected. Kinematic adaptations mainly occurred in increased knee joint flexion over the entire stance phase. Tendencies of kinetic adaptations emerged inconsistent, with overloading and underloading of the injured/reconstructed and the non-injured leg, short- (T2), mid- (T3), and long-term (T4) after the reconstruction compared to the healthy control group.

The findings of the studies are summarized in the general discussion (Chapter 8) and discussed according to the recovery of full knee joint stability and functionality, the return to pre-injury sports, and the potential manifestations of the respective adaptation and compensation mechanisms. Therein, it could get concluded that the analyses and findings confirmed that ACL injured and reconstructed showed wide-spread deficiencies of the knee joint functionality even six months after the reconstruction. These deficiencies emerged on various levels, as besides deficits in biomechanical parameters in daily living and sports locomotion tasks, psychological constraints were found, manifested in a reduced quality of life at six months after reconstruction. The general discussion leads to the conclusions and practical implications of this thesis. Therein, it was stated that due to the complexity of the reduced functionality, a general release in sports of reconstructed ACL individuals is not recommended. For this reason, it is indicated to enhance rehabilitation programs. By a standardized assessment of the knee joint functionality over the rehabilitation cycle, essential knowledge can be acquired and, thus, rehabilitation programs can be adapted more specifically, according to the detected individual functional deficits. Additionally, in relation to the results of the functional tests a better time-point for the return to pre-injury sports can be determined. Finally, potential manifestations of functional adaptations, which can

lead to musculoskeletal imbalances and disorders, can be detected and treated earlier. Thus, this could help to counteract the earlier onset of degenerative joint diseases.

Therefore, this thesis provides comprehensive knowledge about the course of knee joint functionality over the rehabilitation cycle and, hence, important findings and contributions for a general enhancement of rehabilitation programs after ACL tear and surgical reconstruction.

Zusammenfassung

Das vordere Kreuzband hat eine wichtige Funktion für die Kniegelenksstabilität. Daher führt ein Riss des vorderen Kreuzbandes zu schwerwiegenden Beeinträchtigungen für den menschlichen Bewegungsapparat dar, insbesondere durch eine starke Reduktion der Kniegelenksstabilität und Kniegelenksfunktionalität. Dies geht einher mit einer potentiellen lang andauernden Reduzierung des Aktivitätsmaßes in alltäglichen und sportlichen Bewegungen führen kann. Im Jahr 2016 lag die Inzidenzrate in Deutschland bei etwa 42 pro 100.000 Einwohner. Weiterhin wurde in den letzten Jahrzehnten eine Zunahme von vorderen Kreuzbandrupturen bei Freizeitsportlern festgestellt.

Im Verletzungsszenario des vorderen Kreuzbandes können weitere biologische Strukturen des Kniegelenks (Menisken, Seitenbänder, Gelenkknorpel) begleitend verletzt oder stark beeinträchtigt werden. So führen Verletzungen des vorderen Kreuzbandes zu einer erheblichen Beeinträchtigung der Kniegelenkhomöostase. Diese soll durch die operative Rekonstruktion und die nachfolgende Rehabilitation wiederhergestellt werden. Obwohl sich die Rekonstruktionstechniken in den letzten Jahren stark verbessert haben, kann nicht gewährleistet werden, dass die verletzten Personen wieder einen beschwerdefreien Alltag erlangen und das sportliche Niveau von vor der Verletzung erreichen können. Zusätzlich spielt das lebenszeitlich frühere Auftreten von degenerativen Gelenkerkrankungen, (z.B. Gonarthrose) bei den kreuzbandverletzten Personen eine gewichtige Rolle für die zukünftige Lebensqualität und das prospektive Aktivitätsniveau.

Kreuzbandverletzte Personen erfahren postoperativ ein Rehabilitationsprogramm, das auf die Wiedergewinnung der Kniegelenkstabilität und Kniegelenksfunktionalität abzielt. Bei der Rückkehr auf ein sportliches Aktivitätsniveau bilden derzeit zumeist die Zeitdauer seit der operativen Rekonstruktion und die Kniefunktionalität in klinischen Tests (z.B. Lachman-Test) die entscheidenden Kriterien. Diese Kriterien bergen allerdings das das Risiko, dass die Funktionalität des Kniegelenks nicht umfassend genug gemessen wird, da so kaum Informationen über die Kniegelenksfunktionalität in alltäglichen und sportlichen Bewegungen erhoben werden.

Die Notwendigkeit von aktivitätsspezifischen funktionellen Tests sowie die Kombination verschiedener funktioneller Tests, zur Bestimmung der Kniegelenksfunktionalität wurde hinreichend beschrieben. So hat sich die Bestimmung der dynamischen Funktionalität über Einbeinweitsprünge seit den 1980er Jahren etabliert. Diese Tests werden allerdings nicht standardisiert im klinischen und rehabilitativen Bereich eingesetzt. Obwohl Einbeinweitsprünge eine anspruchsvolle sport-spezifische Bewegung darstellen, scheint es aber auf Basis dieser Tests alleine nicht ausreichend zu sein, eine adäquate funktionale Einschätzung für eine Rückkehr in den Sport zu geben. Die Kniegelenkstabilität und Kniefunktionalität werden durch zahlreiche Faktoren in einem komplexen Gefüge bestimmt. Zudem bestehen vielschichtige Anpassungsmöglichkeiten des Bewegungsapparats auf Grund muskuloskeletaler Einschränkungen. Um diesen komplexen Anforderungen gerecht zu werden, sollte

daher eine funktionelle Testbatterie den Anspruch der Ganzheitlichkeit haben und mehrfach über den Rehabilitationsverlauf durchgeführt werden. Einmalige Messungen der Kniegelenksfunktionalität zum Zeitpunkt des potenziellen Wiedereintritts in den Sport erscheint nicht ausreichend. Stattdessen können durch wiederholtes umfassendes funktionelles Testen, wichtige Daten erhoben werden, die ein breiteres Bild über den Status der Kniegelenksfunktionalität liefern. In Bezug zu den erhobenen funktionellen Defiziten, kann dann das Rehabilitationsprogramm spezifisch angepasst werden. So kann der frühzeitigen Manifestierung muskuloskeletaler Dysbalancen entgegengewirkt und die Personen besser auf die Rückkehr in den Sport vorbereitet werden.

Die gesamte Dissertation umfasst neun Hauptkapitel. Kapitel 1 enthält ein Vorwort sowie einen Überblick der Dissertation. In Kapitel 2 ist der gesamte theoretische Hintergrund der Dissertation durch die Aufarbeitung des gegenwärtigen Forschungsstandes dargestellt. Darin sind alle wichtigen anatomischen Zusammenhänge sowie die weitreichenden Konsequenzen, die durch vordere Kreuzbandverletzungen entstehen können, beschrieben. Weiterhin, sind der gegenwärtige Stand des funktionellen Testens sowie gängige Konzepte zur Rückkehr in den Sport nach vorderen Kreuzbandverletzungen kurz beschrieben. Aus den abgeleiteten Forschungslücken, wird in Kapitel das Ziel dieser Dissertation motiviert und spezifisch dargestellt. Darin werden die Hauptforschungsfragen in die Synthese der theoretischen Grundlagen aus Kapitel 2 eingebettet. In Kapitel 3 wird abschließend durch eine Darstellung aller Studien, die durchgeführt wurden, um das Ziel der Dissertation zu erreichen, nämlich die Kniegelenksfunktionalität von kreuzbandverletzten Probanden über den Rehabilitationsverlauf zu analysieren.

Das folgende Kapitel 4 beinhaltet die gesamte Methodik dieser Haupt-Studie. In dieser Haupt-Studie wurde mit kreuzbandverletzten Probanden eine umfassende funktionelle Testbatterie an vier Testzeitpunkten durchgeführt. T1 wurde vor der Rekonstruktion durchgeführt. T2 sieben Wochen, T3 drei Monate und T4 sechs Monate nach der Rekonstruktion. Um den Anspruch der Ganzheitlichkeit der Testbatterie zu gewährleisten wurde die Kniegelenksfunktionalität bei klinischen Tests (passives Bewegungsausmaß in Knieflexion und Knieextension, Umfangsmessungen am Bein), bei Alltagsbewegungen (Gehen in der Ebene, Gehen mit Unebenheiten, Treppen Gehen und Kurven Gehen) und bei sport-spezifischen Tests (unilaterale und bilaterale Sprungtests, isometrische Krafttests) gemessen und analysiert. Neben kinematischen und kinetischen Parametern, lag ein besonderes Augenmerk bei der Untersuchung der Kniegelenksfunktionalität auf dem Seitigkeitsverhältnis der Beine (Bein-Symmetrie-Index). Zudem wurden standardisierte Fragebögen/Scores eingesetzt (Knee Injury and Osteoarthritis Outcome Score und Tegner Activity Score), um die selbsteingeschätzte Funktionalität und den Einfluss der Kniegelenkverletzung auf den Alltag und die Lebensqualität der Probanden sowie das gegenwärtige Aktivitätsniveau zu erfassen.

Auf Basis der erhobenen Parameter der Testbatterie wurde die Funktionalität des Kniegelenks in intraindividuellen Analysen über den Untersuchungszeitraum bis sechs Monate nach der

Kreuzbandrekonstruktion analysiert. Zusätzlich wurden die Ergebnisse der kreuzbandverletzten Probanden an T4 mit anthropometrisch gemachten Kontrollprobanden verglichen.

Da die Reproduzierbarkeit des Kurven Gehens bisher noch nicht in der Literatur beschrieben war, wurde dies in einer methodischen Vorstudie, die Teil dieser Arbeit ist (Kapitel 5), überprüft. Darin konnte, an Hand der Faktoren Lokomotionsstrategie, Bodenkontaktzeiten und medio-lateraler sowie vertikaler Bodenreaktionskraft, bestätigt werden, dass die Lokomotion des Kurven Gehens bei Gesunden über den Tagesverlauf reproduzierbar ausgeführt wird. Auf Grund dieser Ergebnisse wurde das Kurvengehen als weitere zu untersuchende Alltagsbewegung in die Testbatterie der Haupt-Studie eingeschlossen.

Ausgewählte Ergebnisse der Haupt-Studie, die Einklang in diese Dissertation fanden, sind in Kapitel 6 und 7 beschrieben und dargestellt.

Kapitel 6 beinhaltet dabei die Aufarbeitung der klinischen Tests, der sport-spezifischen Tests sowie die Ergebnisse der Fragebögen/Scores. Darin zeigte sich bei den meisten analysierten Parametern der sport-spezifischen Tests ein einheitliches Muster der Kniegelenksfunktionalität über den Untersuchungszeitraum. Zunächst wurde eine starke Reduktion der Funktionalität von T1, vor der Rekonstruktion, zu T2, sieben Wochen nach der Rekonstruktion, festgestellt. Daraufhin verbesserte sich die Funktionalität in den meisten Parametern bis sechs Monate (T4) nach der Kreuzbandrekonstruktion. Jedoch wurde im Mittel das Funktionalitätsniveau der gesunden Kontrollgruppe nicht erreicht. Dieser Verlauf der Funktionalität zeigte sich auch in den klinischen Tests, in der selbsteingeschätzten Kniegelenksfunktion und im Aktivitätsniveau. Aus diesen Ergebnissen wurde geschlossen, dass die kreuzbandverletzten Personen dieser Studie das Niveau der gemachten Kontrollgruppe nicht erreichten und demnach auch nicht ihr Vorverletzungsniveau. Zusätzlich wurde eine große Varianz der Ergebnisse festgestellt, was zusätzlich für einen sehr individuellen Heilungs- und Rehabilitationsprozess spricht.

Die Ergebnisse und Schlussfolgerungen der Analyse der funktionellen Tests wurden durch die deskriptive Analyse des Kurvengehens gestützt (Kapitel 7). Darin wurden in der Hälfte der Kurvengehbedingungen, Tendenzen kinematischer und kinetischer Anpassungen festgestellt. Die kinematischen Anpassungen prägten sich hauptsächlich durch eine erhöhte Knieflexion über die Standphase aus. Die kinetischen Anpassungen zeigten uneinheitlich, eine Über- oder Unterbelastung des verletzten und nicht verletzten Beines, sowohl frühzeitig nach der Rekonstruktion (T2), als auch mittel- (T3) und längerfristig (T4), im Vergleich zu der gesunden Kontrollgruppe.

Die Ergebnisse dieser Studien werden in einer allgemeinen Diskussion (Kapitel 8) zusammengeführt und vor dem Hintergrund der vollen Wiederherstellung der Kniegelenksfunktion, des Rückkehrs in den Sport auf das Vorverletzungsniveau und möglicher Manifestationen jener Anpassung- und Kompensationsmechanismen diskutiert. Darin wurde geschlossen, dass die durchgeführten Analysen bestätigten, dass kreuzbandverletzte Personen ein breit gefächertes Defizit der Kniegelenksfunktionalität auch noch sechs Monate nach der Rekonstruktion zeigen. Dies prägte sich auf mehreren Ebenen aus, da neben biomechanischen Defiziten in Alltags- und Sportbewegungen auch persönliche Defizite gefunden wurden, manifestiert in einer reduzierten Lebensqualität. Diese Diskussion führt schließlich zu den Schlussfolgerungen und praktischen Implikationen dieser Dissertation. Darin wurde festgehalten, dass auf Grund der Komplexität der reduzierten Funktionalität, eine generelle Freigabe von Personen mit vorderen Kreuzbandverletzungen in den Sport nach sechs Monaten nicht generalisiert empfohlen werden sollte. Aus diesem Grund gilt es, Rehabilitationsprogramme stets weiter zu verbessern. Durch die standardisierte Erhebung der Kniegelenksfunktionalität über den Rehabilitationsverlauf, könnten daher wichtige Erkenntnisse gewonnen werden und so die Rehabilitationsprogramme, entsprechend individueller funktioneller Defizite, adaptiert werden. Zusätzlich kann auf Basis von Funktionalitätstests ein besseres Maß für den Wiedereintritt in den Sport gefunden werden. Abschließend könnten frühzeitig Manifestationen funktioneller Adaptationen, die zu muskuloskeletalen Dysbalancen führen können, erkannt und behandelt werden. Dies könnte helfen dem lebenszeitlich früheren Beginn degenerativer Gelenkerkrankungen frühzeitig entgegenzuarbeiten.

Daher liefert diese Dissertation umfassende Erkenntnisse über den Verlauf der Kniegelenksfunktionalität über den Rehabilitationszeitraum und damit einen wichtigen Beitrag zur generellen Verbesserung von Rehabilitationsprogrammen nach Kreuzbandrupturen und deren operativen Rekonstruktionen.

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List of Abbreviations

ACL	Anterior cruciate ligament
ADL	Activities of daily living
BPTP	Bone-Patellar tendon-bone
BW	Bodyweight
CG	Control group
CI	Confidence interval
CNS	Central nervous system
COM	Center of mass
COP	Center of pressure
e.g.	Exempli gratia = for example
FP	Force plate
FPT	Functional performance test
GRF	Ground reaction force
HT	Hamstrings tendon
i.e.	Id est = that is to say
LCL	Lateral collateral ligament
LSI	Leg symmetry index
M.	Musculus
MCL	Medial collateral ligament
Mm.	Musculi
ms	Milliseconds
MoCap	Motion capturing
Nm	Newton meter
OA	Osteoarthritis
QoL	Quality of life
SD	Standard deviation

1 General Introduction

1.1 Preface

Injuries of biological structures of the human body can occur throughout someone's entire lifetime. Especially, injuries of ligaments can occur in nearly any situation of daily life, however, more frequently while performing in sports or physical activities, as a consequence of accidents and due to high-demanding working situations (BAHR & KROSSHAUG 2005; MYKLEBUST et al. 2003).

As ligaments generally have a passive joint stabilizing function in the human body, tearing of ligaments results in a wide range of consequences, such as loss of the joint's function, joint instability or adaptations of locomotion processes due to the joint's loss of function (WHITING & ZERNICKE 2008). Ligamentous injuries within a joint can influence the individual lifestyle not only in form of a reduction of physical activities or sports, but also with regard to a general reduction of the quality of life (QoL) and the activities of daily living (ADL), short- and long-term after the injury (BIEN & DUBUQUE 2015).

Reasons therefore lie in the fact that injuries of stabilizing ligaments in the most important joints can lead to further pathologic changes in surrounding biological structures within the joint, the whole musculoskeletal system or they can lead to changes in activity and general locomotion due to chronic diseases. Summarized, the consequences of such ligamentous injuries within a joint contribute to a deterioration of the joint's interior homeostasis, which consequently intensifies pathologic processes (VON LÜBKEN et al. 2008). Depending on the severity of ligamentous injuries and potential concomitant injuries of surrounding biological structures, joint homeostasis can be influenced to a smaller or larger extent, which consequently also has an impact on the rehabilitative outcome and the time of rehabilitation (VON LÜBKEN et al. 2008).

The knee joint is the biggest joint of the human body and is one of the most important joints for human locomotion. In locomotion processes, the knee joint has important function for transmitting load between the ground and the pelvis in the most economical way. Additionally the knee joint is essential for all motions induced by the legs, with flexion, extension and internal and external rotation. Within the knee joint, the anterior cruciate ligament (ACL) functions as an important structure for knee joint stability, in order to prevent hyperextension of the tibia in relation to the femur and for limiting internal and external rotation of the knee joint.

Due to the importance of the ACL for knee joint stability one has to be aware of the fact that injuries of ACLs, isolated or in combination with injuries of surrounding biological structures (e.g. the Menisci), can lead to far-reaching consequences within the knee joint and the entire lower limbs. If the knee joint's function is not fully recovered, changes can range from chronic knee joint instability, enlarged odds ratio of earlier onset of knee osteoarthritis (OA) in life-time, pathologic changes in the general locomotion processes up to a general reduction of the activity level, which is mostly associated with a reduction of the quality of life (QoL) (MANSSON et al. 2011; MYKLEBUST et al. 2003; MYKLEBUST & BAHR 2005; RUDOLPH et al. 2000; WEXLER et al. 1998). Such a manifested knee deficiency led in 46% of reconstructed individuals to reduce the sports and activity level and in 26% to impairments in daily work (MYKLEBUST et al. 2003). Injury-induced changes in the individual life situation, due to long or general drop-out from sport or work as well as a described general reduction of the activity level due to ACL deficiency are still major concerns after ACL tears and reconstruction (ANDERSSON 1993; DANIEL et al. 1994, 1995; ENGSTRÖM 1994; HAWKINS et al. 1986; MANSSON et al. 2011; NOYES et al. 1983a; ROI et al 2006; ROOS 2005; SCHMIDT-WIETHOFF & DARGEL 2007; SÖDERMAN et al. 2002).

Besides these individual consequences, ACL tearing also leads to a variety of socio-economic problems, because apart of competitive athletes, an increasing number of recreational athletes have been affected in recent years (FEDERAL HEALTH MONITORING OF GERMANY 2016). In Germany, there were about 35,000 ACL tears registered in hospitals in 2013, leading to a cumulative incidence of about 42 ACL tears per 100,000 inhabitants per year. The ACL tear, the subsequent surgical reconstruction and the pre- and post-surgical rehabilitation process lead to longer working incapacities compared to the average working incapacity of all diseases in Germany (FEDERAL HEALTH MONITORING OF GERMANY 2016). Additionally, the average age of 38.4 years of ACL reconstructed individuals requiring stationary rehabilitation in 2012 was remarkably lower than the general average of all diseases, which was 51.7 years for requirement of stationary rehabilitation (FEDERAL HEALTH MONITORING OF GERMANY 2016). These results imply that along with the individual consequences, tears of the ACL have an enormous influence on a national socio-economic and healthcare system, resulting in long-term working incapacities in association with high treatment costs (FEDERAL HEALTH MONITORING OF GERMANY 2016; NUNEZ et al. 2012; MATHER et al. 2013). These social and economic impacts are amplified by acute and chronic diseases, potentially occurring as consequences of ACL tears, like knee OA (MANSSON et al. 2011; MYKLEBUST et al. 2003; ØIESTAD et al. 2009; ROOS 2005; WEXLER et al. 1998). In particular, occurring chronic knee instabilities, concomitant injuries of the Menisci, and manifested compensation strategies can induce an earlier onset of OA in both legs compared to individuals without such a ligamentous knee injury, where about 50% show evidence of knee OA within five to 20 years after the initial ACL tear (FITHIAN et al. 2002; LOHMANDER et al. 2004, 2007; MYKLEBUST et al. 2003; ØIESTAD et al. 2009; ROOS 2005; VON PORAT et al. 2004; WHITING & ZERNICKE 2008). Consequently, artificial joint replacement with endoprosthesis and a complete inability to work might be required potentially earlier in lifetime. Such subsequent chronic diseases or long-term follow-up consequences show that ACL tears and the related consequences can increase the individual burden throughout the whole lifetime.

The rising amount of ACL tears, the described consequences to other biological structures, or the general reduction of the QoL or performance in physical activities prospectively show that the enhancement of knee joint rehabilitation after ACL tears and reconstructions aiming for a full recovery of the knee joints' function is still a substantial scientific field to give contribution to the improvement for the general outcome after ACL tears (ROOS 2005). This has been amplified in recent years by the challenging field of full restoration of knee function and by the aim to find the best individual rehabilitation program to ensure full knee stability, knee joint functionality, symptom-free performance in activities of daily living and the return to pre-injury sports on the pre-injury intensity level. However, although the patients' torn ACL was reconstructed many individuals develop chronic knee joint instabilities and suffer from chronic degenerative joint diseases or as well sustain to a high rate a secondary ACL rupture at the reconstructed leg or a ACL tear at the contralateral leg (BIEN & DUBUQUE 2015; ØIESTAD et al. 2009; PATERNO et al. 2010; PINCZEWSKI et al. 2007; ROOS 2005; RUDOLPH et al. 2000; SALMON et al. 2005; WRIGHT et al. 2007). Even if individuals successfully return to pre-injury sports and activity level, a re-injury rate of ACL reconstructed individuals can be quantified by 10% to 30% (LEYS et al. 2012; PATERNO et al. 2010; SHELBOURNE et al. 2009). This shows that the general prospect that individuals can get reintegrated in pre-injury sports is generally not achievable even for young competitive athletes (ARDERN et al. 2011; ARDERN et al. 2012; BIAU et al. 2007; KVIST et al. 2005; MANSSON et al. 2011; VON PORAT et al. 2004). Out of all athletes, who suffered from ACL tears and underwent an ACL reconstruction, it appeared that only one third is able-bodied to return to pre-injury sports up to one year post-reconstruction (ARDERN et al. 2011, 2012). Even two to seven years after ACL reconstruction, less than 50% have returned to their pre-injury sports on the pre-injury activity level (ARDERN et al. 2011, 2012). Nonetheless, rehabilitation protocols and functional recovery improved in recent decades, as in the middle of the 1980s only 14% without surgical reconstruction could return to the pre-injury sports level and all of the examined reconstructed had to significantly reduce their sports-level or had to discontinue from any sports activity due to chronic knee joint instability (HAWKINS et al. 1986).

However, the majority of studies conducted in the field of examining functionality after ACL reconstruction were mainly designed as cross-sectional studies at specific time points pre- and/or post-reconstruction (ARDERN et al. 2012; DE FONTENEY et al. 2015). Therefore, the main purpose of this thesis, as the first one of its kind, was to conduct a longitudinal study with multiple test sessions from pre-reconstruction throughout the rehabilitation cycle up to six months post-reconstruction. This study design enables to describe the course of functionality fine-grained and comprehensively by its combination of the subjects' functional self-evaluation, objective functional clinical tests, biomechanical analyses of activities of daily living, and functional performance tests (FPTs) of recreational athletes in a mixed sample from pre- to six months post-reconstruction with four test sessions.

Due to the short- and long-term consequences caused by ACL tears, this thesis shall help to contribute knowledge to the wide field of rehabilitation after ACL tears and reconstructions. Furthermore, this thesis aims to provide deeper insights in the functional state of the ACL reconstructed subjects at various, specific time points over the rehabilitation process up six months post-reconstruction.

1.2 Outline of the Thesis

This thesis comprises six main chapters. The subsequent chapter (Chapter 2) provides the relevant theoretical background for a clear deduction of the thesis' purposes and research questions. This includes a brief description of the knee joint anatomy with the functional role of the ACL (Section 2.1), the ACL tearing mechanisms (Section 2.2), the descriptions of the commonly applied ACL reconstruction techniques (Section 2.3), and explanations of functional changes that appear as consequences of ACL tears and reconstructions (Sections 2.4 and 2.5), which represent the main challenges in ACL rehabilitation. This content is based on the findings and conclusions of scientific studies of the last decades, aiming at the examination of an enhancement of post-reconstructive outcome of individuals with ACL tears. This theoretical background serves as the basis of the clear and transparent deduction of the general research questions and the general purposes of this thesis (Section 2.7). The theoretical Chapter 2 is followed by the elaboration of the general methodology of the conducted studies of this thesis in Chapter 3.

Further on, the Chapters 4 to 6 include the illustration of specific results and findings of the conducted studies. Therewith, these Chapters contain all relevant content of data acquisition and data interpretation as source of the novel information of this thesis. These results and findings are built up in the structure of scientific research articles. The first (Chapter 4) and second (Chapter 5) study were published in the international peer-reviewed journals *Gait and Posture* and *PloS one*. The publication of the latter study (Chapter 6) is in preparation. Besides the subsequent listing of the full titles of the included studies of this thesis, an overview of the studies is illustrated in Figure 5 (Section 3.3):

- **Chapter 5 – Study I:**
  Reproducibility of Spatio-Temporal and Dynamic Parameters in Various, Daily Occurring Turning Conditions.
  KRAFFT FC, ECKELT M, KÖLLNER A, WEHRSTEIN M, STEIN T & POTTHAST W. (2015). *Gait and Posture,* 41: 307-312.

- **Chapter 6 – Study II:**
  How Does Functionality Proceed in ACL Reconstructed Subjects? – Proceeding of Functional Performance from Pre- to Six Months Post-ACL Reconstruction.
  KRAFFT FC, STETTER BJ, STEIN T, ELLERMANN A, FLECHTENMACHER J, EBERLE C, SELL S, POTTHAST W. (2017). *PloS one*, 12(5): e0178430.
- **Chapter 7 – Study III:**
  Analysis of Daily Occurring Turns in ACL Reconstructed Subjects from Pre- to Six Months Post-ACL Reconstruction.
  KRAFFT FC, STETTER BJ, POTTHAST W, ELLERMANN A, FLECHTENMACHER J, EBERLE C, SELL S & STEIN T. (2018).

2 Theoretical Background

This chapter comprises the theoretical background of the thesis. The theoretical background serves as the basis for the deduction of the thesis' purposes and research questions (Chapter 3). Besides a brief anatomical and functional description of the ACL (Section 2.1), the ACL injury mechanisms (Section 2.2), as well as common and established ACL reconstruction techniques, the objectives of a surgical ACL reconstruction are presented (Section 2.3). Afterwards, the manifold somatic and behavioral consequences (Sections 2.4, 2.5, and 2.6), occurring after ACL tears and surgical ACL reconstructions are described. After this detailed elaboration of all essential theoretical background, in the subsequent Chapter 3, the research questions is deduced (Section 3.1) out of the presented knowledge and the overall scope of this thesis is presented to complete the theoretical part of this thesis.

2.1 Anatomy and Function of the ACL

Anatomy of the ACL

The ACL is embedded in the articular capsule of the knee joint and represents one of the most important structures for maintaining knee joint stability. It has its origin in the fossa intercondylaris in between both femur condyles at the posterior part of the inner surface of the lateral femoral condyle (Figure 1) (DUHTON et al. 2006). The ACL runs anteriorly, medially, and distally from the femoral attachment to the anterior surface of the midtibial plateau (Figure 1) (DUHTON et al. 2006; WHITING & ZERNICKE 2008).

The ACL consists of two main bundles, the anteromedial bundle and the posterolateral bundle, and has a non-regular cross-sectional shape (BERNARD et al. 1997; DUHTON et al. 2006). The fibers of the ACL fan out as they approach the tibial attachment (BERNARD et al. 1997; DUHTON et al. 2006).

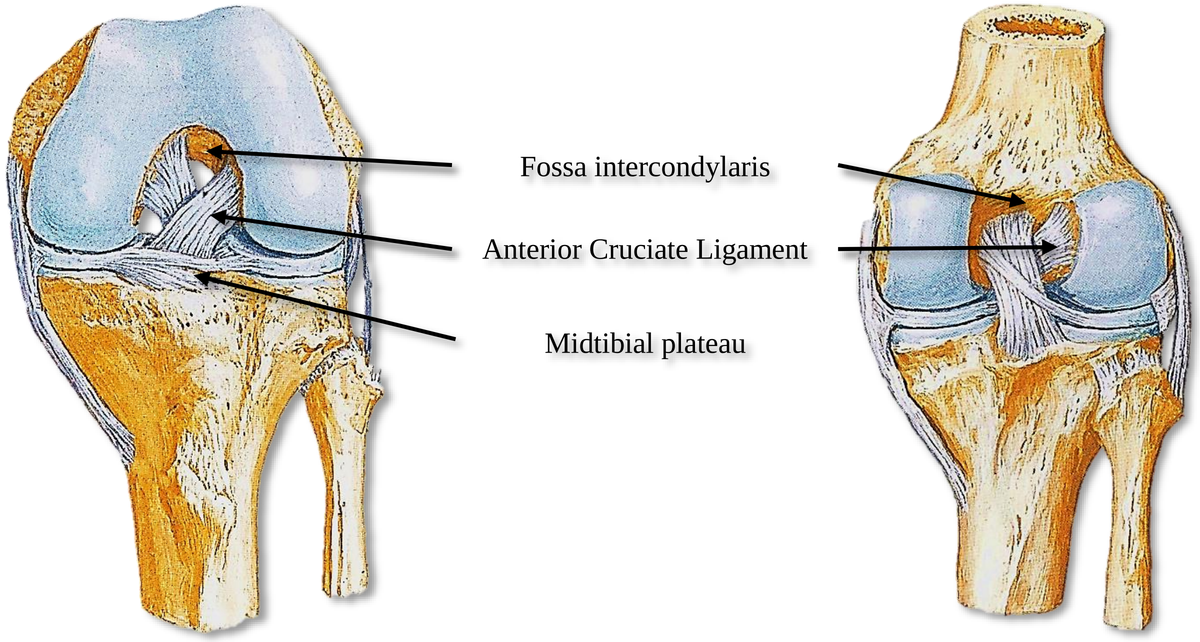


Figure 1. Knee Joint Anatomy. *Left: Ventral view of the knee joint with the illustration of the Fossa Intercondylaris, the Anterior Cruciate Ligament, and the Midtibial Plateau. Right: Dorsal view of the knee joint with the specific illustration of the Fossa Intercondylaris and the Anterior Cruciate Ligament (modified from Netter 2000).*

Function of the ACL

In its joint stabilization function, the ACL primarily controls and limits the anterior translation of the tibia in relation to the femur. Hence, the ACL limits the anterior tibial translation relative to the fixed femur and works as restraint for posterior movement of the femur on the fixed tibia. Additionally, the ACL functions as limitation of the internal rotation of the knee joint, especially when the leg is close to full extension, and furthermore as a restraint to external rotation and varus-valgus angulation of the knee joint, especially under weight-bearing conditions. During anterior tibial translation, 75% of the anterior forces are accepted by the ACL at full knee extension and 85% at 90° knee flexion angle. (Beard et al., 1996; Beynnon et al. 1997; Duhton et al. 2006; Egloff et al., 2011; Matsumoto et al. 2001; Petersen & Renström 2001; Whiting & Zernicke 2008).

Because the ACL receives nerve fibers from the tibial nerve, including certain receptors, the ACL has an additional, essential function for the detection of joint position and joint locomotion besides its joint stabilization function. There are receptors that are sensitive to stretching of the ACL (Ruffini receptors), for rapid movements (Vater-Pacini receptors), and for detection of tension in the ACL (Golgi-like tensions receptors). Furthermore, free-nerve endings are embedded in the ACL, which function as nociceptors with sensitivity for pain. (Duhton et al. 2006; Haus & Halata 1990; Kennedy et al. 1982; Lübken et al. 2008; Zimny et al. 1986).

2.2 Mechanisms of ACL Tears

There are two main ACL tearing mechanism, which are characterized by isolated high knee valgus loads or combined high knee valgus loads and excessive external tibial rotation. Furthermore, the ACL tears in hyper extension situations of the knee, characterized by large anterior displacement of the tibia in relation to the femur with combined internal tibial rotation, as it for instance occurs in one-legged landings (Figure 2). (DeMorat et al. 2004; Fukuda et al. 2003; Hewett et al. 2005; Ireland 2002; Markolf et al. 1995; McLean et al. 2004; Meyer & Haut 2008; Nagano et al. 2009; Olsen et al. 2004; Whiting & Zernicke 2008)

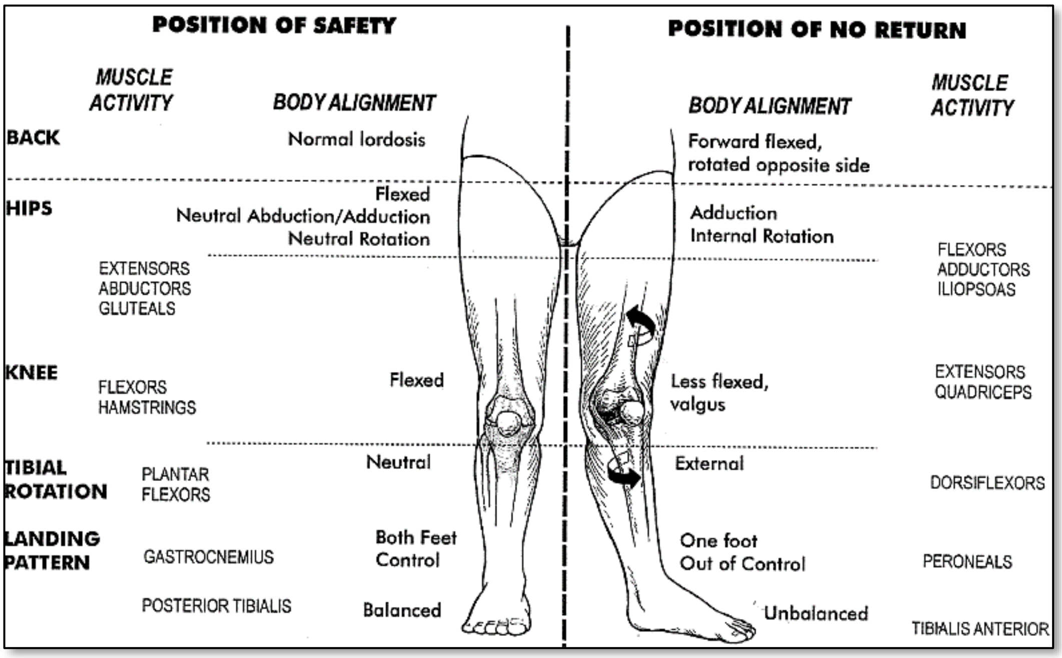


Figure 2. ***ACL Tearing Mechanism.*** *Comparison of body alignment and muscle activity in a safe knee joint position and in the position of no return, which highly increases the risk of an ACL tear (Ireland 2002).*

Tearing of the ACL can occur in non-contact situations or under contact (Ireland 2002). Non-contact tearing of the ACL typically occurs in knee valgus overload situations, in which the foot is in a fixed position on the ground, the tibia externally rotated, the knee close to full extension, and the knee then collapses into a valgus position (Figure 2) (Ireland 2002; Myer et al. 2005). Typically, this injury mechanism occurs in sports where high moments in the knee are produced, such as ski alpine, basketball or football (Ireland 2002; Schmidt-Wiethoff & Dargel 2007).

Tearing under contact especially happens during the interaction with an opponent in game sports. The ACL tears in contact situations, because a high force is acting to the knee joint, as it is common in contact sports such as football, team handball and martial arts, as especially judo (Koshida et al. 2010; Myklebust et al. 2003). Therein, for instance an opponent player impacts the lateral aspect of the knee joint, causing high valgus loadings in combination with internal rotations (WHITING & ZERNICKE 2008). However, non-contact tearing of the ACL occurs remarkably more often than injuries induced by contact (BODEN et al. 2000; IRELAND 2002).

Factors, which encourage the tearing mechanisms, can be extrinsic, such as environmental influences (e.g. ground surface, footwear, opponent player) or intrinsic, such as anatomical risk factors, like anatomical high knee valgus alignment (ALENTORN-GELI et al. 2014; ARENDT et al. 1999; BODEN et al. 2000; EBSTRUP et al. 2000; IRELAND 2002; NOYES et al. 1983a; NOYES et al. 1983b; POSTHUMUS et al. 2011; SERPELL et al. 2012; WHITING & ZERNICKE 2008). ACL tears occur more frequently in sports or physical activities, but as well in ADLs, while working or in accidents (HÖHER 2007). Because of generally wider pelvis, greater flexibility, less-developed musculature, hypoplastic vastus medialis obliquus, more narrow femoral notch, genu valgum, and greater external tibial torsion, which produces relatively greater valgus- and internal rotation moments, women have a greater predisposition for ACL tears and a two to four times higher injury risk than men (ARENDT et al. 1999; IRELAND 2002; MCLEAN et al. 2004; MESSINA et al. 1999; POSTHUMUS et al. 2011; PRODROMOS et al. 2007; SERPELL et al. 2012; SIGWARD & POWERS 2007; WALDÉN et al. 2011; WHITING & ZERNICKE 2008).

After having diagnosed ACL ruptures, it is important to precisely identify the injury mechanism to ensure whether concomitant injuries of other biological structures have occurred (e.g. Menisci, collateral ligaments) within the knee joint. Such concomitant injuries of other or surrounding biological structures within the knee joint, consequently, highly influence the selection of injury treatment and the general rehabilitative outcome with a higher predisposition of prospective degenerative changes of the knee joint the more biological structures are additionally injured (ANDRIACCHI & MÜNDERMANN 2006; ROOS 2005).

2.3 Indications, General Aims and Techniques of ACL Reconstruction

Indications of Surgical Reconstruction

Especially, in athletes performing in competitive or recreational sports, including cutting or pivoting movements, with the aim to return to their pre-injury sports and pre-injury activity level and, additionally, in individuals with clear signs of knee joint instability, surgical reconstruction of the torn ACL is indicated and recommended (ERNST et al. 2000; KOSTOGIANNIS et al. 2007; LEWEK et al. 2003; SCHMIDT-WIETHOFF & DARGEL 2007; WHITING & ZERNICKE 2008). A chronic deficient knee joint leads to a progressive knee joint dysfunction manifested by recurring situations of instability. Consequently, a chronically instable knee joint increases the risk of secondary injuries of the reconstructed ACL, of the Menisci or the joint cartilage, what would highly increase the probability of chronic degenerative changes at the knee joint (DANIEL et al. 1994; HAWKINS et al. 1986; MCHUGH et al. 1994; NOYES et al. 1983a; WROBLE & BRAND 1990).

Aims of Surgical Reconstruction

Generally, a surgical reconstruction of the ACL aims to restore the natural biological structure of the ACL and therewith to restore the entire knee joint homeostasis. The surgical reconstruction shall prevent and reduce the risk of knee joint instability. As mentioned before, it has been shown that changes in a substantial structure of a joint lead to pathologic changes of other attached substantial joint structures, which can lead to a deterioration of the entire joint function (FREMEREY et al. 1998; KESSLER et al. 2008; REIDER et al. 2003; VON LÜBKEN et al. 2008). Furthermore, the surgical restoration shall ensure to prevent secondary injuries of the reconstructed ACL, injuries of concomitant surrounding structures like the Menisci, the joint cartilage and the collateral ligaments of the knee joint and to enable individuals to regain full knee joint stability and functionality, to reach a higher probability of a safe return to all ADLs and to pre-injury sports and sports-level with a reduced risk of re-rupture of the reconstructed ACL (HOLSGAARD-LARSEN et al. 2014; KESSLER et al. 2008; TASHMAN et al. 2004). However, even though the surgical reconstruction aims for full functional knee joint recovery, 10% to 30% of all reconstructed individuals suffer from a re-rupture of the reconstructed ACL (SHELBOURNE et al. 2009; PATERNO et al. 2010; LEYS et al. 2012). This shows that ACL reconstruction alone does not guarantee full functional recovery of the knee joint. Instead, full recovery of the knee joint depends, besides a successful surgical reconstruction, on a successful functional rehabilitation with the recovery of muscular strength and neuromuscular capabilities.

Reconstruction Techniques

Various possibilities with regard to graft types for the reconstruction of a torn ACL exist. They reach from bone-patellar tendon-bone autografts, to M. gracilis and M. semitendinosus hamstrings autografts, quadriceps tendon autografts or to smaller amounts allografts from other sources, such as cadavers (ANDERSON et al. 2016; GOBBI & FRANCISCO 2006; SCHMIDT-WIETHOFF & DARGEL 2007; WHITING & ZERNICKE 2008). Two graft types have been established in ACL reconstruction in recent years: The bone-patellar tendon-bone (BPTB) autografts and hamstring tendon (HT) grafts of the M. gracilis and M. semitendinosus tendons (Figure 3) (ANDERSON et al. 2016; AUNE et al. 2001; GOBBI & FRANCISCO 2006; SCHMIDT-WIETHOFF & DARGEL 2007; WHITING & ZERNICKE 2008).

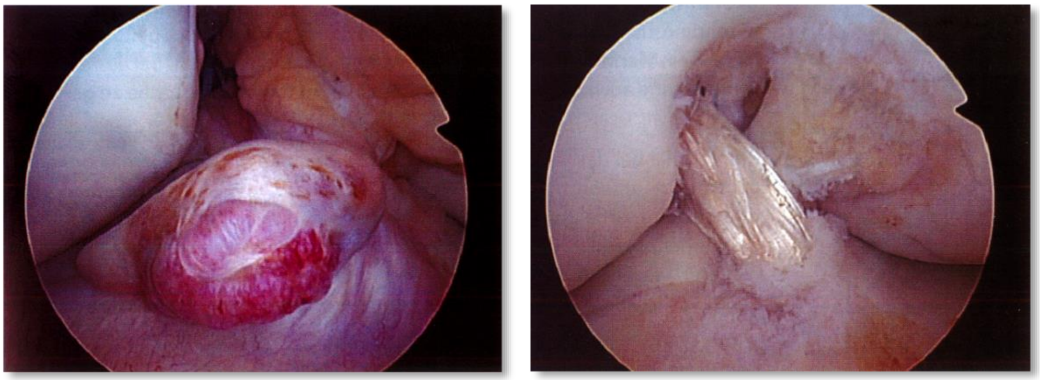


Figure 3. Arthroscopic Illustration of the Torn and Reconstructed ACL. *Left: Arthroscopic Picture of a teared ACL. Right: Arthroscopic picture of a reconstructed ACL with semitendinosus-tendon autograft. (ARCUS Sports Clinics, Pforzheim)*

As the BPTB autografts have bone plugs at each end of the graft, these grafts enable good fixation to the femoral and tibial attachment sites (Anderson et al. 2016). However, individuals reconstructed with BPTB autografts have reported a higher number symptoms at the harvested side, higher kneeling pain and a higher incidence of mild OA in comparison to individuals where the autograft was harvested from the hamstring muscle tendons, even at ten years after reconstruction (Aune et al. 2001; Biau et al. 2006; Magnussen et al. 2011; Mohtadi et al. 2011; Pinczewski et al. 2007; Spindler et al. 2004; Whiting & Zernicke 2008). As reconstructions with the HT autografts result in lower morbidity at the donor site, this reconstruction technique has established itself for reconstructing the ACL in recent years even though, due to the absence of bone plugs in these autografts, the initial integrity of attachment site fixation is reduced (Aune et al. 2001; Pinczewski et al. 2007; Schmidt-Wiethoff & Dargel 2007; Whiting & Zernicke 2008). Therefore, HT autografts are commonly fixed to the distal femur with a button and to the proximal tibia with a screw (Figure 4).

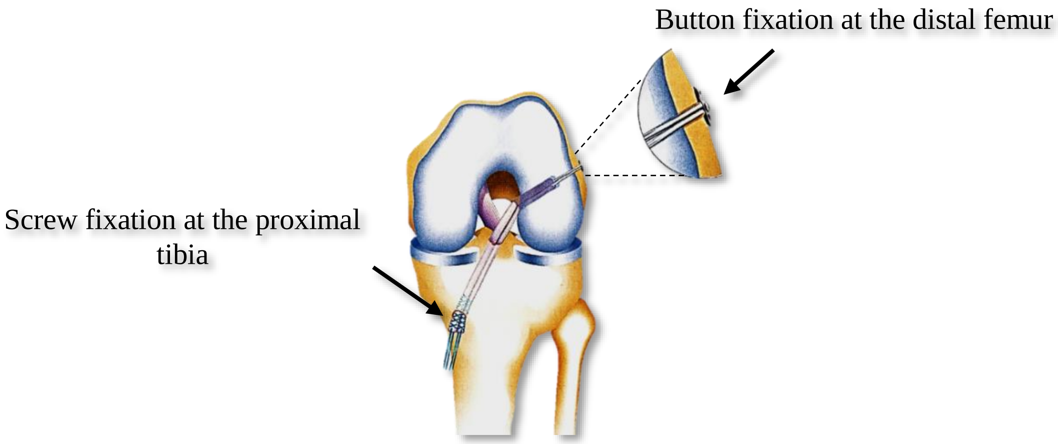


Figure 4. ACL Reconstruction Technique. *Fixation of the hamstrings tendon autograft at the distal femur (button) and the proximal tibia (screw)* (modified according to *Arcus Sports Clinics*, Pforzheim)

Although aspired, even optimal reconstruction does not guarantee that individuals can fully return to pre-injury sports on pre-injury level (GOBBI & FRANCISCO 2006). To regain full knee joint functionality and stability the individuals need, besides a successful reconstruction, a well-steered rehabilitation program including a high intrinsic motivation and willingness for successful completion of the rehabilitation program along with the self-confidence to regain full functionality (GOBBI & FRANCISCO 2006).

2.4 Consequences of ACL Tears

General Consequences

General consequences emerging by ACL tears and the subsequent reconstruction are manifold and widespread. They range from concomitant or subsequent impairments of other biological structures of the knee joint, over neuromuscular changes in the knee joint and the injured leg, up to consequences in ADL, recreational activities and sport-specific movements, as well as to psychological consequences, which have an impact on the general QoL. These consequences will be described in the subsequent chapter and serve as conclusive theoretical content for the deduction of the thesis' purposes and the research questions.

Consequences to Other Biological Structures of the Knee Joint

Consequences of ACL tears to other biological structures of the knee joint occur in the form of concomitant injuries of these structures in the ACL injury situation, such as tearing of the medial collateral ligament (MCL) and/ or the medial Meniscus. Generally, it can be said, that the tear of the ACL leads to changes of the normal femoral and tibial gliding and rolling mechanism in the knee joint (ANDRIACCHI & MÜNDERMANN 2006; ENGEBRETSEN et al. 1993; GILLQUIST & MESSNER 1999; MYKLEBUST & BAHR 2005; ROOS 2005; WEXLER et al. 1998). Such collateral injuries increase the risk of concomitant or subsequent injuries of the Menisci and the joint cartilage (ROOS 2005; WEXLER et al. 1998). Furthermore, besides direct concomitant injuries, secondary injuries or chronic diseases of biological structures (e.g. knee OA) occur with high incidence due to the ACL tear and a subsequently insufficient rehabilitation of the knee joint because of chronic knee joint instabilities (ENGEBRETSEN et al. 1993; ØIESTAD et al. 2009; ROOS 2005; WEXLER et al. 1998; WHITING & ZERNICKE 2008). Due the ACL tearing situation, bone bruises at tibial plateau are evident in 80% to 90% of the injured knee joints, which alongside with the ACL tear lead to acute chondral changes (ENGEBRETSEN et al. 1993; MYKLEBUST & BAHR 2005). Progression of such chondral changes to OA was reported to range between 48% and 92% within five and 20 years after the ACL injury (FINK et al. 2001; GILLQUIST & MESSNER

1999; KANNUS & JÄRVINEN 1988; MCDANIEL & DAMRON 1983; LOHMANDER et al. 2007; MCHUGH et al. 1994; MYKLEBUST et al. 2003; NOYES et al. 1983a; ØIESTAD et al. 2009; ROOS et al. 1995; ROOS 2005; SOMMERLATH et al. 1991; VON PORAT et al. 2004).

As the ACL is a major structure for knee joint stabilization, tearing of the ACL should never be evaluated in isolation. This means, it is always indicated to determine whether other biological structures that function as additional indispensable parts of a joint were also damaged during the ACL injury situation. Especially, due to the ACL injury mechanisms, with its isolated or combined pivoting, valgus or hyperextension overload in the knee joint, it frequently occurs that tears of the ACL are accompanied by injuries of other knee joint structures, such as the Menisci, the MCL or the lateral collateral ligaments (LCL), the joint cartilage, the subchondral bone, and the bone spongiosa (ENGEBRETSEN et al. 1993; MYKLEBUST & BAHR 2005; WHITING & ZERNICKE 2008). Such concomitant or subsequent injuries can highly influence the reconstructive and rehabilitative outcome, reduce the success of full rehabilitation of knee joint functionality and increase the risk of prospective development of chronic degenerative changes at the knee joint, such as knee OA (FAUDE et al. 2006; GILLQUIST & MESSNER 1999; KANNUS & JÄRVINEN 1988; KEAYS et al. 2003; LOHMANDER et al. 2004; LOHMANDER et al. 2007; MYKLEBUST & BAHR 2005; Roos 2005; SOMMERLATH et al. 1991; VON PORAT et al. 2004).

Therefore, it is important to detect potential concomitant injuries, because joint homeostasis can only be restored or maintained if all structures are in a good and balanced condition. Normally, impairment of one structure, acute or chronic, always has needs to be compensated by other structures (ANDRIACCHI & MÜNDERMANN 2006). Failure or degradation of one structure gradually leads to a degeneration of other structures and therewith to a general impairment of the joint homeostasis, because every structure has essential functions for the joint homeostasis and cannot be totally replaced or compensated by the associated concomitant structures of a joint (ANDRIACCHI & MÜNDERMANN 2006; NOYES et al. 1992; ROOS 2005). Therefore, it is decisive to restore and recover the injured structures within a joint in the best way possible, for maintaining joint homeostasis and for preventing prospective degenerative changes in the joint. To reach such a joint homeostasis again, if possible at all, it is necessary to enhance rehabilitation processes along with a good acute surgical reconstruction treatment. Therefore, in the field of functional ACL rehabilitation it is not only sufficient to restore the ACL with a graft. It seems essential to recover all locomotion influencing systems to regain pre-injury joint condition in the best way possible. Therefore, knee joint rehabilitation after ACL tears is a challenging field, because full joint recovery is generally not achievable at all. This is underlined by various studies with the purpose of enhancing knee joint rehabilitation and return-to-sports concepts (BEYNNON et al. 2002; NARDUCCI et al. 2011; NEETER et al. 2006; REIMAN & MANSKE 2009; VON PORAT et al. 2004). Such studies showed that in almost all ACL injured and deficient knees higher loads on soft tissue structures or changes in the functionality of the legs, e.g. as altered joint mechanics, were detected (ERNST et al. 2000; KEAYS et al. 2003; MYKLEBUST et al. 2003; NEETER et al. 2006; NOYES et al. 1992;

ROOS 2005). This leads, especially to higher knee adduction moments in the knee joints, which clearly indicates that higher loads on the medial component of the knee joint occur (HURWITZ et al. 2002; SCHIPPLEIN & ANDRIACCHI 1991; SHARMA et al. 1998). Such overload of the medial compartment in the knee joint leads inevitably to a destructive way within the knee joint, with a general shift of load to the medial compartment of the knee joint, which highly accelerates the onset of knee OA in lifetime (BALIUNAS et al. 2000; HURWITZ et al. 2000; NOYES et al. 1992; PRODROMOS et al. 1985; ROOS 2005; SCHNITZER et al. 1993; SCHIPPLEIN & ANDRIACCHI 1991; SHARMA et al. 1998). Such degenerative changes lead to further individual and socioeconomic problems with a general reduction of the QoL (FELSON et al. 1987; HURWITZ et al. 2000). As a mid-term consequence, the whole process of joint impairment is encouraged and as long-term consequence a total artificial knee joint replacement often unavoidable (JORDAN et al. 2003). On basis of the depicted general consequences with immense individual compensations and adaptations in movements of daily life, it is shown that the rehabilitation after ACL injuries is still a substantial scientific field. Results and findings out of such studies provide knowledge to further enhance the rehabilitation program after ACL reconstruction for reaching the best individual functional outcome.

Consequences for the Afferent and Efferent Sensory Systems and Types of Instability

Adjacent to the described potential concomitant injuries of other biological structures of the knee joint, ACL injuries are always accompanied by neuromuscular deficiencies (NEEDLE et al. 2017; ROOS 2005). Within the ACL various sensory receptors are embedded, which have an important function for the sensory feedback of joint position detection during locomotion (BONSFILLS et al. 2008; DHILLON et al. 2012; ROOS 2005; ROOS et al. 2011; VON LÜBKEN et al. 2008). A tear of the ACL leads to impairments or total disruptions of these receptors and their neurological pathways, which alters somatosensory signals and leads to a decrease of the afferent input to the central nervous system (CNS) (BIEN & DUBUQUE 2015; BONSFILLS et al. 2008; DHILLON et al. 2012; ROOS et al. 2011; VON LÜBKEN et al. 2008). Consequently, the impaired afferent and efferent sensory pathways result in a prolonged altered motor output (LEPLEY et al. 2013; NEEDLE et al. 2017; PIETROSIMONE et al. 2012). These alterations result in a deficiency of the legs' whole sensorimotor system, because afferent pathways and sensory receptors are disrupted or impaired by the tear of the ACL and additionally, afferent receptors of the remaining structures of the joint are also immensely influenced (HARRISON et al. 1994; HOGERVORST & BRAND 1998; VON LÜBKEN et al. 2008; MCHUGH et al. 2002). Consequently, these alterations of the sensorimotor system lead to an altered proprioception in the joints, altered postural control strategies, and reduced strength capacities in the legs alongside with a potential reduced ability of the sensorimotor system to adequately prepare and react to unanticipated events and loads, occurring in ADLs, physical activities and sports (BONSFILLS et al. 2008; HOUCK et al. 2007a; HOUCK et al. 2007b; ROOS et al. 2011). These neuromuscular changes generally lead to a degradation of the proprioception and the kinesthesia, along with increased nociceptor activity associated with pain and effusion (HOPKINS & INGERSOLL 2000). As a consequence it was found that such changes in the sensorimotor system and the high adaptation potential of the CNS lead to adjustments in the motor cortex subsequently to ligamentous knee joint injuries to maintain the joint’s function (KAPRELI et al. 2009; SWANIK 2015; WIKSTROM et al. 2013). These consequences and changes in the sensorimotor system can lead to impairments of motor control and motor output and are one reason for the prolonged entire knee joint instability and the low functional state after ACL tears (KAPRELI & ATHANASOPOULOS 2006; NEEDLE et al. 2017). Because of the changes in the sensitivity of the afferent receptors, it can be assumed that an ACL tear may lead to a reorganization of the CNS and may result in general changes in activation patterns of sensorimotor cortical areas (KAPRELI et al. 2009). Such adaptation processes might lead to general reorganizations or impairments of the joint function, because due to these facts the ability to activate the joints’ stabilizing musculature is decreased, which in contrast results in greater demands for the CNS (HOPKINS & INGERSOLL 2000). All these changes and adaptation processes consequently enhance the loss of functionality of the joint, increase the probability of joint instability, and therewith lead to a general insecurity in motion (NEEDLE et al. 2017). An impaired neuromuscular system is an important factor, which emphasizes the knee joint instability and low functionality, occurring during movements (VON LÜBKEN et al. 2008). This is confirmed by the fact that deficits in the neuromuscular control and significant or pronounced side-to-side differences of the legs’ biomechanics are considered as major reasons for re-rupture of the reconstructed ACL (FREMEREY et al. 2000; HEWETT et al. 2005; KNOLL et al. 2004a; VAIRO et al. 2008). Therefore, it is underlined that an intact sensorimotor system is crucial for the correct interior detection of body position, postural stability and general body movements, which makes the recovery of the sensorimotor system an essential part of the post-surgical rehabilitation, as an non-intact sensorimotor system makes a symptom-free return to physical activity and sports unlikely (HARRISON et al. 1994; WIKSTROM et al. 2013).

The surgical reconstruction of the ACL and the subsequent rehabilitation program shall overcome these neuromuscular deficiencies. However, this is generally not achieved, resulting in the phenomenon that some individuals remain stable, so called copers, and some remain instable, so called non-copers, after surgical or non-surgical treatment of the torn ACL (LEWEK et al. 2003; RUDOLPH et al. 2000).

An instability, which is induced by the described deficiencies of the sensorimotor system, is declared as functional instability (VON LÜBKEN et al. 2008). Because it was found that pain fibers and mechanoreceptors can be determined in the reconstructed ACL no earlier than four to twelve months after surgical reconstruction, it can be assumed that neuromuscular recovery takes more time than the regain of muscle mass acting around the knee (GOERTZEN et al 1992; SHIMIZU et al. 1999).

Summarized, one main factor for knee joint instability after ACL tears and reconstructions results from a deficient sensorimotor system because sensory pathways of the ACL are impaired and disrupted and simultaneously the afferent and efferent nervous pathways of the remaining joint structures are impaired (Hogerborst & Brand, 1998; LEPLEY et al. 2013; NEEDLE et al. 2017; VON LÜBKEN et al. 2008; PIETROSIMONE et al. 2012).

Besides functional instability, there also appears a mechanical instability, which is described as *giving way-syndrome* (VON LÜBKEN et al. 2008). Such a mechanical instability is caused by the hyper mobility of the tibia in anterior direction in relation to the femur resulting in yielding or subluxation of the tibiofemoral joint, leading to pain and joint effusion or at worst to a re-rupture of the reconstructed ACL (FITZGERALD et al. 2000; FRANK & JACKSON 1997; VON LÜBKEN et al. 2008; RUDOLPH et al. 2000). This mechanical instability occurs due to the general deficiency of the legs' musculature, which is additionally essential for knee joint stabilization.

The surgical reconstruction of the ACL aims to remodel the ACL's morphologic structure with all embedded sensory receptors, which shall restore the pre-injury state of the knee joint with the recovery of the overall joint stability, the regain of full functionality and the reduction of the risk to develop knee OA prospectively (DHILLON et al. 2012; TASHMAN et al. 2004; ERNST et al. 2000; KESSLER et al. 2008). This surgical reconstruction shall therefore overcome the functional and mechanical knee joint instability, along with a restoration of the joint homeostasis to realize a full recovery of knee joint function and thus enlarge the potential to return to an active lifestyle on pre-injury level without symptoms of knee joint instability and insecurity (ERNST et al. 2000).

In relation to ACL rehabilitation programs, this means that for the recovery of the afferent and efferent pathways every passive or active movement activates a huge amount of receptors. The afferent signals are initially interconnected and transmitted in the CNS where a correction signal is generated before an efferent signal is transmitted to the knee joint. This implies that early mobilization of the knee joint after the reconstruction is beneficial for the probability of reaching full recovery and reorganization of the afferent and efferent pathways and all neuromuscular signal processing prospectively. Therefore, it can be concluded, that by active and passive movement exercises the neuromuscular deficits can be reduced. (BARTLETT & WARREN 2002; BOUET & GAHÉRY 2000; LEPHART et al. 1996; MELNYK et al. 2007)

Depending on the studies, it has been reported that recovery of neuromuscular capacities can take a long time. It has been shown that one, two, or even more years after ACL reconstruction, individuals, when returning to normal physical activities, still have sensorimotor deficits in the injured leg compared to the uninjured leg in activities such as jumping or squatting (CASTANHARO et al. 2011; COLBY et al. 1999; PATERNO et al. 2007; RUDROFF 2003). This shows how pronounced and individually different the neuromuscular deficits emerge, how much time the recovery of the neuromuscular pathways necessitates and how long the neuromuscular deficits after ACL tear and reconstruction can persist.

Therefore, it is reasonable to include sensorimotor monitoring in a comprehensive determination of functionality after ACL injury and reconstruction throughout the rehabilitation process, because it contributes important insights about the state of recovery of knee joint functionality. This appears because not all locomotion organization processes recover on the same timeline, and neuromuscular capabilities have decisive influence on the functional outcome of ACL reconstructed individuals.

Muscular Consequences

Initially after the reconstruction, the knee joint has to be immobilized to a large extent to prevent an overload of the implanted graft. It has been established that during the early phase of rehabilitation, bracing results in fewer problems with swelling, lower prevalence of hemarthrosis and wound drainage, and less pain than without bracing (BEYNNON et al. 2005b; YOUNG et al. 1987). Besides, the primary reason for bracing the knee in the early phase after reconstruction, secondarily, the individuals shall get assisted in the prevention of flexion contractures and the implanted graft shall get protected by preventing full knee extension and flexion, as full knee extension provokes high stress on the ACL graft (BEYNNON et al. 2005b; YOUNG et al. 1987). Nonetheless, bracing the knee cannot prevent muscular atrophy associated with muscular weakness in the injured limb (ROOS et al. 2011; SUTER & HERZOG 2000). As the knee joint's range of motion (ROM) is limited in knee extension by the brace, the M. quadriceps is in a shortened position and therefore more liable to atrophy than its antagonists (KANNUS et al. 1992; YOUNG et al. 1987). Thigh muscle atrophy is present post-operatively both, in the knee extensors and the knee flexors muscles (THOMAS et al. 2013; THOMAS et al. 2016; YOUNG et al. 1987). Additionally, it was identified that weaknesses in the hip and core muscles occur simultaneously, which underlines the general low state of the injured leg's musculature and, consequently, serves as a predictor of increased perspective lower extremity injury risk (IRELAND 2002; LEETUN et al. 2004; POWERS 2010).

Due to the repetitive occurring of before-mentioned situations of instability of the knee joint after ACL tears and reconstructions, the individuals tend to reduce their general activity level, which additionally encourages the muscular weakness and the process of muscular degradation. Consequently, the individuals' feeling of insecurity in movements is enlarged (RUDOLPH et al. 2001). However, such a reduction in the activity level further supports the reduction of the muscle mass, muscular weakness, and leads therewith to a reduction of the legs' muscular strength (KANNUS et al. 1992). The reduction in muscular strength was described to appear larger than 10% in the side-to-side difference of the legs even after knee joint rehabilitation (ARANGIO et al. 1997; ERNST et al. 2000; KEAYS et al. 2003; LEWEK et al. 2002; MATTACOLA et al. 2002; PFEIFER & BANZER 1999; RISBERG et al. 1999; URBACH et al. 2001; WOJTYS & HUSTON 2000).

As knee joint stability depends on a good muscular state of the involved muscles, individuals with low muscular function show a high degree of knee instability and low functionality of the knee joint (STERGIOU et al. 2007). Although it has been shown that the ability to generate high M. quadriceps moments is important for maintaining stability, it is insufficient for maintaining knee joint stability alone. Although it was described that copers and non-copers both had good M. quadriceps strength, the non-copers were not able to stabilize their knee joint (EASTLACK et al. 1999; RUDOLPH et al. 2000; LEWEK et al. 2003). However, there is consensus that deficiencies and weaknesses of the M. quadriceps after ACL tear and reconstructions emerge and can manifest in the future (MCHUGH et al. 2002; YASUDA et al. 1992). A manifestation of the reduction in muscular strength is considered as an essential factor for impaired return to sports on pre-injury level (LEPLEY et al. 2015; PATERNO et al. 2007). Related to that, it was claimed that ACL reconstructed individuals should reach a peak M. quadriceps moment in the reconstructed leg of 85% compared to the uninjured leg (CASTANHARO et al. 2011).

In this context, it was described that the Hamstrings-Quadriceps-Ratio (HQ-Ratio) plays an important role for evaluating the recovery of the legs' musculature, although, there is no full consensus on whether Quadriceps or Hamstrings musculature is more responsible for functional stability (KEAYS et al. 2003). One clear reason for these pronounced deficiencies of the M. quadriceps is related to the fact that in the 1990s and the beginning of the 21st century the patellar tendon was commonly used as autograft. As the patellar tendon function is to transfer muscular strength of the quadriceps to the lower leg, with its insertion at the Tuberositas Tibiae, it is reasonable that the removal of parts of this tendon leads to pain at the notch and to deficiencies in the acting muscle. Because nowadays mainly parts of the hamstrings are commonly used as autograft, in particular a combination of parts of the tendons of the M. semitendinosus, M. gracilis or M. semimembranosus, deficiencies in the M. quadriceps are reduced (AUNE et al. 2001). In contrast, the Hamstrings muscles show increased deficiencies at the donor site (AUNE et al. 2001).

The described changes in the muscular level show that the regain of muscular mass and muscular capabilities is essential for the functional rehabilitation after ACL tears and reconstructions and for the return to pre-injury sports and activity levels (LEPLEY et al. 2015; PATERNO et al. 2007). However, due to the before-mentioned neuromuscular deficiencies, it is suggestable that the regain of muscular capabilities is not sufficient alone for the recovery of knee joint stability. As the neuromuscular and muscular capabilities are coherent systems and cannot be considered separately in terms of rehabilitation of an important structure, such as the ACL, rehabilitation should always include exercises and training programs that aim to recover as many systems involved as possible. However, there is a lack of knowledge of the effectiveness of different training and rehabilitation programs. Because it is such a complex framework of coherent systems, which is responsible for maintenance of knee joint functionality and stability, and accordingly the recovery of these different systems does not follow a uniform but a very individual course, it is reasonable to monitor and screen individuals after an ACL tear more comprehensively. Only with a comprehensive monitoring of functionality with all its determining factors, deficiencies and, hence, reasons for potential instabilities or a low level of functionality can be detected adequately.

As it is essential for the recovery of neuromuscular capacities to re-mobilize the impaired knee joint in a specific adequate way as soon as possible after the reconstruction, early re-mobilization is also helpful for a good recovery of the legs' musculature. This appears, because all movements, executed passively or actively, train the recovery of the coherent neuromuscular and muscular systems. Therefore, along with passive movement exercises, active training of the thigh musculature as early as possible after the reconstruction is essential to control and limit the extent of the muscular atrophy as good as possible. Additionally, the early re-mobilization helps to support the immediate recovery of the neuromuscular system, because a large number of afferent receptors are activated. Such afferent signals are transmitted in the central nervous system (CNS) and therefore lead to a re-organization of the locomotion relevant sensory pathways. Therefore, active and passive movement exercises help the whole sensorimotor system to reduce the neuromuscular deficit. (BARLETT & WARREN 2002; BOUET & GAHÉRY 2000; LEPHART et al. 1996; MELNYK et al. 2007; PFEIFER & BANZER 1999)

Summarized, due to the beneficial impact on the locomotion system, an early post-reconstructive re-mobilization can help to support ACL reconstructed individuals in the rehabilitation process to reach less-deficient individual functional outcome. Therefore, early re-mobilization should start immediately after the tear or reconstruction with passive joint motions by a therapist or a therapeutic machine. Such passive joint motions are described to be beneficial in order to maintain the knee joint's ROM, which is seen as essential basement to reach a better functional outcome (NOYES et al. 1987).

2.5 Functional Consequences, Performance Deficiencies and Return to Sports

The described consequences of an ACL tear to collateral biological structures of the knee joint, to the neuromuscular system as well as to muscle morphology, have influence on the performance in ADLs, in recreational activities and in sport-specific movements. This is due to the fact that for a successful and economic performance of movements all involved biological structures and the whole locomotion system should be in a good state. This is essential because imbalances in morphology as well as in the locomotion system can lead to general or specific adaptation or compensation mechanisms, on a morphologic and a behavioral level. Consequently, such compensation or adaptation mechanisms can lead to a continuous cascade of deterioration in the involved or collateral morphologic structures of the respective joints. Therefore, if the described impairments of the concomitant biological structures and the locomotion's sub-systems are not recovered, movements can hardly be performed on a pre-injury state, and performance on pre-injury activity level and in pre-injury sports can hardly be achieved (MYKLEBUST et al. 2003). Functional deficits emerge in a reduced ROM of the knee joint in 44%, instability of the knee joint in 26%, reduced muscular strength of the lower extremities in 25% and joint effusion in 23% of ACL reconstructed individuals seven to eleven years after ACL injury (MYKLEBUST et al. 2003). Such imbalances of the biological structures and the locomotion systems alongside with persistent functional deficits, lead to higher odds ratios of re-ruptures of the reconstructed ACL and higher probabilities of prospective degenerative changes at the involved or uninvolved joint of the contralateral leg (MYKLEBUST et al. 2003; PATERNO et al. 2010). This becomes also apparent, as the majority of the individuals are younger than 30 years when tearing their ACL. Therefore, a rupture of the ACL is to a great amount responsible for an earlier onset of knee OA associated with pain, functional impairments and a reduction of the quality of life (QoL) at the age of 30 to 50. (LOHMANDER et al. 2004; LOHMANDER et al. 2007; VON PORAT et al. 2004). As, additionally, 10 to 30% of the individuals, who returned to pre-injury sports and pre-injury activity level, suffer from a secondary knee injury, and as the risk of an ACL in the sound leg remains high, the achievement of full functional recovery is one of the main challenges for rehabilitation after ACL reconstruction (BIEN & Dubuque 2015; BJORKLUND et al. 2009; SHELBOURNE et al. 2009; PATERNO et al. 2010; LEYS et al. 2012).

As a good state of the before mentioned components is essential for movement executions, wide consequences can emerge for the performance in ADLs, recreational and sports activities by ACL tears and reconstructions if the movement determining components, morphologically or functionally, are not fully recovered (BJORKLUND et al. 2009). This underlines the high importance of a well-balanced post-reconstructive rehabilitation process for the ACL reconstructed individuals, aiming for the best achievable individual functional outcome.

To determine functionality after ACL tears and reconstructions adequately, scientists and clinicians have been trying to develop functional tests for a valid determination of functionality since the 1980s (NOYES et al. 1983b; FITZGERALD et al. 2000; WHITING & ZERNICKE 2008) Depending on the studies' specificity there is a variety of possible approaches to analyze the functionality of the legs. This can be done by self-evaluation (ROOS et al. 1998; TEGNER & LYSHOLM 1985) of reconstructed individuals, by applying functional clinical tests (PETERSEN & ZANTOP 2013), by analyses of functional performance tasks (FITZGERALD et al. 2000; NARDUCCI et al. 2011), or by analyses of ADLs (BERCHUCK et al. 1990; WEXLER et al. 1998). With these approaches specific movement conditions or movement situations of daily living are being analyzed. These conditions or situations can be static or dynamic and are deduced of a specific viewpoint (i.e. self-evaluation, clinician, and scientist). Respectively, depending on each approach, functionality is interpreted out of the objectives of the applied tests. Therefore, to cover the issue of functionality more comprehensively, it seems advisable to include combinations of tests of different approaches determining functionality after ACL tears and reconstructions. The necessity for and importance of functional analyses from a more holistic and comprehensive approach was underlined and described recently (NARDUCCI et al. 2011).

Anyway, with the help of recently and formerly conducted studies, some tests have been established for assessing functionality post-ACL tears and reconstructions.

Testing in relation to functionality was conducted from various perspectives. These are specifically described subsequently, as the main purpose of this thesis was to monitor and evaluate functionality with a comprehensive approach including the subjects' self-evaluations, functional clinical tests, FPTs, and analyses of ADLs.

Functional Clinical Tests

In hospitals or surgeries especially, clinicians and therapists evaluate the knee function with established functional clinical tests. These are convenient to conduct and give insight into certain important parameters of an injured joint, such as measurements of joint flexibility with, for instance, passive ROM testing. However, in order to apply these tests properly, the tester should be experienced with the tests' procedure for reduction of intra- and inter-tester variance in the measurements. Such functional clinical tests are commonly used by surgeons and therapists to release ACL reconstructed individuals back to pre-injury sports and training after a specific time period (PETERSEN & ZANTOP 2013). Regarding the functional clinical tests, it is described that mostly Lachman tests (81.7%) are applied, followed by ROM measurements (78.4%), and pivot shift testing (60.1%) (PETERSEN & ZANTOP 2013). Anyway, by applying these tests, functionality is rather evaluated from a passive or a static approach than out of a dynamic perspective, meaning, an examiner evaluates the injured and non-injured leg while executing passive movements with the patients' legs.

Nonetheless, by applying these functional clinical tests, the joint's functionality is assessed. However, joint functionality and stability is not only determinable by a free ROM and the absence of hyper mobility or anterior-posterior laxity of the tibia in relation to the femur. It was described that after ACL tear and reconstruction, atrophy of the legs' musculature occurred and therewith pronounced deficiencies in the legs' strength capabilities. However, a good state of the legs' musculature should also be included in assessing the functionality, if a comprehensive approach shall be achieved even from a clinical point of view (MCHUGH et al. 2002; THOMAS et al. 2016). Therefore, measurements of the legs' circumferences at standardized positions provide substantial information about the musculatures' state of recovery (SØDERBERG et al. 1996).

Due to the fact that low knee joint functionality and instability occur in various situations, especially while performing ADLs, recreational or sports activities, it seems not sufficient to mainly rely on functional clinical tests to assess the state of functional recovery of an individual's knee and to give valid return-to-sports recommendations. Instead, it is advised that assessments of functionality under dynamic conditions are included in functional testing to give a more comprehensive picture of each individual's respective functional state. To achieve the objective of comprehensive analyses of knee joint functionality after ACL reconstructions, functional clinical tests should be accompanied by tests of the functional performance in dynamic situations. In various studies, tests of specific FPTs have been established, especially jumping tests, in recent decades (BARBER et al. 1990; NARDUCCI et al. 2011; NOYES et al. 1991).

Functional Performance Tests

For enhanced qualitative and quantitative analyses of the legs' functionality after ACL reconstructions, out of respective studies some FPTs were deduced as appropriate in recent years (BARBER et al. 1990; REIMAN & MANSKE 2009; NARDUCCI et al. 2011; NOYES et al. 1991; TEGNER et al. 1986). Dynamic demanding testing tasks, represented by FPTs, give deeper insights into the functional state of the ACL reconstructed subjects and enable to determine the level of leg functionality (NARDUCCI et al. 2011). Especially, various one-legged jumping (OLJ) tasks, such as vertical jumping, jumping for distance, and timed jumping have been established, whereas the OLJ is the most frequently applied test isolated or in combination with other FPTs (ALMANGOUSH & HERRINGTON 2014; BARBER et al. 1990; ERNST et al. 2000; GUSTAVSSON et al. 2006; KVIST 2004; LENTZ et al. 2009; MYER et al. 2008; NARDUCCI et al. 2011; NOYES et al. 1991; TEGNER et al. 1986). Jumping tasks are described to be suitable for assessing functionality in a dynamic demanding task, because the interaction of muscular and neuromuscular systems is required for good performances of jumps and for realizing stability after landing (ORISHIMO et al. 2010). Such a multi-dimensional interaction of motion determining systems is required in jumping during take-off and especially in the landing situations. Take-off situations are appropriate to analyze the capabilities of force or impulse generation of the legs in a dynamic situation, as this represents the most important factor for realizing take-off from the ground and reaching a high performance outcome. Additionally, assessments of landing situations are adequate to get insight into and information on how ACL reconstructed individuals compensate for high loads, emerging in landing of jumps, and which locomotion strategies are applied to provide whole body stabilization, which is similar to demands athletes have to tolerate during competitive sports (GOKELER et al. 2009; OBERLÄNDER et al. 2012; OBERLÄNDER et al. 2013; ORISHIMO et al. 2010; RUDOLPH et al. 2000). Therefore, jumping tasks generally represent a valid tool for assessing functionality, locomotion and neuromuscular control in high-demanding movement situations. Therefore, jumping tasks were often applied to discriminate in relation to performance outcomes between an injured and non-injured leg or in comparison to healthy individuals (BARBER et al. 1990; EASTLACK et al. 1999; GUSTAVSSON et al. 2006; ITOH et al. 1998; REID et al. 2007; RUDOLPH et al. 2000; TEGNER et al. 1986).

From studies examining functionality by dynamical FPTs, it has been established that a jumping ability of 85% to 90% of the injured compared to the non-injured leg is defined as normal and as a potential criterion to release ACL reconstructed individuals back to pre-injury sports (ERNST et al. 2000; GUSTAVSSON et al. 2006; MUNRO & HERRINGTON 2011; NOYES et al. 1991; ORISHIMO et al. 2010; RISBERG et al. 1995; RUDOLPH et al. 2000). In the respective studies, jumping tasks were sometimes combined with other FPTs, such as (one-legged) lunges, shuttle run tests, side step tests, and assessments of muscular strength in knee flexion and extension situations (BJORKLUND et al. 2009; NARDUCCI et al. 2011; REIMAN & MANSKE 2009). Combinations of one-legged jumping tasks, such as triple or crossover hop tests, were not generally conducted in the mentioned studies, but at least in 44% of the evaluated studies (ALMANGOUSH & HERRINGTON 2014). In these studies, various deficits and deficiencies were detected in the injured as well as in the reconstructed leg. These deficits were identified in comparison to the non-injured, healthy leg or in comparison to healthy control group subjects at various time-points after the ACL reconstruction. Deficits in the injured leg emerged to be higher than 50% compared to the non-injured leg. Therefore, it was concluded that a deduction of leg deficiencies in relation to absolute performance values in jumping tasks, such as the jumping distance, is not sufficiently sensitive and decisive for a gradual or a fine-grained determination of functional deficits (RUDOLPH et al. 2000). Furthermore, it was assumed that even a combination of various one-legged jumping tasks is not sensitive enough for a comprehensive detection of functional limitations (NOYES et al. 1991). Specifically, to deduce functionality more decisive in relation to task-specific functionality, it is suggestable to evaluate an individual's functionality not only in terms of the performance outcome results, such as jumping distance, but rather in terms of the parameters, which are most relevant for the determination of an outcome result of the performed task. Therefore, in FPTs as jumping, parameters, such as the distribution of generating forces or moments in each leg during take-off and the distribution of load compensations during the landing situations, seem to be more valid for the evaluation of leg functionality, because these parameters provide insight into the parameters, which determine the outcome result (COLBY et al. 1999). This assumption is supported, because it was described that ACL reconstructed individuals reached with the reconstructed leg a jumping distance in OLJs of 85% of the non-injured leg, but in contrast, showed substantial deficiencies in the knee joints' ROM in the reconstructed leg compared to the non-injured leg. Furthermore, although peak ground reaction forces (GRFs) did not differ between the legs, 40% of the individuals reduced their peak extension moments in the reconstructed compared to the non-injured leg during OLJs. Such a reduced peak moment in the knee joint had to be compensated by the hip and ankle joints, where higher peak moments in the reconstructed leg occurred (ORISHIMO et al. 2010). Accordingly, although ACL reconstructed individuals had been designated as fully rehabilitated, compensation strategies during one-legged landing were detected, targeting at load reductions in the reconstructed knee joint, which was specifically realized by a more erect knee joint position in the landing situation (DECKER et al. 2002).

Consequently, it can be assumed that testing of functional performance should include various approaches of dynamic situations and performance determining parameters to detect functionality as comprehensively and detailed as possible. Furthermore, if examining jumping tasks in order to determine the functionality in a dynamic situation, it is indicated to include detailed analyses of the landing situations in a comprehensive analysis of functionality.

However, although some studies examined a pre- and post-reconstructive state of functionality in relation to FPTs, especially in the performance of OLJs, there is no study yet with the objective to comprehensively examine functional performance in dynamic tasks from pre- to six months post-reconstruction with multiple session.

NARDUCCI et al. (2011) underlined the necessity of studies with a more comprehensive approach of functional testing within one year after ACL reconstruction because no valid functional performance test battery exists, which would provide a more specific and particularized picture of functionality. Such a comprehensive analysis of functionality would, however, support therapists and clinicians in applying a better adjusted individual rehabilitation program and thereof, better deduced recommendations for return-to-sports in relation to each specific individual functional state (BEYNNON et al. 2002; GUSTAVSSON et al. 2006; MURPHY et al. 2003).

As described before, muscular capabilities are deficient due to muscular atrophy after ACL tears and reconstructions (THOMAS et al. 2016). Hence, it was assumed that for a comprehensive analysis of functionality, jumping tasks, as representatives for high-demanding dynamic tasks, should at least be combined with measurements of isolated force generation of the legs in static conditions. Such strength testing of the legs' musculature shall help to get deeper insights into the strength capabilities of the legs' musculature, especially in the post-reconstruction phase up to six to eight months after reconstruction, where most individuals achieve to return to pre-injury sports (KEAYS et al. 2000). As it is described that the strength capabilities of the legs are essential for the recovery of full knee joint functionality and for providing full knee joint stability after ACL reconstructions, a combination of dynamic and static testing of muscular capabilities reveals valid basis for a comprehensive assessment of the functionality of the legs. Additionally to jumping tasks, the measuring of isolated strength capabilities of the legs' musculature from an isometric or isokinetic approach is established for revealing strength relationships between the legs of healthy or impaired individuals (ARAMPATZIS et al. 2004; DELITTO et al. 1988; FITZGERALD et al. 2000; KEAYS et al. 2000; SNYDER-MACKLER et al. 1993; THOMAS et al. 2013; WIGERSTAD-LOSSING et al. 1988).

Studies, which mainly included strength testing into functional test batteries, conducted rather isokinetic tests in recent years (THOMAS et al. 2013). However, it was described that in isokinetic testing differences between the measured and the resultant knee joint moment arms occurred, and the angular displacement of the dynamometer differed from the angular motion during knee extension situations (ARAMPATZIS et al. 2004, 2005; HERZOG 1988). This leads to the conclusion that isometric testing seems more adequate for examining isolated muscular strength than isokinetic testing and thus were applied in studies with ACL injured individuals for determining force capacity of the injured and non-injured leg (FITZGERALD et al. 2000).

Summarized it can be stated, that to really give a comprehensive picture of functionality, assessments of functional clinical tests, such as ROM measurements and leg circumference measurements, should be accompanied by dynamic and isolated FPTs. On the one hand, this gives insights into the passive functionality of the knee joint and the state of muscular atrophy, and on the other hand, into the recovery of functionality in dynamic movement situations and into the recovery of strength capabilities in isolated static and dynamic situations. The combined analyses of all these situations and the revealing parameters lead to a more comprehensive picture of functionality. However, to actually reach the claim of full comprehensive analysis of functionality, it seems absolutely essential to analyze ADLs, accordingly. As ADLs are executed every day to great extents, compensations or adaptations in daily activity locomotion can result in low functionality prospectively, due to the potential manifestation of the individual compensation strategies. As described in the FPTs, such compensation strategies in ADLs mainly appear as over-loading of the non-injured leg and, respectively, an under-loading of the injured leg. Such adaptation processes in locomotion can lead to and accelerate a gradual deterioration of the biological structures of joint and therewith enhance the general impairment of the whole joint's functionality.

Activities of Daily Living

As described, for a comprehensive elaboration of functionality after an ACL tear, it seems, not sufficient to mainly rely on the knee joint functionality in performance of dynamic sport-specific movements, such as jumping, or on the outcome of functional clinical tests. Certainly, sport-specific movement tasks (i.e. jumping) are highly-demanding and require a well-balanced and well-developed level of functionality for their successful realization. As described earlier, this makes dynamic FPTs appropriate for examining the functionality after ACL tears. Alongside, functional clinical tests give information on the state of recovery of each individuals' knee joint in a static or passive movement situation.

However, as normal life is characterized to a large extent by specific, daily occurring ADLs, compensations and adaptations in the locomotion of ADLs can lead to far-reaching consequences to the biological structures of a joint. A general approach for the interpretation of asymmetries in ADLs, as gait, is based on the support and the mobility of each leg and because even in healthy subjects asymmetries in ADLs were found (POLK et al. 2017; SADEGHI et al. 2000).

Therefore, such functional consequences, in terms of adaptations or compensations of the locomotion process, can develop acute or chronic, in form of degenerative diseases, such as knee OA, due to acute or manifested abnormal or unbalanced loading situations between the legs (ANDRIACCHI & DYRBY 2005; BERCHUCK et al. 1990; HALL et al. 2012; KNOLL et al. 2004b; WEXLER et al. 1998). Apparently, in ADLs, single loads are not on the same level like in sport-specific movements. However, the high number of repetitions of ADL movements throughout a day, in combination with potential shifts of loading within a joint throughout these movements, can result in a variety of problems for individuals with ACL tears and can encourage the framework of degenerative joint diseases (HALL et al. 2012). Such compensations in form of a shift of load in ACL reconstructed individuals can be apparent even a long time after the injury and reconstruction.

Such unequal or unbeneficial load ratios between the injured and the non-injured legs were detected in straight ahead gait due to abnormalities of gait locomotion induced by the deficient ACL (ANDRIACCHI & DYRBY 2005; BERCHUCK et al. 1990; GARDINIER et al. 2012). Such a pathologic unbalanced load ratio will lead to a slight but significant overload of the formerly non-injured leg. This is described as one major reason for the high incidences of subsequent injuries or impairments of other biological structures of the knee joint, such as the Menisci, the joint cartilages, as well as the higher odds ratio to develop knee joint degeneration in chronic knee OA, prospectively (ANDRIACCHI & DYRBY 2005; DANIEL et al. 1994; HALL et al. 2012; HAWKINS et al. 1986; MCDANIEL & DAMRON 1983). Since the biological structures of a joint need a certain load for their well-being, over-loading as well as under-loading can engage pathologic degenerative processes of the biological structures of the knee joints and of the entire leg as well (DANIEL et al. 1994; MCHUGH et al. 1994; WEXLER et al. 1998; ZABALA et al. 2013). Therefore, isolated under-loading of the injured or reconstructed knee is no key for regaining full knee joint functionality and does not recover the knee joint homeostasis. But changing of the load distribution in the knee joint, in direction to a higher internal knee adduction moment, increases the risk for developing knee OA by a factor of six with each 1% increase of this moment (MIYAZAKI et al. 2002).

Walking on flat ground is the ADL mainly performed throughout a day. Straight ahead gait was analyzed in various studies with ACL reconstructed or ACL deficient subjects at various times after the ACL reconstruction (ANDRIACCHI & DYRBY 2005; BERCHUCK et al. 1990; DEVITA et al. 1997; GARDINIER et al. 2012; HALL et al. 2012; WEXLER et al. 1998). Therein, the subjects with ACL deficiencies showed a general reorganization of their gait locomotion to reduce demands and loads to the knee extension musculature (i.e. M. quadriceps femoris) in terms of decreased internal knee extensor moments and reduced knee flexion angles throughout the whole stance phase of a gait cycle (BERCHUCK et al. 1990; CHMIELEWSKI et al. 2001; DEVITA et al. 1997; GARDINIER et al. 2012; RUDOLPH et al. 1998; WEXLER et al. 1998). Associated with the reduction of demands to the M. quadriceps femoris, loads to the reconstructed ACL are reduced. BERCHUCK and colleagues characterized this phenomenon as *quadriceps avoidance gait*. Such movement adaptations were found in 57% (WEXLER et al. 1998) to 75% (BERCHUCK et al. 1990) of the subjects with ACL deficiency even up to two years after the ACL tear. This quadriceps avoidance gait emerges to reduce the load and the stress to the reconstructed or deficient ACL by reducing the internal knee extension moment to avoid excessive anterior translation of the femur, which would be provoked by intense M. quadriceps femoris activation (BERCHUCK et al. 1990; GARDINIER et al. 2012; GEORGOULIS et al. 2003; HALL et al. 2012; RUDOLPH et al. 1998; TIMONEY et al. 1993; WEBSTER et al. 2005; WEXLER et al. 1998). This described quadriceps avoidance gait was not only seen in ACL reconstructed individuals, but also in non-reconstructed non-copers (ACL deficiency after non-surgical treatment of ACL tear), who reduced their knee ROM and the knee joint moments in the sagittal plane as stiffening strategy for maintaining knee joint stability (GARDINIER et al. 2012; LEWEK et al. 2003). Therefore, it is assumed that such a compensation strategy for knee joint stabilization negatively influences the long-term outcome of joint functionality and therewith represents another main factor for the high incidence of the earlier onset of knee OA after ACL tears compared to non-injured individuals, independently of whether the ACL tear was treated by a reconstruction or non-surgical therapy (GEORGOULIS et al. 2003; LEWEK et al. 2003; ZABALA et al. 2013). In contrast, there are also chronic ACL deficient individuals, who do not develop the quadriceps avoidance gait (KNOLL et al. 2004a; Knoll et al. 2004b; ROBERTS et al. 1999; RUDOLPH et al. 1998). As in the FPTs, these findings show that there do not exist generalizable recovery processes, which provides a clear rationale to analyze functionality after ACL tears and reconstructions as comprehensively as possible.

Additionally, as further potential adaptation process due to ACL tears in ADLs, a lower knee adduction moment was detected during straight gait and stair ascending and descending in the reconstructed knees in comparison to the non-injured contralateral leg (WEBSTER et al. 2012; ZABALA et al. 2013). As the knee adduction moment is lower in the reconstructed knee, it consequently has to be higher in the non-injured knee joint. The knee adduction moment is directly associated with the load distribution between the medial and lateral compartment of the knee joint (SCHIPPLEIN & ANDRIACCHI 1991; SHARMA et al. 1998). Therefore, a higher knee adduction moment results in a higher load on the medial compartment. Higher loads on the medial compartment of the knee joint are directly related to an enhanced risk for development of knee OA (MIYAZAKI et al. 2002; SCHIPPLEIN & ANDRIACCHI 1991; SHARMA et al. 1998). Thus, over-loading of the non-injured knee joint as well as under-loading of the reconstructed knee joint can lead to an acceleration of the knee OA processes in the injured or reconstructed knee joint as well as in the non-injured knee joint (MIYAZAKI et al. 2002; ZABALA et al. 2013).

These described adaptation and compensation mechanisms due to the ACL tear show that the ACL injured and reconstructed subjects do not generally recover to a normal movement locomotion, as it was detected in the described abnormal gait patterns. Such locomotion adaptations were not even seen in straight ahead walk immediately or short-term after ACL reconstruction but also from half a year up to two years after ACL reconstruction (BERCHUCK et al. 1990; DEVITA et al. 1997; HOOPER et al. 2002; TIMONEY et al. 1993; WEXLER et al. 1998).

Accordingly, some studies also examined locomotion of ACL reconstructed subjects during walking up and down stairs (ZABALA et al. 2013). However, as straight ahead walking patterns are widely examined, analyses of more strenuous or complex ADLs, such as walking stairs or turning, are underrepresent.

In summary, it has been shown that most subjects with reconstructed ACL tears and ACL deficiency adapt their gait pattern by reducing load to the reconstructed or impaired ACL and by changing kinematic gait patterns in the ADLs straight ahead gait, and ascending and descending stairs (GARDINIER et al. 2012; HALL et al. 2012; WEBSTER & FELLER 2011; SCANLAN et al. 2010; TASHMAN et al. 2004; ZABALA et al. 2013). Such adaptations of the locomotion patterns in ADLs and recreational activities were apparent even though sufficient or insufficient muscular capabilities were detected in the examined individuals (DEVITA et al. 1992; GARDINIER et al. 2012). However, as it was shown that not all individuals with ACL tears and chronic or acute ACL deficiency develop the quadriceps avoidance gait pattern (HALL et al. 2012), it is assumable that rehabilitation of ADL remains very individual.

This leads to the conclusion that due to the described alterations in the movement patterns on a dynamic and kinematic level, it seems absolutely reasonable to examine additional ADLs in ACL reconstructed subjects, to figure out if in these ADLs, pathologic movement adaptations occur as well or if such functional adaptations of locomotion patterns only appear during straight locomotion tasks (GEORGOULIS et al. 2003; ZABALA et al. 2013). The results and findings of movement analyses of these ADLs shall contribute important knowledge to the comprehensive analysis of functionality after ACL reconstructions. Therein, the analyses of various daily occurring movements alongside with functional clinical tests and FPTs lead to a more differentiated picture of functionality in ACL reconstructed and healthy subjects. Inclusion of ADLs, therefore, strongly enlarges the comprehensive approach of determination functionality, because ADLs require knee joint functionality for different demands than FPTs. Hence, with a comprehensive testing of various ADLs, variations or adaptations in locomotion patterns can be detected more detailed, and it can be analyzed whether recovery of full functionality in ADLs and all other settings of an active life is achievable with currently applied post-surgical treatment methods.

Leg Symmetry

As the detailed description of various approaches for determining knee functionality showed, it seems not sufficient to mainly rely on absolute performance values in the evaluation of functionality. Therefore, it has been established to calculate the relationship of the performance parameters between the legs, the so-called leg symmetry index (LSI) (BARBER et al. 1990; FITZGERALD et al. 2000; NOYES et al. 1983a; NOYES et al. 1991; GUSTAVSSON et al. 2006; NARDUCCI et al. 2011). Out of recently conducted studies, it has been shown that there are task-specific symmetry levels in static and dynamic movement conditions, which make a fully recovered knee joint function definable and help for the evaluation of functional recovery as well as the determination of a potential return to pre-injury sports (MYER et al. 2008; NEETER et al. 2006; ROHMAN et al. 2015; SHELBOURNE & KLOTZ 2006). Such definitions of healthy or normal symmetry levels for an evaluation of the functional recovery levels are drawn out of recently and formerly detected LSI levels of healthy, injured, and reconstructed individuals

(BARBER et al. 1990; MYER et al. 2008; NOYES et al. 1991). Identifications and understandings of side-to-side asymmetries or deficiencies in performance parameters or performance outcome results of ACL reconstructed individuals help to assess and compare functional imbalances, which is helpful for the modification of rehabilitation protocols (ORISHIMO et al. 2010). Nonetheless, one should not rely only on the LSI results, as a reduction in a performance parameter in the non-injured can lead to an increase in the LSI, even though the injured and reconstructed leg has not enhanced its performance outcome parameters. Therefore, absolute performance outcome parameters and LSIs should always be taken into account simultaneously in comprehensive analyses of knee joint functionality. However, the LSIs can be used as valid parameters for the evaluation of functionality, because LSIs provide direct information on how pronounced deficits appear between the injured and non-injured leg (FITZGERALD et al. 2000). This is in particular recommended in the evaluation of FPTs, such as jumps (NOYES et al. 1991) or strength testing (SNYDER-MACKLER et al. 1993), where leg symmetry levels of 85% or higher in females and males irrespective of the sports and activity level have been established to define normality (BARBER et al. 1990; MYER et al. 2008; NOYES et al. 1991; SNYDER-MACKLER et al. 1993). Nonetheless, although LSIs are valid measures of functionality, less than 50% of studies reported LSIs of the reconstructed leg in comparison to the non-reconstructed leg (ALMANGOUSH & HERRINGTON 2014). And finally, LSIs provide better comparability between various FPTs, as all tested tasks can get analyzed in relation to the same parameter, what additionally relieves essential information on the relative deficit of the injured and reconstructed leg compared to the non-injured leg, according to the emerging deficit in each respective test.

2.6 Psychological Consequences on Quality of Life

Besides the importance of the morphological and functional recovery after an ACL tear and subsequent reconstruction, it has been described that full recovery of the functionality and return to pre-injury sports can be better achieved, if reconstructed individuals have a positive self-conception and a positive attitude in relation to their injury, in combination with high motivation and self-responsibility with regard to the participation of the ambulatory and self-exhibited rehabilitation exercises (EVERHART et al. 2015; FITZGERALD et al. 2000; TE WIERKE et al. 2013). Accordingly, psychological as physiological impairments and imbalances immediately lead to functional deficiencies, which are seen as predispositions for subsequent ACL injuries and earlier onset of knee OA in lifetime (BEYNNON et al. 2005a; CHMIELEWSKI et al. 2008; DANIEL et al. 1994; EVERHART et al. 2015; HAWKINS et al. 1986; HERTEL et al. 2005; KANNUS & JÄRVINEN 1989; LOHMANDER et al. 2004; MALETIUS & MESSNER 1999; MCDANIEL & DAMRON 1983; PATERNO et al. 2010; TE WIERKE et al. 2013). As testing of functional performance tasks is highly specific in relation to the analyzed task (AAGAARD et al. 1996; GIBOIN et al. 2015; KRAEMER et al. 2002), functionality can also be assessed out of the ACL reconstructed individual's view by scores or questionnaires. In combination with functional testing, this enables to detect a comprehensive overview of the functional level of an individual.

Therefore, self-evaluative questionnaires contribute important information to the extent of functional impairments, as a general reduction of the sports and activity level or injury-induced long or general drop-out from activity or sports has shown to negatively affect an ACL reconstructed individual's QoL and remain major concerns after ACL tears (Dekker et al. 1993; MANSSON et al. 2011; ROI et al. 2006; SÖDERMAN et al. 2002; VON PORAT et al. 2004). The extension of information about functional impairments is enabled by including various situations of daily life, which immensely enlarges the comprehensive picture of functional state of an individual (ROOS et al. 1998).

The importance of including self-evaluative questionnaires and scores in the analysis of functionality is underlined by the fact that the psychovitality of individuals who returned to sports was higher than in those who had to cease from all sports activities after ACL tear and reconstruction (GOBBI & FRANCISCO 2006). Furthermore, many ACL reconstructed individuals suffer from functional impairments and the resulting reduction of social activities and a decrease of emotional well-being (VON PORAT et al. 2004), which is also detectable by such scores and questionnaires. In line, individuals with greater fear of a repetitive tear of the reconstructed ACL return less often to pre-injury sports and sports levels compared to individuals with less fear of re-injury (KVIST et al. 2005).

For the detection of social and functional deficits, a variety of questionnaires and scores exist (ROOS et al. 1998). However, it appears that the Knee Injury and Osteoarthritis Outcome Score (KOOS) is best fitting for the requirements of a comprehensive analysis of functionality after a knee injury (ROOS et al. 1998). Due to its variety of questions the KOOS provides the most decisive and fine-grained results in relation to the individual state of knee joint functionality due to the knee injury (ROOS et al. 1998). Other self-evaluative questionnaires and scores appear to be rather specific (ROOS et al. 1998). For instance, the Lysholm Score (TEGNER & LYSHOLM 1985) is mainly focused on short-term consequences and cumulates symptoms and function in one score, the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) (BELLAMY et al. 1988) has its focus on the evaluation of long-term consequences (ROOS et al. 1998). In contrast, the KOOS enables, besides its wide variety of questions, a separate analysis of all included sub-categories (pain, symptoms, ADL, sport and recreation function, knee related QoL), which allows a more specific detection of individual functional deficiencies (ROOS et al. 1998). The wide scope of the KOOS implies that the inclusion of this self-evaluative questionnaire provides meaningful insights into the functionality of ACL reconstructed individuals. Therefore, it is indicated to include at least one questionnaire for the self-evaluation of knee joint functionality into a comprehensive evaluation of functionality after a knee injury or chronic disease.

3 Synthesis of Findings, Research Question and Scope of the Thesis

3.1 Synthesis of Findings

Summarizing chapter 2.1 to 2.6, it can be concluded that tears of the ACL can lead to a variety of morphologic and behavioral consequences, which support and enhance the development of the knee joint instabilities and the loss of the knee joint function post-operatively (HARRISSON et al. 1994). These consequences can lead in isolation or in combination to functional imbalances short-, mid- and long-term after the reconstruction, which can contribute to an increased risk of musculoskeletal disorders and chronic degenerative joint diseases.

Summarized, after ACL tears and reconstructions, generally, alterations can occur,

- In associated biological structures of the injured knee joint, as well as in impairments of the whole injured and non-injured leg (e.g. atrophy of the legs' musculature, destruction and degeneration of the Menisci as well as knee oa).
- In the performance or the performance level in sport-specific movements (e.g. jumping, running, cutting maneuvers).
- In daily living locomotion tasks (e.g. walking or walking up- and downstairs).
- In psychological consequences, which can highly influence the somatic and behavioral rehabilitation (e.g. reduction of the quality of life or a lower activity level).

Even though reconstruction techniques and rehabilitation programs have improved in recent years, full recovery of the knee joint functionality cannot generally be ensured and guaranteed in ACL reconstructed subjects. Instead, limitations in ADLs, in recreational activities, and sports can persist short-term or long-term after the ACL tears and the subsequent reconstructions or sometimes even for the entire life-time (BOERBOOM et al. 2000; HARTIGAN et al. 2010). Therefore, a main goal of all therapeutic and rehabilitative treatment after ACL reconstructions is to regain full functionality of the knee joints in ADLs, recreational activities and sports and to prevent the onset of chronic joint diseases, such as knee OA (BEYNNON et al. 2005a; MURPHY et al. 2003; TEGNER et al. 1986).

Although, many studies were conducted in recent years to contribute their results and findings to the enhancement of knee joint rehabilitation after ACL tears, there is no consensus on the optimal rehabilitative approach, the optimal detection of knee joint functionality post-operatively, and the determination of the best time to return to pre-injury sports or activities (BEYNNON et al. 2005a). Therefore, the conduction of studies to enhance the rehabilitation after ACL tears and reconstructions remains an important, substantial field of investigations.

Although there could not be found any consensus, the major aims of rehabilitation programs are defined by the desire and the purpose of the reconstructed individuals to regain full knee joint functionality and stability in all situations of daily life and to return in pre-injury sports and activities on pre-injury intensity level (BEYNNON et al. 2005a; MURPHY et al. 2003). However, due to insufficient recovery processes, many reconstructed individuals develop chronic knee joint instabilities, chronic joint diseases, or suffer from re-rupture or secondary injuries of the knee joint (PINCZEWSKI et al. 2007; RUDOLPH et al. 2000; SALMON et al. 2005; WRIGHT et al. 2007). Due to this short- and long-term consequences, which can be the result of an incomplete rehabilitation process, many individuals experience a reduction of the overall QoL and a return to pre-injury sports and activities is unattainable (BEYNNON et al. 2005a; MURPHY et al. 2003). Furthermore, therapists and clinicians mainly rely on the time period after a surgical reconstruction as major criterion to assume that an individual is functionally recovered and can get released back to sports (BARBER-WESTIN & NOYES 2011; PETERSEN & ZANTOP 2013). However, to release ACL reconstructed individuals back to pre-injury sports without any functional testing, has a high risk to overstrain the potentially insufficient recovered reconstructed knee joint. Overstraining the knee joint could lead to a higher potential of a re-rupture or of secondary injuries of the injured knee joint or contralateral non-injured knee joint.

Present functional testing of ACL reconstructed individuals, for determination of knee joint functionality, is dominated by conducting functional clinical tests, such as the Lachman test or testing of the joint's passive ROM. The results of these functional clinical tests, along with the passed time since the reconstruction, are used as major criteria to release an ACL reconstructed individual back in pre-injury sports and activities. Assessments of muscular strength testing or the application of other FPTs are underrepresent for the decision making. (PETERSEN & ZANTOP 2013)

This shows that conducting FPTs in the post-reconstructive process has not been established in the past years. However, as FPTs provide important insight into the level of functionality while performing dynamic demanding movements, it is absolutely suggestable to motivate therapists and clinicians to integrate FPTs in the assessment of functionality after an ACL tear and reconstruction. As the level of functionality changes in relation to the state of recovery, it is additionally indicated to consequently conduct the functional testing repetitively into the rehabilitation process. By such a functional testing, knee joint functionality could be detected more precisely and detailed, which would help to detect a clearer picture of the individual's state of functionality.

Therefore, it is assumable that it is of great value to establish screening procedures, detecting the functional state of the knee joint of ACL reconstructed individuals more comprehensively at certain stages of the rehabilitation cycle. Such a comprehensive analysis of functionality would provide a very specific and fine-grained individual picture of the functionality. The detected results and findings would be beneficial for therapists to adapt the respective rehabilitation programs more specifically, according to the individual functional deficits. Furthermore, to detect the course of functionality over the rehabilitation cycle more detailed and comprehensively, would help to obtain important knowledge on the general development of various aspects and parameters of knee joint functionality. Overall, such an approach in the detection of functionality could beneficially support a more individually controlled rehabilitation program with a potentially better functional outcome of the ACL reconstructed individuals. All these findings and results shall help to determine the complex framework of knee joint functionality more specifically. Such specific analyses of the functional state are of great interest to better determine the point in time when ACL reconstructed individuals have reached the same functional level as healthy individuals, which is assumed essential for a symptom-free performance in ADLs and the safe return to pre-injury sports and activities on pre-injury intensity level with a reduced risk of re-ruptures (GUSTAVSSON et al. 2006).

3.2 Purpose and Research Questions

Deduced of this findings, the main purpose of the thesis is to examine the knee joint functionality of ACL injured and reconstructed subjects with a comprehensive approach at multiple times from pre-reconstruction up to six months post-reconstruction. Additionally, in order to determine if the ACL reconstructed subjects have regained the pre-injury level of functionality, their results will be compared to the results of matched healthy control subjects at six months post-reconstruction. With this purpose, important knowledge over the course and the development of functionality should be determined. This knowledge shall contribute to enhance post-reconstructive rehabilitation processes by a more individually steered functional rehabilitation program and to better detect the time for releasing individuals back in pre-injury sports and activities.

Out of the purpose, the main research questions of the thesis were deduced:

(1) How does knee joint functionality proceed in functional clinical tests, functional performance tasks and activities of daily living in ACL reconstructed subjects from pre- to six months post-ACL reconstruction?

(2) How does the ACL reconstructed subjects' self-evaluated knee joint functionality proceed from pre- to six months post-reconstruction?

(3) What level of knee joint functionality do ACL reconstructed subjects reach in functional clinical and functional performance tests compared to matched healthy control subjects at six months post-ACL reconstruction?

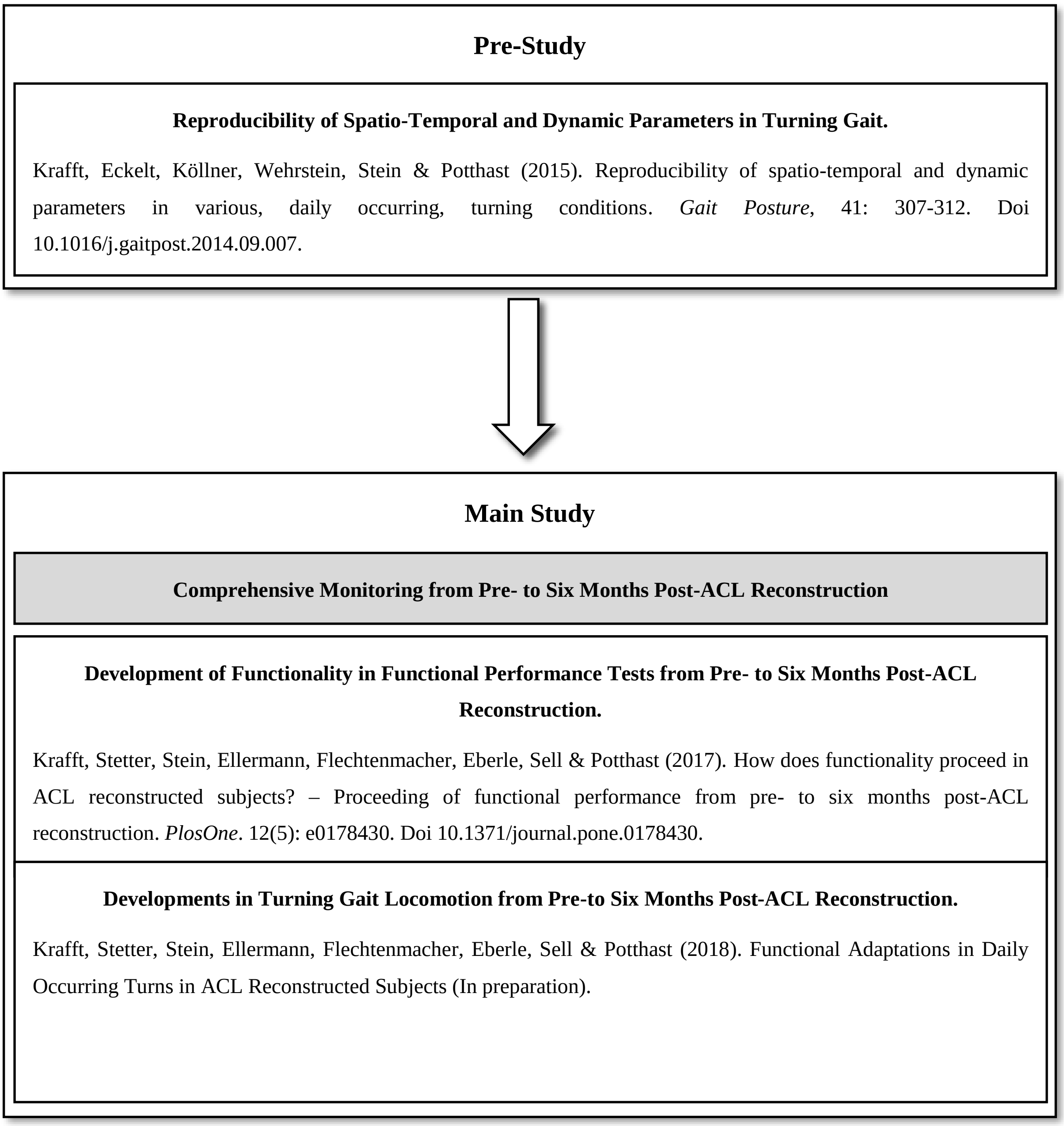
(4) Do ACL reconstructed subjects show functional alterations and compensation strategies in activities of daily living compared to matched healthy control subjects at six months post-ACL reconstruction.

3.3 Scope of the Thesis

To reach the purpose and address the research questions, the thesis comprises the results and findings of a methodological pre-study (Chapter 4) as well as selected analyses, results and findings of the thesis' main study (Chapters 5 and 6).

The pre-study's purpose was to examine the reproducibility of three daily occurring turns, in relation to the spatio-temporal parameter ground contact time and the dynamic parameters vertical and medio-lateral GRF components. This pre-study was conducted as an examination of the reproducibility of turning locomotion was lacking in scientific literature. However, for an inclusion of these daily occurring turns into the test battery of the main study, it was essential to bear warranty that the conducted turning conditions are reproduced reliable and, thus, turning movements are in the performance independent of the applied test setting.

After finalizing this pre-study, the main study of this thesis was conducted. Therein, a longitudinal study with four test sessions was designed, including a test battery, aiming for a comprehensive evaluation of the knee function by combining the subjects' functional self-evaluation with biomechanical analyzes of ADLs and FPTs (Chapter 4). The methodology of this main study is subsequently described in detail (4.1 to 4.5). This shall give an overview over the whole scope of the main study of this thesis. However, as the conduct of the whole test battery led to an extensive amount of data, not all results of all conducted tests could be analyzed and embedded in the framework of this thesis. Therefore, only the results of the subjects' self-evaluation, the functional clinical tests, and the FPTs, as well as the results and findings of the analysis of two daily occurring turns (90° and 180° turning conditions) could have been integrated into the scope of the thesis. Figure 5 gives a general overview of the thesis' structure and illustrates the included studies, which were embedded in this thesis.



Pre-Study

Reproducibility of Spatio-Temporal and Dynamic Parameters in Turning Gait.

Krafft, Eckelt, Köllner, Wehrstein, Stein & Potthast (2015). Reproducibility of spatio-temporal and dynamic parameters in various, daily occurring, turning conditions. *Gait Posture*, 41: 307-312. Doi 10.1016/j.gaitpost.2014.09.007.

Main Study

Comprehensive Monitoring from Pre- to Six Months Post-ACL Reconstruction

Development of Functionality in Functional Performance Tests from Pre- to Six Months Post-ACL Reconstruction.

Krafft, Stetter, Stein, Ellermann, Flechtenmacher, Eberle, Sell & Potthast (2017). How does functionality proceed in ACL reconstructed subjects? – Proceeding of functional performance from pre- to six months post-ACL reconstruction. *PlosOne*. 12(5): e0178430. Doi 10.1371/journal.pone.0178430.

Developments in Turning Gait Locomotion from Pre-to Six Months Post-ACL Reconstruction.

Krafft, Stetter, Stein, Ellermann, Flechtenmacher, Eberle, Sell & Potthast (2018). Functional Adaptations in Daily Occurring Turns in ACL Reconstructed Subjects (In preparation).

Figure 5. General Structure of the Thesis. *Overview of the research process of the conducted pre-study (Chapter 5) and the sub-studies of the main study (Chapter 6 and 7), which were included in the framework of the thesis. All studies were conducted in the BioMotion Center of the Institute of Sports and Sports Science at the Karlsruhe Institute of Technology.*

4 General Methodology

This methodological chapter comprises five sections. The first section gives an overview of the general methodology of the main study (Section 4.1), including the sample characteristics and all applied measurement methods, which were used to record and assess the movement tasks of the test battery. These tested movement tasks, which were conducted at each test session with all subjects of the ACL group and the control group (CG) are described in detail (Sections 4.2 to 4.5). The general methodology described in this Chapter 4 represents mainly the general description of the entire methodology of the conducted main study. The specific methodology of the conducted pre-study is described in the Methods section (Section 5.3) of Chapter 5, wherein the study and its findings are presented. The specific methods, as well as the specific results and findings from specific tests that were part of the main study, are analyzed separately and described in Chapters 6 and 7.

All tasks of the applied test battery were conducted in the biomechanical movement analysis laboratory, BioMotion Center, at the Institute of Sports and Sports Science at the Karlsruhe Institute of Technology. The realization of the main study was approved by the ethics committee of the State Medical Council of Baden-Württemberg (Stuttgart, Germany)[1]. Furthermore, all subjects, who participated in the study, provided written informed consent for the study participation.

4.1 Methodology of the Main Study

Sample

20 subjects with unilateral tears of the ACL were included for the measurements of the thesis' main study (Table 1). The subjects with ACL tears were acquired in cooperation with the Ortho-Zentrum, Karlsruhe[2] and the ARUCS Sports Clinics, Pforzheim[3]. All subjects with ACL tears received a uniform reconstruction technique with a combined semitendinosus and gracilis autograft, via the double-bundle technique, resulting in quadruple-bundle autografts (SCHMIDT-WIETHOFF & DARGEL 2007). The ACL autograft was fixed to the distal femur with a button and to the proximal tibia with a screw (Figure 4). Healthy control subjects were matched to the ACL injured subjects by the matching

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[1] Ethik-Kommission der Landesärztekammer Baden-Württemberg, Jahnstr. 40, 70597 Stuttgart (www.aerztekammer-bw.de/ethik)

[2] Ortho-Zentrum, Orthopädische Gemeinschaftspraxis, Waldstr. 67, 76133 Karlsruhe (www.ortho-zentrum.de).

[3] ARCUS Sportklinik, Rastatter Str. 17-19, 75179 Pforzheim (www.sportklinik.de).

factors: sex, age, height, body mass and pre-injury activity level, determined by the Tegner Activity Score (TAS) (Table 1).

Table 1. Study Sample.

	Age [yr]	**Height [cm]**	**Mass [kg]**	**Body-mass index [kg/m^2]**	**Activity Level (TAS)**
ACL group	32.0 ± 13.8	174.6 ± 9.2	73.3 ± 8.8	24.2 ± 3.5	6.4 ± 1.4
Control group	33.3 ± 13.4	175.4 ± 10.4	74.7 ± 8.4	24.4 ± 2.6	6.0 ± 1.4

Mean values and standard deviations (SD) of the age, the anthropometric parameters body height [cm], body mass [kg], the Body-Mass-Index [kg/m^2], and the activity level determined with the Tegner Activity Score (TAS) of the ACL group subjects and the matched healthy control group subjects. TAS in the ACL group subjects is related to the pre-injury activity level.

Analysis of the homogeneity of the variances of both groups revealed no significant differences in the matching factors: age ($F=0.003$, $p=0.955$), height ($F=0.342$, $p=0.562$), body mass ($F=0.005$, $p=0.945$) and activity level ($F=0.361$, $p=0.552$).

Before the movement analyses were conducted, all ACL group and CG subjects had to complete personal questionnaires, consisting of subjects' specific questions, participation criteria, declaration of consent and subjects' personal specifications (Appendix 10.1).

Study Design

The ACL injured and reconstructed subjects had to attend at four test sessions up to about six months after ACL reconstruction (Figure 6). Time periods between the test sessions were set according to the generally applied rehabilitation program after ACL tears and reconstructions of the German Health insurance system (see paragraph *Rehabilitation Program* in this Section).

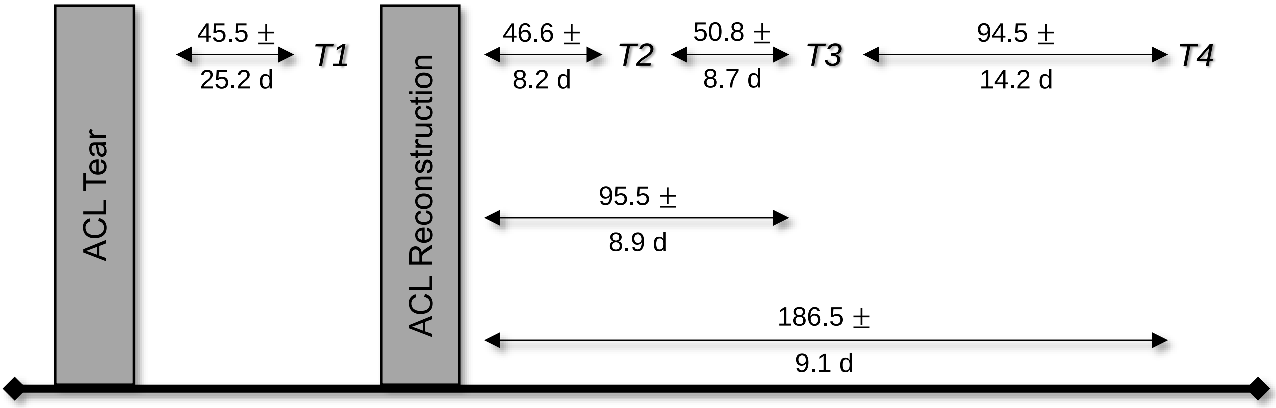

Figure 6. Study Design. *Mean days (d) and standard deviations between the test sessions of the ACL reconstructed subjects. T1 was at about seven weeks after the ACL tear, immediately before the ACL reconstruction surgery. T2 was at about six to seven weeks after the ACL reconstruction surgery. T3 was about three months and T4 was about six months after the ACL reconstruction surgery.*

Rehabilitation Program

After the surgical reconstruction of the torn ACL, all subjects received a standardized rehabilitation program according to the German Health Insurance System.

The rehabilitation program can be generally separated into three main stages and was monitored in this study by activity diaries, the subjects had to keep in between the test sessions:

- Low-intensity (passive) activities up to 6 weeks after reconstruction. Including physiotherapy with lymphatic drainage, passive movement exercises (by machine or a therapist), sensorimotor training, weight-bearing exercises, and isometric training under therapists' supervision.
- Medium-intensity activities with muscular and balance training up to three months post-ACL-reconstruction. Including physiotherapy with lymphatic drainage, passive movement exercises, independent strength training, balance training, and activities and sports without pivoting movements (e.g. cycling, crawl swimming, (nordic) walking).
- Medium-to-high-intensity activities, including intense strength training, if possible, up to six months after reconstruction under self-responsibility. Additionally, sports training (without pivoting movements) and slight return to pre-injury sports and sports-level with jumps, intense cycling and strength training.

Overall, the stages were adaptable and variable according to the rehabilitative functional state of an individuals' knee joint. Such a stepwise, 3-staged structure is common in rehabilitation programs after ACL reconstructions (WHITING & ZERNICKE 2008). The summarized rehabilitation program with the applied exercises and training program as well as the performable activities and sports of the ACL subjects of this study is presented in detail in the Appendix 10.5.

Data acquisition

Data acquisition took place in the movement analysis laboratory of the BioMotion Center of the Institute of Sports and Sports Science of the Karlsruhe Institute of Technology with all the ACL injured and reconstructed subjects and all the healthy CG subjects at each test session.

In advance to the movement analyses, specific anthropometrics of all subjects were measured in relation to the user manual of the ALASKA modelling system (HÄRTEL & HERMSDORF 2006) (Figure 8; Table 8 Appendix 10.3). Afterwards, 42 retro-reflective spherical markers (Diameter 19 mm, lightweight super-spherical markers; Qualisys AB, Gothenburg, Sweden[4]) were attached to model-specific anatomical landmarks using double-sided tape according to a modified version of the multi-body model, ALASKA Dynamicus 9 (HÄRTEL & HERMSDORF 2006; ALASKA, Advanced Lagrangian Solver in Kinetic Analysis, Institute of Mechatronics, Chemnitz University of Technology, Germany[5]). (Figure 7; Table 10 Appendix 10.4)

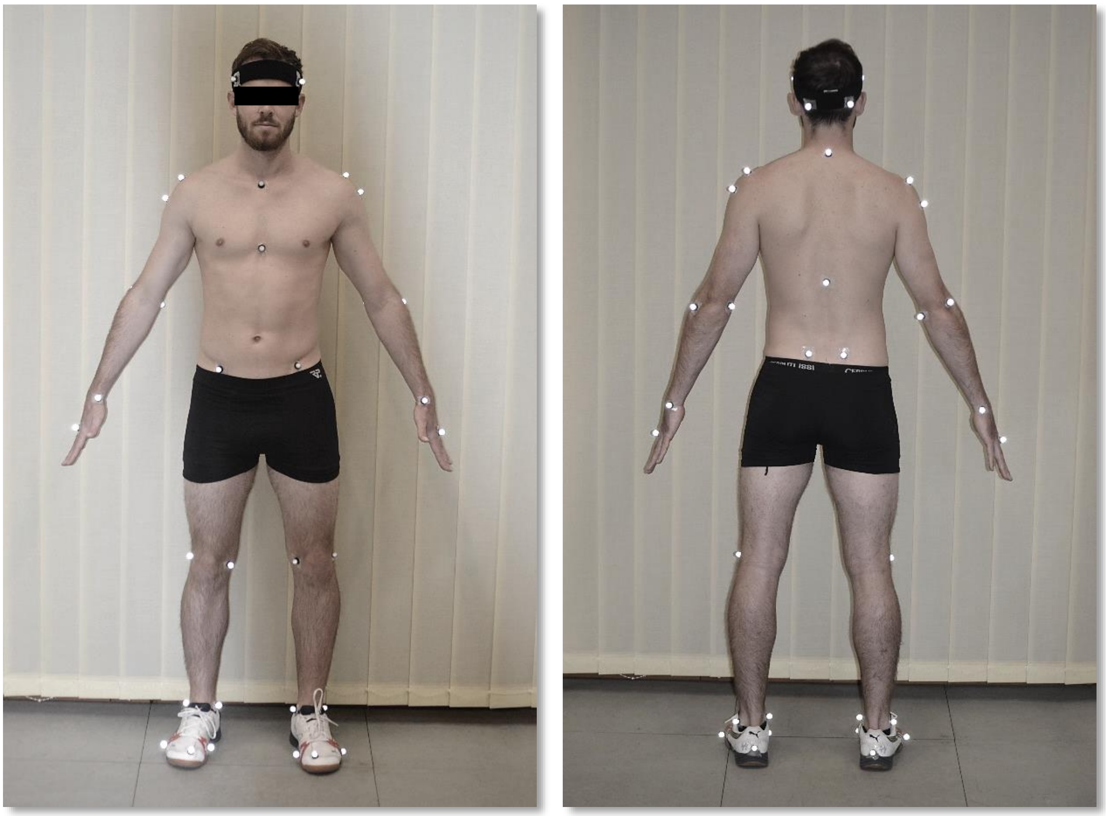

Figure 7. Marker Set. *Left: Frontal view and Right: Dorsal view of a subject with the attached 42 retro-reflective spherical markers (diameter 19 mm) according to the ALSAKA Dynamicus 9 model (HÄRTEL & HERMSDORF 2006).*

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[4] Qualisys AB, Kvarnbergsgatan 2, 41105 Göteborg, Sweden, www.qualisys.com.

[5] Institute of Mechatronics, Chemnitz University of Technology, Reichenheiner Str. 88, 09126 Chemnitz, Germany, www.ifm-chemnitz.de.

Kinematics of all tested movement tasks (FPTs and ADLs) were recorded by a three-dimensional (3D) Motion Capture (MoCap)-System, consisting of 13 3D Infrared-Tracking-Cameras (200 Hz; VICON® Oxford, UK; 12 MX13 cameras and 1 MX3 camera). The cameras were installed in the laboratory to reach a measurement volume, which covered an area of about 15 square meters.

For an optimal tracking of the attached markers, each marker has to be trackable by at least two cameras in each location of the measurement volume. Prior to the dynamic movements, one static trial in the Neutral Subtalar Position was recorded to capture the neutral position of all joints. Movement kinetics were captured with two 3D force plates (FP) (1000 Hz; 90 x 60 cm; AMTI®, model ORG 6,

Advanced Mechanical Technology, Watertown, MA, USA), which were linked to the MoCap-System for simultaneous data acquisition.

After capturing the respective movement trials, in the post-recording process, the kinematic data had to be reconstructed and labelled to receive gap-free trajectories of the multi-body model throughout the whole movement trial. Gaps of the marker trajectories were filled by software-implied algorithms applying the pattern fill or spline fill technique. This data pre-processing was conducted with the software Vicon Nexus® (Version 1.8.5; Oxford, UK).

For the calculation of kinematic data (e.g. joint angles), kinetic data (e.g. GRFs), as well as the inverse dynamics (e.g. joint torques), all movement files were processed with the Dynamicus Alaska Modeller studio software (Version 9.3, Institute of Mechatronics, Technical University Chemnitz, Germany). Before processing the Vicon movement files with the Dynamicus Alaska Modeller studio software, processing of the data with Matlab was essential (Version R2017a; The MathWorks® Inc., Natick, Massachusetts, USA). Matlab processing was necessary, to prepare the captured movement files along with the anthropometric data for calculation of the inverse dynamics with the ALASKA Dynamicus 9 model (HÄRTEL & HERMSDORF 2006).

By employing the multi-body model, subject-specific re-modelling of the recorded movements is enabled. By this re-modelling process, in combination with the recording of marker data (kinematics) and before measured subject-specific anthropometric data (Figure 8; Table 8 Appendix 10.3), individual subject-specific modelling is enabled in relation to subject-specific anthropometry (ROBERTSON et al. 2004).

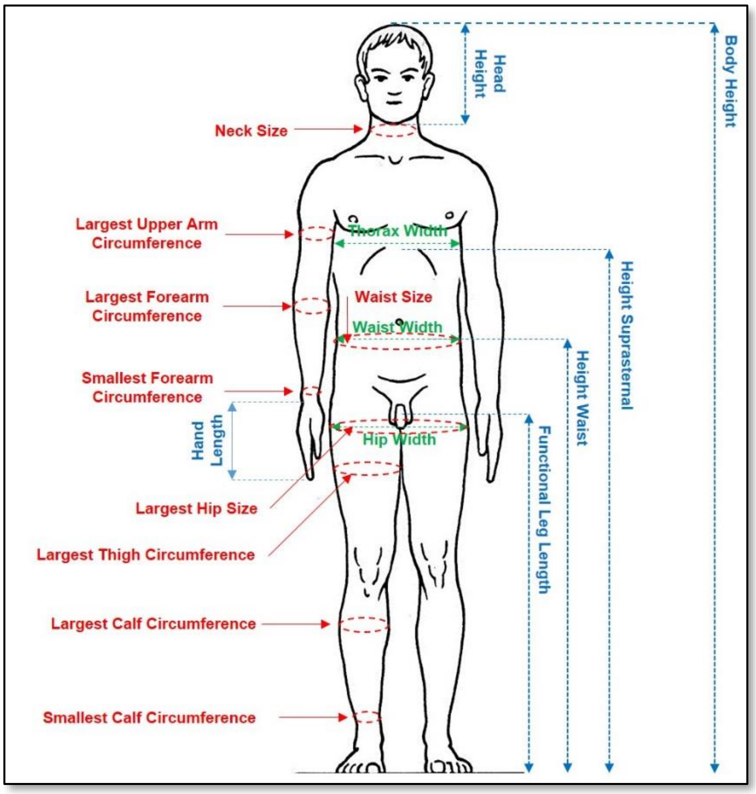

Figure 8. Anthropometric Landmarks and Parameters. *Landmarks and parameters of the anthropometric measurements, which were conducted at each test session before the markers were attached, according to the ALASKA Dynamicus model (Härtel & Hermsdorf 2006)*

By a combination of such a 3D movement analysis with 3D FPs, all kinematic and kinetic parameters of a movement can be sampled and quantified. This combined setting represents the gold standard of human movement analysis and represents the base for the inverse dynamics approach. The combined recording of kinematic and dynamic data, along with inertial properties of the movement, enables the indirect determination of forces and moments acting in the respective joints by the closed inverse dynamics approach (Robertson et al. 2004). Therein, three-dimensional kinetic data, i.e. moments and forces acting in the joints, are computed. These kinetic data are calculable because the application point of the GRF to the foot, the so so-called center of pressure (COP), is known by the recordings of the FPs. In combination with the kinematic and GRF data, specific kinetic data acting in the respective joints, for instance the knee or the hip joint, can be computed by applying Newtonian mechanics (Aldersen & Elliot 2009). By computing the inverse dynamics, it is possible to measure the net effect of all internal forces and moments that acted across several joints (Robertson et al. 2004).

Data Processing

For determination of knee joint function in all conducted tests, the measured performance outcome parameters of each leg were initially measured and analyzed separately. Such isolated measurements of the legs' performances enable the calculation of exact performance relationships between the legs. Such an isolated analyses of the legs' performances and, thereof, the calculable leg symmetry index (LSI) are established methods for determining and assessing functionality in healthy and diseased samples (AUGUSTSSON et al. 2004; BARBER et al. 1990; EASTLACK et al. 1999; FITZGERALD et al. 2000; ITOH et al. 1998; JERRE et al. 2001; JURIS et al. 1997; NOYES et al. 1991; RUDOLPH et al. 2000). The calculation of the LSIs, means, standard deviations (SDs), and 95% confidence intervals (CIs) of the relevant parameters were computed with Microsoft Office Excel (Versions 2013 and 2016; Microsoft Corporation, Redmond, Washington, USA). Out of the means, the LSIs for all relevant parameters were calculated.

For the calculation of the LSIs in the ACL group subjects, the performance outcome of the ACL teared leg was divided by the performance outcome of the non-injured leg:

$$LSI_{ACL} = \frac{performance\ outcome\ ACL\ teared\ leg}{performance\ outcome\ uninjured\ leg}$$

For the calculation of the LSIs in the healthy CG subjects, the performance outcome of the non-dominant leg was divided by the performance outcome of the dominant leg:

$$LSI_{CG} = \frac{performance\ outcome\ non-dominant\ leg}{performance\ outcome\ dominant\ leg}$$

The calculation of the LSIs yielded unit-free results and provided information about the relative difference of the performance of the injured leg in comparison to the non-injured leg in the ACL group subjects and of the performance of the non-dominant leg in comparison to the dominant leg in the healthy CG, respectively (BARBER et al. 1990; FITZGERALD et al. 2000; NOYES et al. 1991).

Leg dominance was determined in advance by self-evaluation of all subjects with three questions, which are established for determining leg dominance and were selected according to CHAPMAN et al. (1987). These questions were included in the subjects' personal specifications-questionnaire (Section 10.1). Therein, the foot dominance query consisted of the questions:

- Which foot is preferred to kick a ball?
- Which leg is rather preferred in single-leg jumping tasks?
- Which leg is more stable in single-leg balance tasks?

Statistical Analyses

All descriptive statistics (means, SDs, and 95% CIs) were calculated with Microsoft Excel 2013 and 2016. Calculations of inferential statistics in the ACL group subjects between the test sessions and between the ACL group subjects and the healthy CG subjects were employed with the statistical analysis software SPSS 22 and SPSS 24 (IBM, Armonk, NY, USA).

Therein, to calculate inferential statistics of the analyzed parameters in the ACL group subjects over the test sessions, one-way analysis of variance with repeated measures (RM-ANOVA) were employed. If the RM-ANOVA revealed significant differences, Holm-Bonferroni corrected post-hoc *t*-tests for dependent samples were employed to determine statistical differences between the four test sessions (HOLM 1979). Comparison of data between the ACL group subjects at six months post-reconstruction (T_4) and the healthy CG subjects were calculated by using *t*-tests for independent samples. The level of significance was set a priori for all statistical calculations at $p \leq 0.05$.

For prevention of over-interpreting statistical significance values, a magnitude or size of an effect was expressed by the computation of effect sizes. For the size of an effect, for the RM-ANOVAS partial eta squared (η_p^2) and for the *t*-tests COHEN's *d* was calculated (COHEN 1992). According to COHEN (1992), large effects are indicated by η_p^2 = 0.14, medium-sized effects by η_p^2=0.06, and small effects by η_p^2=0.01. In terms of COHEN's *d*, large effects are indicated by *d* = 0.8, medium-sized effects by *d* = 0.5 and small effects by *d* = 0.2.

4.2 Questionnaires and Scores

Questionnaire for Self-Administered Evaluation of the Knee Functionality

Various approaches exist for the self-administered evaluation of a current state of functionality after knee injuries or chronic knee joint diseases with questionnaires or scores. Examples are the Lysholm Score (TEGNER & LYSHOLM 1985), the WOMAC (BELLAMY et al. 1988) or the KOOS (KESSLER et al. 2003; ROOS et al. 1998).

In this study, the KOOS was applied. The KOOS' construct and content validity, as well as its test-retest reliability (interclass correlation coefficient (ICC) > 0.75) were proven. Hence, the KOOS is a valid and established assessment tool for self-administered self-evaluation of knee function after knee injuries or chronic knee joint diseases (ROOS et al. 1998; ROOS et al. 2003). In the present study, the validated German version of the KOOS was applied (KESSLER et al. 2003).

In general, the KOOS consists of five dimensions or sub-categories (*Symptoms & Stiffness, Pain, activities of daily living, sport and recreation function, and knee-related quality of life)*. Each sub-category consists of a certain amount of function related questions. Each question contains standardized options of reply (Likert boxes) and each reply is linked with a certain score, ranging between 0 (no symptoms or problems) and 4 (heavy symptoms or problems). For calculation of the overall score of a sub-category, the points related with each reply of each sub-category were cumulated and divided by the maximal reachable scores of each-subcategory. Therewith, each sub-category, as well as the whole questionnaire is standardized and normalized to a maximal reachable score of 100. A score of 100 indicates that a subject has no symptoms or restrictions of functionality in any sub-category. A score of 0 indicates extremely severe problems or limitations by the knee injury or the disease. The calculation of the score of each sub-category can be expressed with the following equation (ROOS et al. 1998):

$$Score_{sub-category} = 100 - \frac{Actual\ raw\ score\ \cdot\ 100}{Possible\ raw\ score}$$

This specific rating approach for analyzing the results of this score, represents a great benefit of the KOOS. By this procedure, the whole score is comparable with all its sub-categories and, furthermore, all the sub-categories can be compared among each other. Additionally, as each sub-category only consists of questions that correspond to a specific topic (e.g. symptoms or pain), ceiling effects are reduced (Appendix 10.2).

Questionnaire for Assessment of the Pre-injury and Current Activity Level

Besides the KOOS, for assessing the pre-injury activity level and the current activity level at each respective test session, the TAS was applied and had to be completed by all subjects prior to the measurements (TEGNER & LYSHOLM, 1985). The TAS enables each individual to the self-administered rating of the current activity level from 0 (s*ick leave or disability pension because of knee problems)* to a maximal reachable score of 10 (*Competitive sports: soccer – national and international elite*). This score for self-administered evaluation of the activity level is established in the scientific community and was widely included in several studies (LEITER et al. 2014; TEGNER & LYSHOLM, 1985). The complete version of the TAS is presented in the Appendix 10.2.

4.3 Functional Clinical Tests

Functional clinical tests are applied and used to determine the function of a specific joint (HIRSCHMANN & MÜLLER 2015). In this study, passive ROM measurements in knee flexion and knee extension situations, according to JANDA (2002), were conducted for the analyses of the function of the thigh's major musculature. Therein, the subjects had to lie in prone position for measurements of passive knee flexion ROMs and in supine position, with the leg hanging over the edge of an examination couch, for measurements of passive knee extension ROMs. To reduce inter-rater-variances, the ROM measurements were conducted at each test sessions by the same examiner. Each ROM measurement was conducted three times, to calculate the average value out of the three measurements and to reduce intra-rater variances. Assessments of knee ROM after ACL injuries and reconstructions provide essential information of the knee joint's state of recovery, as it was described that deficiencies of the passive ROM after ACL tears and reconstructions occur (ERNST et al. 2000). Furthermore, deficiencies of the ROMs during knee joint flexion and extension are seen as a determining limiting factor for all movements and the prospective level of knee joint functionality, especially in FPTs (ERNST et al. 2000). Additionally, to assess changes of the thigh musculature of an external viewpoint, leg circumference measurements at four standardized positions, according to SØDERBERG et al. (1996), were conducted. The circumference measurement positions at the leg were: the joint line (JL), 5cm below the joint line (I5), 5cm (S5), and 15cm (S15) above the joint line (Figure 9).

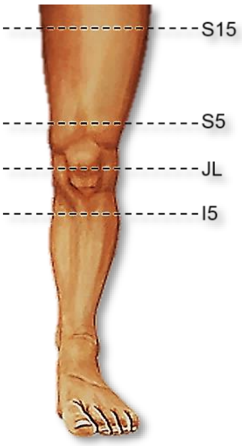

Figure 9. Landmarks of the Leg Circumference Measurements. *The circumference of the thigh was measured at 5 cm (S5) and 15 cm (S15) superior of the joint line. The circumference of the knee joint was measured directly at the joint line (JL) and the circumference of the shank 5 cm (I5) inferior of the joint line. (SØDERBERG et al. 1996)*

Furthermore, all circumference measurements were conducted at all test sessions by the same examiner. Subsequently, to reduce intra-rater variances, the means out of three circumference measurements at each landmark were calculated.

In contrast to other conducted studies, instrumented measurements of the knee joints' anteroposterior laxity, which was often conducted as a measure of an objective determination of knee joint laxity with the KT-1000 arthrometer (MEDmetric® Corp., San Diego, California, USA), were not conducted. As recent studies have shown that instrumented based measurements of the knee joint laxity in relation to the anterior drawer test with the KT-1000 arthrometer is strongly dependent on the examiner's experience, and even then, only moderate to low inter- and intraclass correlation coefficients were able to be revealed (ICCs < 0.60) (SERNERT et al. 2001; WIERTSEMA et al. 2008). Furthermore, the often described definition of pathologic anteroposterior laxity of 3mm and larger is untenable, because such laxities were also found in individuals who had functionally stable or asymptomatic knee joints

(MYKLEBUST et al. 2003). Therefore, it has been shown that measurement of anteroposterior laxity with the KT-1000 arthrometer is no adequate or valid test for instrumented monitoring of functional stability, as no neuromuscular abilities are taken into account (VERGIS et al. 1997).

4.4 Functional Performance Tests

For comprehensive monitoring and evaluation of the subjects' knee functionality, dynamic movement situations have to be included into a test battery besides functional clinical tests. Such demanding dynamic movements can be operationalized by FPTs. As FPTs provide certain insight into specific movement determining components, some testing tasks have been established for assessment of leg functionality in recent years. In individuals with ACL tears and surgical reconstruction of the torn ligament, different jumping tasks have been established for assessing functionality under dynamic conditions (ALMANGOUSH & HERRINGTON 2014; BARBER et al. 1990; ERNST et al. 2000; GUSTAVSSON et al. 2006; KVIST 2004; LENTZ et al. 2009; MYER et al. 2008; NARDUCCI et al. 2011; NOYES et al. 1991; TEGNER et al. 1986).

In the present study, three different FPTs were conducted with all subjects at each test session:

- One-Leg jumps for distance (OLJs)
- Counter Movement Jumps (CMJs)
- Isometric force tests.

These FPTs were chosen, because the functionality of the legs can be assessed out of three various viewpoints. Firstly, to analyze the one-legged functionality in a dynamic movement task (OLJs). Secondly, to analyze the legs' functionality in a bilateral movement task (CMJs), and thirdly, to analyze the thigh musculatures' ability to generate force in an isolated static contraction situation (Isometric force tests). With the combination of these three tests, which are, subsequently, described in detail, a comprehensive approach for assessment of the legs' functionality in specific movement tasks is achieved.

One-Leg Jumps for Distance

OLJs for distance were conducted most frequently in studies examining the level of functionality of subjects with reconstructed or non-reconstructed tears of the ACL (ALMANGOUSH & HERRINGTON 2014; BARBER et al. 1990; ERNST et al. 2000; GUSTAVSSON et al. 2006; KVIST 2004; LENTZ et al. 2009; MYER et al. 2008; NARDUCCI et al. 2011; NOYES et al. 1991; RUDOLPH et al. 2000; TEGNER et al. 1986). The construct validity and sensitivity of OLJs as a measure of function was assessed in various studies (BJORKLUND et al. 2009; COLBY et al. 1999; FITZGERALD et al. 2000; GUSTAVSSON et al. 2006; NEETER et al. 2006; NOYES et al. 1991; PATERNO & GREENBERGER 1996; PETSCHNIG et al. 1998; REID et al.

2007). In OLJs, the subjects' purpose is to maximize the horizontal distance between take-off and landing position (ENOKA 2002). The main factors for a good realization of this task are the displacement of the center of mass (COM) and the leaning of the whole body during take-off and landing situation, as leaning forward during take-off and backward at landing increases the jumping distance due to the fact that the leaning processes add distance to the displacement of the COM (ENOKA 2002). During the execution of the OLJs for distance, the subjects had to realize jump-off and landing with the same leg akimbo (Figure 10). A jump was considered valid when the landing was stable. Stable landing was obtained when the subjects did not move their landing foot on the floor and the contralateral leg did not have any contact to the floor after landing. If stable landing could not be realized, the jump was repeated. All subjects had to perform three valid jumps. If a subject was not able to perform OLJs in general or could not fulfill the validation criteria, because of insecurity or instability, the performance outcome of the three jumps was graded with a jumping distance of 0cm. For determination of functionality, the net jumping distances (realized jumping distance from tiptoe at jump-off to heel at landing) of the injured legs were divided by the net jumping distances of the non-injured legs for the calculation of the LSIs (BARBER et al. 1990; DE FONTENEY et al. 2015; EASTLACK et al. 1999; FITZGERALD et al. 2000; GOKELER et al. 2009; GUSTAVSSON et al. 2006; HARTIGAN et al. 2010; LENTZ et al. 2009; MYER et al. 2008; NOYES et al. 1991; ORISHIMO et al. 2010; PETSCHNIG et al. 1998; REID et al. 2007; ROHMAN et al. 2015; SERNERT et al. 1999; TEGNER & LYSHOLM 1985). In previous studies, which established OLJs as measure of determination of knee functionality after ACL injuries, an 85% (BARBER et al. 1990; NOYES et al. 1989) to 90% (JURIS et al. 1997; PETSCHNIG et al. 1998; RISBERG et al. 1995) jumping distance of the injured leg compared to the non-injured leg was determined as decisive factor to declare the knee functionality of ACL reconstructed individuals as normal.

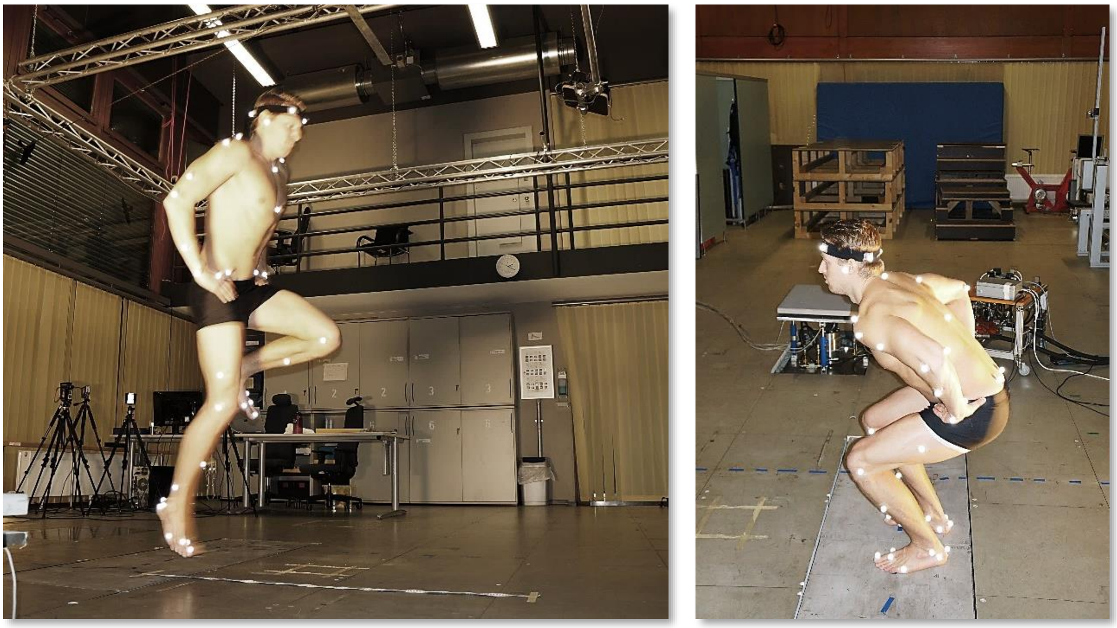

Figure 10. Jumping Tasks of the Test Battery. *Left: One-legged jumping task for distance akimbo. In this task, the subjects had to jump-off and land stable on the same leg. The task was performed with both legs separately. Right: Bilateral counter movement jumping task akimbo. The subjects had to jump-off and land stable on both force plates. The jumping task was determined valid, if each foot was placed separately on one force plate during the jump-off and landing phase.*

Vertical Counter Movement Jumps

Vertical CMJs are established dynamic performance tests to examine the subjects' maximum performance of the legs in a bilateral dynamic situation. CMJs have to be performed with the aim to reach maximum vertical height. The jumping movement starts from an upright erect position, followed by a downward squatting movement by flexing at the knee, the hips and the ankle joint (ENOKA 2002). (Figure 10) This downward movement is followed by a rapid extension of the legs, leading to take-off from the ground (ENOKA 2002). This jumping strategy is named countermovement, because the movement starts in the opposite direction. However, the primary goal of this initial opposite directed movement is, to maximize the upward directed vertical velocity at take-off, which leads to higher performance outcomes compared to jumping movements without initial countermovement (ENOKA 2002). Because of this movement execution, CMJs are a representative of movements with benefits of the stretch-shortening cycle (LINTHORNE 2001). As many human movements, such as running and jumping, require preliminary muscular actions in the opposite direction before a movement in the desired directions is achieved, CMJs are valid for the examination of the legs' functionality. The subjects of this study were advised to place each foot separately on one isolated FP. Such a testing procedure allows to assess the subject's legs kinetic and kinematic movement patterns independently. (HARMAN et al. 1990; LINTHORNE 2001)

Isometric Force Tests

The static muscular capabilities of the muscles involved in knee flexion and knee extension were measured under isometric conditions with a custom-made adjustable dynamometer rigid chair, equipped with a strain-gauge system (linear range, 0–2000 N; 1000 Hz; sensitivity, 3.6 mV/N; Figure 11). The muscular capabilities of both legs were assessed, in flexion and extension conditions with the knee at 90° and 110° (0° indicated a straight leg) (FITZGERALD et al. 2000; KUBO et al. 2004). The subjects were seated with a hip flexion of 90°. The tested leg was fixed in position with a strap around the malleoli. For each knee angle and type of contraction, two maximum voluntary contractions with 1-min rest periods were performed in a block-randomized order. The subjects were asked to produce their maximal force as fast as possible and to maintain the contraction between 3–5 s. The subjects received standardized verbal encouragement throughout every trial. To minimize extraneous body movements, straps were applied firmly across the shoulders, chest and stomach. Additionally, the subjects had to cross their arms over their chest to avoid any contribution of the trunk in force generation. The recorded signal was filtered through a digital fourth-order low-pass Butterworth filter, by using a cutoff frequency of 10 Hz. The trial with the highest absolute peak force was used for further analysis. Peak force (F_{max}), peak rate of force development (RFD_{max}), and RFD in 0–200 ms (RFD_{200max}) were determined, and the LSIs for each of these parameters were calculated (AAGAARD et al. 2002).

Figure 11. Isometric Force Test. *This figure presents the testing condition under 90° knee flexion angle. The subjects were fixed to the rigid chair with seat belts around the chest and the stomach. The backrest was fixed perpendicular to the seat. The subjects had to cross the arms over their chests to prevent any support of the arms during the force measurements. The strap, which was connected to the force sensor (strain-gauge system), was fixed around the ankle joint in horizontal extension to the force sensor. This ensured a stable knee angle position throughout the contraction. The subjects had to perform maximum voluntary contractions against the resistance of the fixed strap under isometric conditions. By changing the direction of the strap, force capacities were detectable under isometric knee flexion and isometric knee extension situation with the same measurement device.*

4.5 Activities of Daily Living

To reach the claim of a comprehensive approach of the whole test battery, it is inevitable to include analyses of ADL into a functional testing along with the before-mentioned functional clinical tests and the FPTs. This is essential due to the fact that an ACL tear can lead to variations, adaptations and compensations of the locomotion processes in all types of movements. Unnatural or unbalanced manifestations or adaptations of movements lead to unbalanced, pathological loads to the biological structures of the lower body, especially to the joints of the legs. Such unbalanced load situations in the legs induce and support the onset and progress of pathologies and chronic diseases (i.e. knee OA) of musculo-skeletal structures (ALTMAN et al. 1986; HURWITZ et al. 2000; HURWITZ et al. 2002). Consequently, due to ACL tears the biological structures of the injured as well as of the non-injured leg, especially in the knee joint, are at high risk to develop the most common degenerative chronic joint disease, which is knee OA (ALTMAN et al. 1986; HURWITZ et al. 2000; HURWITZ et al. 2002).

Therefore, the described study design of the thesis included various ADLs for examining potential adaptation mechanisms in the legs out of various viewpoints:

- Straight ahead gait over flat ground with self-selected gait velocity and with 5km/h (± 10%).
- Straight ahead gait over uneven ground with gait velocity of 5 km/h (± 10%). (Figure 12)
- Walking stairs upwards and downwards with self-selected gait velocity. (Figure 12)
- Walking turns of 90°, 180° and turns as if avoiding an obstacle with self-selected gait velocity (Figure 12).

As mentioned earlier (Section 3.3), in the scope of this thesis, only the results of the 90° and 180° turns were integrated in the framework of this thesis (Chapter 7). In all recorded ADLs, for an objective sampling of the individual locomotion patterns, any restrictions that could influence the individual locomotion pattern were excluded besides stepping with each foot separately on each force plate and to control the gait velocity in the straight ahead walking task. Generally, in the main study, the turns were conducted with the same method as the methodological pre-study (Chapter 5).

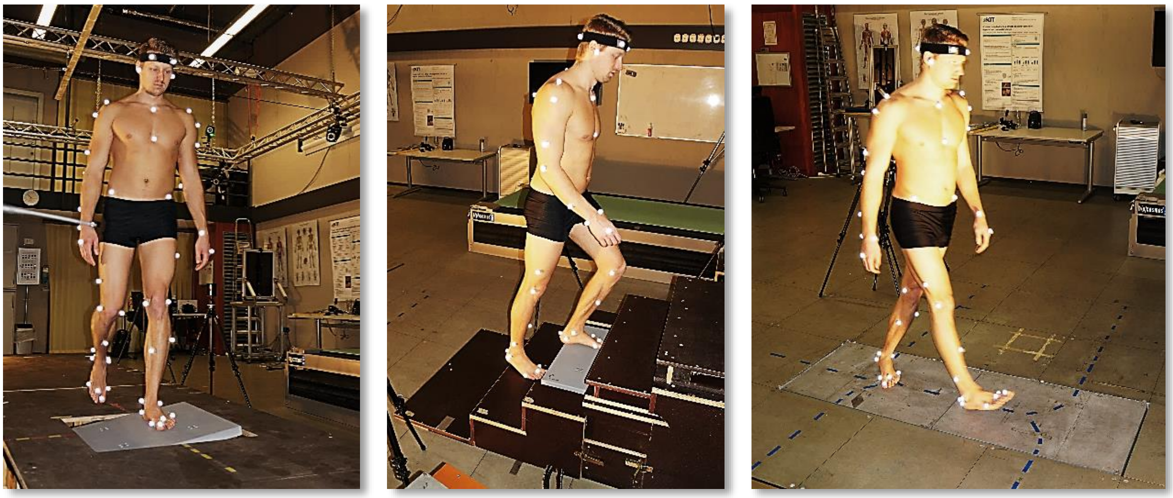

Figure 12. Illustrations of the Tested Activities of Daily Living. *Left: Straight ahead gait over uneven ground. The subjects had to walk with 5 km/h over a tilted force plate. The force plate tilted in anterior, posterior, medial, or lateral direction after walking through a light barrier. The subjects saw the direction of tilting one stride before the foot was placed onto the tilted force plate. Middle: Stair walking task. The subjects had to walk up and down a standard stairway with a self-selected gait velocity in their own walking rhythm. Right: Walking turns. The subjects had to walk three types of daily occurring turns (90°, 180°, and if avoiding an obstacle) clockwise and counter-clockwise at a self-selected gait velocity with their individual locomotion strategy.*

5 Study I: Reproducibility of Spatio-temporal and Dynamic Parameters in Various, Daily Occurring, Turning Conditions

Slightly modified version of the published paper.

KRAFFT FC, ECKELT M, KÖLLNER A, WEHRSTEIN M, STEIN T & POTTHAST W. (2015). Reproducibility of spatio-temporal and dynamic parameters in various, daily occurring, turning conditions. *Gait and Posture*, 41, 307-312.

5.1 Abstract

Objective. This study aims to assess the test-retest reproducibility of specific spatio-temporal (foot placement, foot contact time) and dynamic (resultant horizontal and vertical ground reaction force) gait parameters of three different, everyday occurring, turning conditions. The subjects were tested at two subsequent days. Out of this setting the purpose of this study is to clarify, if turning locomotion is stable when performed at different test occurrences. **Methods**. Eight subjects completed three different daily occurring turning conditions along turns with a given walking velocity of 5 km/h (± 10 %). Subjects had to complete the turns three times clockwise and counter clockwise. The measurements were recorded with a 3D motion analysis system (Vicon®) and two force sensitive platforms (AMTI®), connected to the motion analysis system. **Results.** The analysis yields for most of the parameters and turning conditions ICCs from good ($\boldsymbol{r} = 0.72$; $p = .06$) to high ($\boldsymbol{r} = 0.96$; $p < .01$) magnitude for the measured spatio-temporal and dynamic parameters. **Conclusions**. Based on our findings it can be assumed that locomotion strategies, related to the measured gait parameters of common daily turning tasks, are stable and reproducible.

5.2 Introduction

Clinical gait analysis is often used to detect influences of musculoskeletal disorders or diseases on human gait (LAROCHE et al. 2011). In order to identify and assess gait abnormalities it is necessary to determine previously healthy people's gait characteristics. Therefore, it is mandatory to examine the reproducibility of the human gait in different testing sessions (SEKIYA & NAGASAKI 1998). An understanding of potentially emerging differences is required to distinguish gait abnormalities from physiologic variabilities (SEKIYA & NAGASAKI 1998). Along with straight ahead movement tasks, daily life also necessitates to cope with various turning conditions (HARBOURNE & STERGIOU 2009). Turning or curve walking locomotion is a substantial field in gait research (COURTINE & SCHIEPPATI 2003; HASE & STEIN 1999; HICHEUR et al. 2005; IMAI et al., 2001; SREENIVASA et al., 2008). However, previous studies focused on locomotion strategies while turning or walking a curve, such as the ankle rotation during foot placement (COURTINE & SCHIEPPATI 2003; HASE & STEIN 1999) or the relation between head tilt, head rotation, and trunk rotation to initiate a turn (HASE & STEIN 1999; HICHEUR et al. 2005; IMAI et al. 2001; SREENIVASA et al. 2008). All these studies report a higher complexity of gait during turning conditions compared to straight ahead walking. Hence, an inclusion of turning tasks into gait analysis provides the opportunity for a more comprehensive gait assessment. Because of the higher complexity of turning tasks, such an analysis could possibly reveal movement abnormalities even if straight ahead walking tasks do not show any abnormalities. So far, there is no study on the reproducibility of turning gait tasks in any setting. Therefore, we investigated the gait reproducibility during turning tasks of young, healthy subjects by assessing spatio-temporal and dynamic parameters in a test-retest-design.

5.3 Methods

Subjects

Eight healthy male subjects [1.85 m ± 0.03 m, 79.4 kg ± 7.9 kg, 24.5 y ± 2.2 y] participated in our study. Written informed consent was obtained after approval of the test-protocol by the Institutional Review Board. Six of eight subjects were right-handed and declared the left leg as dominant for postural and force specific tasks. Handedness was measured referring to OLDFIELD (1971) and footedness referring to CHAPMAN et al. (1987).

Assessment

Spatio-temporal and Ground Reaction Force (GRF) parameters during turning gait were assessed in an experimental and comparative setting. The subjects were instructed to walk three different turns at a predetermined gait velocity on two subsequent days. The turns should represent typical, daily occurring turns, such as turning by 90° (90), turning by 180° (180), and turning as if avoiding an obstacle (O) (Figure 13).

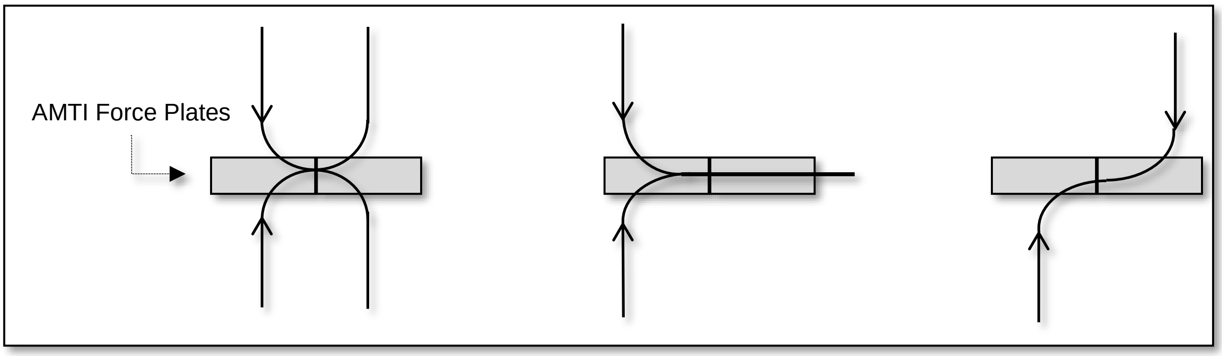

Figure 13. Types of Curve Walking Conditions. Left: 180° turn (180). Middle: 90° turn. Right: Turning as if avoiding an obstacle (O); Arrows mark both tested walking directions

The turning gait pathways were marked on the floor of the laboratory. All turns had to be walked clockwise and counter-clockwise to determine eventual effects on the locomotion strategies depending on the walking direction. The subjects had to complete three valid trials for each turn and each walking direction, so that each subject had to complete 18 valid trials. Validation was defined as walking with a velocity of 5 km/h (± 10 %), measured via light barriers, and placing each foot fully on one FP. Failing in the defined performance led to a repetition of the failed trial. Subjects could freely choose which foot was placed as first and second step on the FPs. The study was conducted with a 3D motion analysis system (Vicon®; 200Hz) and two FPs (AMTI®; 1000Hz). Data were analyzed with the software Vicon Nexus® (Version 1.7.1). The subjects had to walk the six turning conditions in a block randomized order (three trials of one turning condition as one block) to exclude learning effects from one condition to another.

To evaluate the reproducibility of turning locomotion the following parameters were measured:

- Ground contact time for each step on FPs.
- Maximal vertical GRF during stance phase normalized to bodyweight (BW) [N/kg]. Vertical direction was defined as z-axis in the Cartesian Coordinates System.
- Maximal horizontal GRF during stance phase normalized to BW [N/kg]. Sideway direction (medio-lateral) was defined as y-axis in the Cartesian Coordinates System.
- Foot placed first and second on FPs.

Both feet were measured and analyzed separately.

Statistics

For assessment of the test-retest reproducibility the Intraclass Correlation Coefficients (ICCs) of the above mentioned variables were calculated between the two testing sessions for each turn and both walking directions. Hence, ICCs were calculated for the identic turning condition (type and orientation) between the two testing sessions and for first and second step separately. Statistical analysis was conducted with SPSS 20. In consistency with other gait analysis studies (HASE & STEIN 1999; LAROCHE et al. 2011) ICCs > 0.70 were defined as good correlation coefficients. To calculate mean ICCs, the ICCs were z-transformed using Fisher's transformation (LYNCH 2013). Subsequently the mean values were calculated in the z-domain, followed by retransformation of the mean z-values into mean ICCs.

5.4 Results

Analysis of the ground contact times revealed ICCs higher than $r = 0.82$ ($p \leq .02$) for eleven of twelve tested conditions. In one condition (90 right 1st foot) a lower ICC ($r = 0.64$; $p = .10$) was found. Mean ICC of the ground contact time across all conditions is high ($r = 0.90$) (Table 2).

Table 2. Correlation-Coefficients of the Turning Locomotion Conditions. *Intraclass Correlation-coefficients (ICCs) and p-values of the ground contact time of the 1st (leading leg) and 2nd foot (trailing leg) contact and the maximal resultant vertical and horizontal (medio-lateral) ground reaction force (GRF) normalized to bodyweight [N/kg] from test to retest.*

	180 left				**180 right**				**90 left**				**90 right**				**O left**				**O right**				
	1st foot		2nd foot		1st foot		2nd foot		1st foot		2nd foot		1st foot		2nd foot		1st foot		2nd foot		1st foot		2nd foot		Mean
	ICC	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**	*p*	**ICC**
Ground Contact Time	**0.86**	*.01*	**0.93**	*<.01*	**0.92**	*<.01*	**0.90**	*<.01*	**0.83**	*.02*	**0.95**	*<.01*	**0.64**	*.10*	**0.82**	*.02*	**0.96**	*<.01*	**0.95**	*<.01*	**0.89**	*<.01*	**0.85**	*.01*	**0.90**
Vertical GRF	**0.78**	*.04*	**0.91**	*<.01*	**0.95**	*<.01*	**0.39**	*.28*	**0.89**	*<.01*	**0.85**	*<.01*	**0.89**	*<.01*	**0.67**	*.08*	**0.85**	*.02*	**0.84**	*.02*	**0.95**	*<.01*	**0.78**	*.04*	**0.84**
Horizontal (medio-lateral) GRF	**0.45**	*.24*	**0.86**	*.01*	**0.85**	*.01*	**0.83**	*.02*	**0.40**	*.28*	**0.75**	*.04*	**0.90**	*<.01*	**0.28**	*.35*	**0.58**	*.16*	**0.89**	*<.01*	**0.91**	*<.01*	**0.72**	*.06*	**0.76**

The analysis of the vertical GRF revealed ICCs of $r \geq 0.78$ ($p \leq .04$) in ten of twelve conditions. In two conditions (180 right 2nd foot; 90 right 2nd foot) lower ICCs were found. The mean ICC of the vertical GRF was high as well ($r = 0.84$) (Table 2). Analysis of the ICCs for the horizontal GRF revealed ICCs of $r \geq 0.72$ ($p \leq .06$) in eight of twelve conditions. Four conditions (180 left 1st foot; 90 left 1st foot; 90 right 2nd foot; O left 1st foot) had ICCs below the defined threshold value for good correlations. Nonetheless, the mean ICC for the horizontal GRF was still above the level for good correlation ($r = 0.76$) (Table 2). The statistical results are supported by the progessions of vertical and horizontal force over time (Figure 36; Appendix 10.6), which exhibit qualitatively highly similar profiles. Moreover, the results showed, that most of the subjects walked the left directed turns as spin turns (Figure 14). In contrast, the analysis of the right-directed turns revealed no clear preference for spin or step turn strategy while turning. These findings of the turning strategy were stable across the two testing sessions (Figure 14).

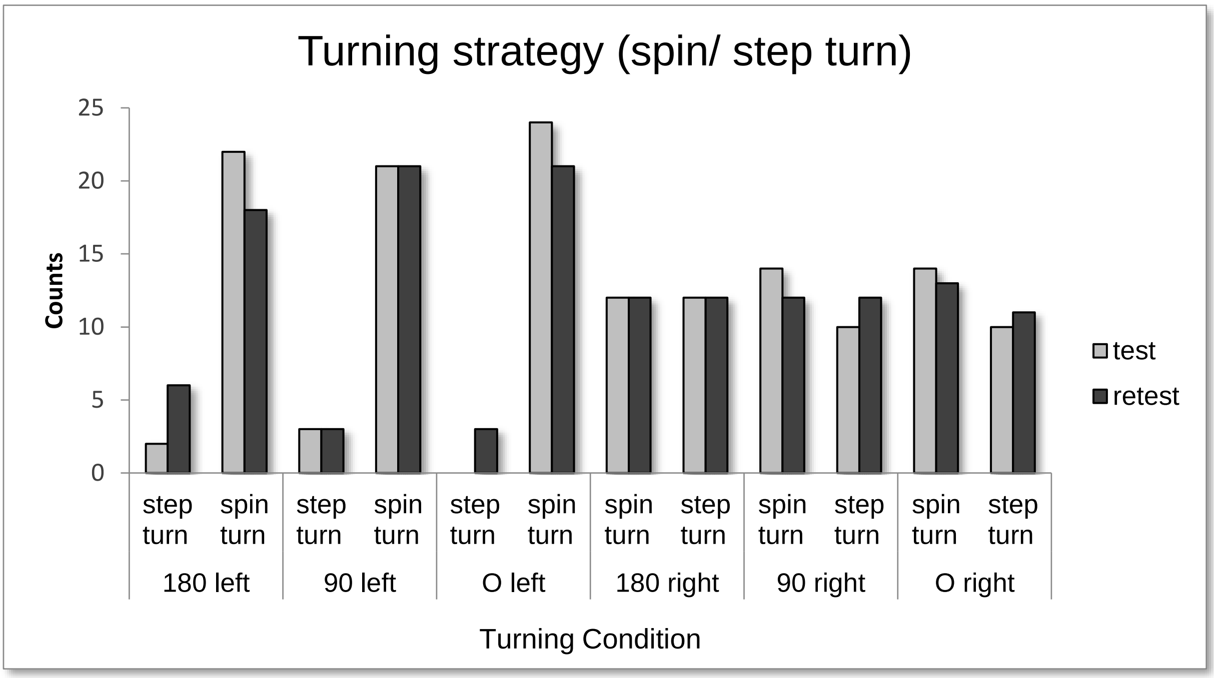

Figure 14. Distribution of performed turning strategy. *Count of subjects performed step or spin turns at the respective test sessions. Dark grey represents the test session and light grey the retest session.*

5.5 Discussion

To our best knowledge, there is no study on the reproducibility of turning locomotion in different turning conditions. Hence, the purpose of this study was to evaluate the reproducibility of turning locomotion via specific spatio-temporal and dynamic gait parameters during different, daily occurring turns in a test-retest design. Our results showed mean ICCs for the ground contact time, the horizontal and the vertical GRF on a high level ($r \geq 0.76$) over all conditions. Additionally, the turning strategy results also support a high reproducibility, as the observed locomotion strategy between left and right directed turns was stable over both testing sessions (Figure 14). Based on our sample and measured parameters, we therefore conclude that turning tasks can be reproducibly performed although turning is a more complex movement than straight ahead walking (COURTINE & SCHIEPPATI 2003; HASE & STEIN 1999; HICHEUR et al. 2005; IMAI et al. 2001; SREENIVASA et al. 2008). The conducted study has, however, some limitations. The informative value is limited by the number and the health characteristics of the subjects. Therefore, the generalizability of our results might be limited. Accordingly, further studies should consider larger sample sizes and subjects with varying health characteristics to overcome these potential limitations. Nevertheless, our study provides a starting point for the investigation of the reproducibility of human's turning gait and could serve as a baseline for future measurements of turning locomotion.

6 Study II: How Does Functionality Proceed in ACL Reconstructed Subjects? – Proceeding of Functional Performance from Pre- to Six Months Post-ACL Reconstruction

Slightly modified version of the published paper.

KRAFFT FC, STETTER BJ, STEIN T, ELLERMANN A, FLECHTENMACHER J, EBERLE C, SELL S & POTTHAST W. (2017). How does functionality proceed in ACL reconstructed subjects? – Proceeding of functional performance from pre- to six months post-ACL reconstruction. *PlosOne*, *12*(5): e01078430.

6.1 Abstract

Objective. This is the first study examining functionality of subjects with anterior cruciate ligament (ACL) tears and a subsequent reconstruction comprehensively by multiple test sessions from pre- to six months post-reconstruction. The purpose was to evaluate if a generally applied rehabilitation program restores functionality to levels of healthy controls. **Methods.** Subjects with unilateral tears of the ACL were compared to matched healthy controls throughout the rehabilitation. 20 recreational athletes were tested: T_1 (preoperative), 6 weeks after tear; T_2, 6 weeks, T_3, 3 months and T_4, 6 months post-reconstruction. At all test sessions, subjects self-evaluated their activity level with the Tegner activity score and their knee state with the Knee Injury and Osteoarthritis Outcome Score. Passive range of motion during knee flexion and extension and leg circumference were measured as functional clinical tests. Bilateral countermovement jumps, one-leg jumps for distance and isometric force tests in knee flexion and extension with 90° and 110° knee angle were conducted as functional performance tests. For determination of functionality, leg symmetry indices (LSIs) were calculated by dividing values of the injured by the non-injured leg. **Results.** In the ACL group, most LSIs decreased from T_1 to T_2, and increased from T_2 and T_3 to T_4. LSIs of the ACL subjects remained lower than LSIs of healthy controls at 6 months post-reconstruction in nearly all parameters. Self-evaluation of the ACL subjects showed, additionally, that the activity level was lower than the pre-injury level at 6 months post-reconstruction. Low LSIs and low self-evaluation indicate that knee joint functionality is not completely restored at 6 months post-reconstruction. **Conclusions.** The study shows that multiple comprehensive testing throughout the rehabilitation gives detailed images of the functional state. Therefore, the functional state of ACL reconstructed individuals should be evaluated comprehensively and continuously throughout

the rehabilitation to detect persisting deficiencies detailed and adapt rehabilitation programs individually depending on the functionality.

6.2 Introduction

Tears of the anterior cruciate ligament (ACL) can lead to chronic knee instability and a loss of joint function (DANIEL et al. 1994; EASTLACK et al. 1999; RUDOLPH et al. 2000). Common treatment of the torn ligament in industrial countries – e.g. Germany and USA (FEDERAL HEALTH MONITORING OF GERMANY 2016; LENTZ et al. 2009) – is the surgical reconstruction of the torn ligament. After the reconstruction a long-term rehabilitation process is required, which, however, does not ensure full stability and functionality of the knee joint in activities of daily living (ADL) and in sports activities. Thus, ACL ruptures, can highly influence the quality of life (QoL) and the subsequent ability to engage in sports on pre-injury level (DANIEL et al. 1994; EASTLACK et al. 1999; LENTZ et al. 2009; MYER et al. 2008; MYKLEBUST et al. 2003; THE MARS GROUP 2010; WILLIAMS et al. 2001).

ACL tears lead to thigh muscle atrophy (MCHUGH et al. 2002, THOMAS et al. 2016). Thigh muscle atrophy contributes to joint instability, because the muscles and ligaments surrounding the knee are crucial for knee stability and functionality during sports activities (EASTLACK et al. 1999; MYKLEBUST et al. 2003; WALDÉN et al. 2011) and for maintaining stability and compensation of unexpected situations or postural balance disturbances in ADL (AAGAARD et al. 2002; LORENTZON et al. 1989; THOMAS et al. 2016). Additionally, the sensory feedback from the mechanoreceptors of the torn ACL is deficient, which besides alters joint and locomotion biomechanics and therewith contributes instability processes (LORENTZON et al. 1989; WILLIAMS et al. 2001).

Studies of the last three decades show that the development of knee joint instabilities are multifactorial and therefore, no consensus about the origin and persistence of instabilities in elite and recreational athletes could be achieved (BARBER et al. 1990; DE FONTENEY et al. 2015; EASTLACK et al. 1999; FITZGERALD et al. 2000; GOKELER et al. 2009; GUSTAVSSON et al. 2006; HARTIGAN et al. 2010; LENTZ et al. 2009; LI et al. 1996; NARDUCCI et al. 2011; ORISHIMO et al. 2010; PETSCHNIG et al. 1998; PHILIPS et al. 2000; REID et al. 2007; RUDOLPH et al. 2000; TEGNER & LYSHOLM 1985; WILK et al. 1994). Due to the ACL tear, the injured leg as well as the non-injured leg can get influenced, resulting in a pathologic asymmetry level between the legs (ALMANGOUSH & HERRINGTON 2014; DE FONTENEY et al. 2015). However, it seems that task-specific symmetry levels in static and dynamic situations exist. Furthermore, symmetry levels are essential for full recovery of knee joint functionality and a safe return in ADL and sports activities (NEETER et al. 2006; MYER et al. 2008; ROHMAN et al. 2015; SHELBOURNE & KLOTZ 2006). In order to quantify the symmetry level as a measure of knee joint functionality, the leg symmetry index (LSIs) is an established method (DE FONTENEY et al. 2015; HEWETT et al. 2005; MYER et al. 2008; ROHMAN et al. 2015; SHELBOURNE & KLOTZ 2006). To date no study investigated detailed functional characteristics of ACL reconstructed subjects longitudinally up to six months post-reconstruction by combining functional clinical tests, functional performance tests (FPTs) and questionnaires for functional self-evaluation. However, in long-term knee rehabilitation it is helpful to measure deficits of functionality repetitively from various viewpoints in order to develop more individualized rehabilitation programs for a high functional outcome. Furthermore, objective parameters determining functionality should be monitored and taken into consideration before ACL reconstructed individuals get released in pre-injury sports. Hence, it is necessary to understand how the specific biomechanical components, determining and limiting knee function (i.e. passive range of motion (ROM), muscular and neuromuscular capabilities in dynamic and static conditions), develop during the recuperation process after ACL reconstruction (FITZGERALD et al. 2000; GUSTAVSSON et al. 2006; LENTZ et al. 2009; LORENTON et al. 1989; ROHMAN et al. 2015). This is underlined by the results of various authors, which suggest a comprehensive assessment of functionality after ACL reconstruction from various viewpoints, instead of one specific viewpoint (i.e. the combination of different types of one-legged jumps (OLJs)) (ALMANGOUSH & HERRINGTON 2014; FITZGERALD et al. 2000; GUSTAVSSON et al. 2006; MYKLEBUST et al. 2003; NARDUCCI et al. 2011; NEETER et al. 2006; PETERSEN & ZANTOP 2013; PETSCHNIG et al. 1998; REID et al. 2007; SERNER et al. 1995; SHELBOURNE & KLOTZ 2006; TEGNER & LYSHOLM 1985). Such comprehensive assessments provide a broader picture of the knee joint functionality and can therefore help to gauge functional deficits more accurate. Accordingly, comprehensive studies should combine objective measures for both, clinical outcome and functional knee performance, along with functional self-evaluation of the ACL reconstructed subjects. With functional clinical tests (e.g. measurements of the knee's passive ROM) the functionality of the knee is assessed under passive conditions (SØDERBERG et al. 1996; JANDA 2002). By functional performance tests (e.g. OLJs), the functionality of the knee joint is measured under specific dynamic conditions (BARBER et al. 1990). Thereby, the subjects need to generate active motor commands based on sensory information about the state of their body and the environment to coordinate the movements. Complementary, by self-evaluative questionnaires the subjects' self-reflection about the knee functionality is assessed, which provides individual, examiner independent data from the subject's point of view (ROOS et al. 1998).

Therefore, the purpose of this study was to examine the functional state of ACL reconstructed subjects comprehensively by the combination of self-evaluating questionnaires, functional clinical as well as static and dynamic FPTs and in comparison to matched healthy control subjects. The implementation of such a test battery, along with a close monitoring of four test sessions up to six months post-reconstruction, will enable a more detailed understanding of the functional development of the knee status during rehabilitation. Therewith, a fine-grained picture of the subjects' functional state at a specific time in the rehabilitation cycle can be provided. Such information can help clinicians and therapists to determine the functional knee state more comprehensively and to obtain more accurate criteria for decision making during the rehabilitation process (FITZGERALD et al. 2000; GUSTAVSSON et al. 2006; RUDOLPH et al. 2000; LENTZ et al. 2009; NARDUCCI et al. 2011; NEETER et al. 2006; ORISHIMO et al. 2010; REID et al. 2007). As ACL tears and reconstructions highly impact knee function, we hypothesized that in the post-reconstruction phase, subjects will gradually regain task-specific LSIs during the rehabilitation phase but will not reach the LSIs of healthy control subjects up to six months post-reconstruction.

6.3 Methods

Sample

Subjects with tears of the ACL (n = 20) and healthy control subjects (n = 20), without any history of leg injuries, participated in the study (Table 3). Inclusion criteria was that the subjects had unilateral tears and underwent uniform ACL reconstruction technique with a combined semitendinosus and gracilis autograft, via the double-bundle technique (SCHMIDT-WIETHOFF & DARGEL 2007). Exclusion criteria were concomitant severe injuries of the Menisci or the collateral ligaments of the knee joint. Inclusion criteria of the control subjects was that they did not had any history of leg injuries. Control subjects were excluded if they had any leg injuries and if they did not fulfill the matching criteria. The control subjects were matched to the ACL subjects according to: sex, age, height, body mass, and activity level before the ACL tear, as determined using the TAS. The study was approved by the ethics committee of the State Medical Council of Baden-Württemberg (Stuttgart, Germany). All subjects provided written informed consent for their study participation.

Table 3. Sample Characteristics. *Means and standard deviations.*

	Age [yr]	Height [cm]	Mass [kg]	Body-mass index [kg/m^2]	Activity Level (TAS)
ACL group	32.0 ± 13.3	174.7 ± 9.0	73.2 ± 8.7	24.1 ± 3.4	6.4 ± 1.4
Control group	33.3 ± 13.4	175.4 ± 10.4	74.7 ± 8.2	24.4 ± 2.6	6.0 ± 1.4

Mean values and standard deviations (SD) of the ACL subjects and the control subjects. ACL, anterior cruciate ligament; TAS, Tegner activity score; TAS in the ACL group subjects is related to the pre-injury activity level.

Study Design

As indicated in the introduction, a comprehensive understanding of the development of different components of knee function after ACL reconstruction is missing. Therefore, the study was designed as a longitudinal non-randomized controlled trial to evaluate an existing and commonly applied rehabilitation program after ACL reconstruction in a chronologically and functionality detailed manner. Therewith, it is assumable to identify possible time effects between or within parameters determining knee function and in comparison with healthy subjects. Accordingly, the ACL reconstructed subjects were tested at four different test sessions over a period of seven to eight months. The first test was performed preoperatively, immediately before the reconstruction and about seven weeks after the ACL tear (T1). All following tests were postoperative (T2-T4). T2 was about seven weeks, T3 was approximately three months and T4 approximately six months after ACL reconstruction. The control subjects attended only one test session. The test design was aligned to the three main stages of the rehabilitation process (Figure 15).

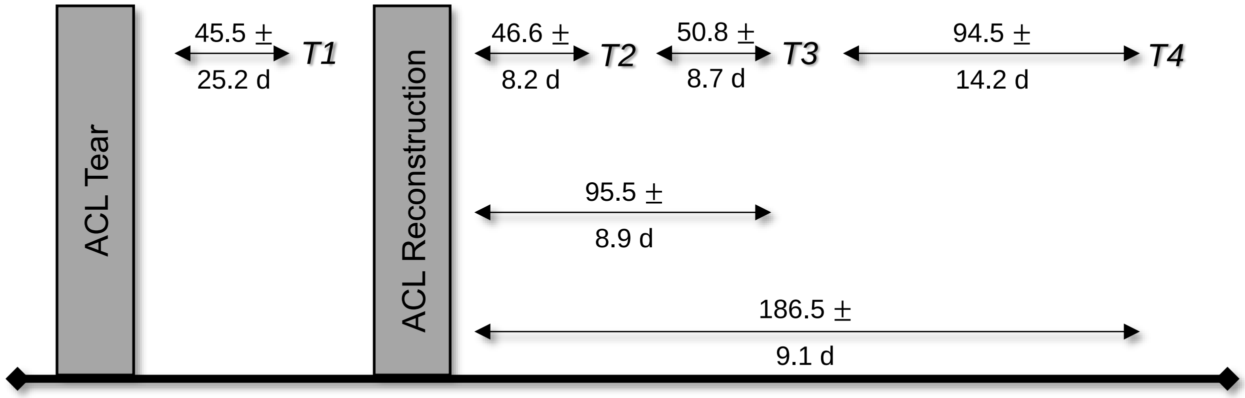

Figure 15. Study Design. *Mean days (d) and standard deviations between the test sessions of the ACL reconstructed subjects. T1 was at about six to seven weeks after the ACL tear, immediately before the ACL reconstruction surgery. T2 was at about six to seven weeks after the ACL reconstruction surgery. T3 was about three months and T4 was about six months after the ACL reconstruction surgery.*

Test Battery

In the conducted test battery questionnaires for self-evaluation of the knee function, functional clinical tests and FPTs were combined. The selection of the tests should give a comprehensive image of the knee function and enables also good feasibility for practical implementations.

Questionnaires

We included questionnaires for self-evaluation of the knee function and the activity level in the test battery to receive independent data of the subjects' view about the influence of the ACL injury to their general life. All subjects completed two questionnaires: The Knee Injury and Osteoarthritis Outcome Score (KOOS), for self-evaluation of the subjects' knee function (KESSLER et al. 2003; ROOS et al. 1998). The KOOS consists of the sub-categories *Pain*, *Symptoms*, *Activities of daily living*, *Sport and recreation function*, and *Knee-related quality of life*. The whole questionnaire as all sub-categories are standardized to maximum reachable score of 100 (ROOS et al. 1998). For assessment of the subjects' pre-injury and current activity levels, the TAS was applied (TEGNER & LYSHOLM 1985).

Functional Clinical Tests

In addition to the questionnaires we included functional clinical tests in the test battery to measure the subjects' knee functionality under static conditions. As functional clinical tests, leg circumference (LC) and passive ROMs of the knee joint were assessed. The LC was measured at four specific landmarks (SØDERBERG et al. 1996): the joint line (JL), and 5 cm (S5) and 15 cm (S15) superior and 5 cm inferior (I5) to the joint line. The passive ROM of the knee joint was assessed three times during flexion prone and extension supine (JANDA 2002). All ROM measurements were conducted by the examiner with a manual goniometer. The measurements were conducted at each leg separately to calculate the LSIs. Means of the three measurements were calculated for further analyses and for calculation of the LSIs.

Functional Performance Tests

Finally, we included FPTs, wherein subjects in contrast to the functional clinical tests need to actively generate motor commands to coordinate their movements. Subjects performed three countermovement jumps (CMJs) akimbo. The highest jump was used for analysis (SERNERT et al. 1999; TEGNER & LYSHOLM 1985). While performing the CMJs, the subjects stood with each leg on a separate FP (AMTI, 1000 Hz). Jumping height (absolute value), acceleration impulse during take-off (LSI) and the deceleration impulse during landing (LSI) were analyzed. Additionally, the subjects performed three one leg jumps (OLJs) for distance akimbo, with each leg. The subjects had to jump off and land on the same leg. Landing had to be stable with no movement of the landing foot and no ground contact of the contralateral leg. Landing pose had to be maintained for 3s. Jumps with the largest distance were used for LSI calculations of the jumping distances and acceleration impulses during take-off. Both jumping tests were applied to compare the functional state of the ACL reconstructed subjects in a one-legged and a bilateral movement.

The static muscular capabilities of knee flexion and knee extension musculature were measured under isometric conditions with a custom-made adjustable dynamometer rigid chair, equipped with a strain-gauge system (linear range, 0–2000 N; 1000 Hz; sensitivity, 3.6 mV/N). Isometric force tests were applied to get isolated information of the capabilities of the knee flexion and extension musculature. Isometric strength testing was applied because the reliability of isokinetic testing is reduced over higher ROMs, which is caused by the shift of the joint axes of the dynamometer in relation to the anatomical joint axes in isokinetic testing (ARAMPATZIS et al. 2004, 2005; HERZOG 1988). The muscular capabilities of both legs were assessed, in flexion and extension with knee angles of 90° and 110° (0° indicated a straight leg) (KUBO et al. 2004). The subjects were seated with a hip flexion angle of 90°. The tested leg was fixed in position with a strap around the malleoli. For each knee angle and type of contraction, two maximum voluntary contractions with 1-min rest periods were performed in a block-randomized order.

The subjects were asked to produce their maximal force as fast as possible and to maintain the contraction between 3–5 s. The subjects received standardized verbal encouragement throughout every trial. To minimize extraneous body movements, straps were applied firmly across the shoulders, chest and stomach. Additionally, the subjects had to cross their arms over their chest to avoid any contribution of the trunk in force generation. The recorded signal was filtered through a digital fourth-order low-pass Butterworth filter, by using a cutoff frequency of 10 Hz. The trial with the highest maximum force was used for further analysis. Maximum force (F_{max}), maximum rate of force development (RFD_{max}) and RFD in 0–200 ms (RFD_{200max}) were determined, and the LSIs for each of these parameters were calculated (AAGAARD et al. 2002).

Rehabilitation Program

All subjects received a standardized post-surgical rehabilitation program, according to the German health insurance system. This consists of three stages: The first stage consists of low-intensity (passive) activities up to six weeks post-reconstruction. Including physiotherapy with lymphatic drainage, passive movement exercises (by machine or therapist), sensorimotor training, weight-bearing exercises, and isometric training under therapists' supervision. The second stage consists of medium-intensity activities with muscular and balance training up to three months post-reconstruction. Including physiotherapy with lymphatic drainage, passive movement exercises, independent strength training, balance training, and activities and sports without pivoting movements (e.g. cycling, swimming, (nordic) walking). The third stage consists of medium-to-high-intensity activities. Including intense strength training, if possible, up to six months post-reconstruction. As well, sports training (without pivoting movements) and slight return to pre-injury sports and sports-level with jumps, intense cycling, and strength training. All stages were adaptable according to the rehabilitation state of the individuals' knee joint. Such a stepwise, 3-staged structure is common in rehabilitation after ACL reconstruction (WHITING & ZERNICKE 2008). The summarized rehabilitation program of the ACL subjects, including the applied exercises and training as well as the performable activities and sports, is presented in the Appendix 10.5.

Data analysis

LSIs were calculated for all parameters by the related discrete values of the injured leg divided by the non-injured leg in the ACL subjects and by the non-dominant leg divided by the dominant leg in the control subjects, respectively. LSIs provide comparable results between all subjects. An LSI of 1.0 indicates that the performance of both legs was equivalent. LSIs are a widely used method to compare results between the legs and for determining functionality (BARBER et al. 1990; DE FONTENEY et al. 2015; EASTLACK et al. 1999; FITZGERALD et al. 2000; GOKELER et al. 2009; GUSTAVSSON et al. 2006; HARTIGAN et al. 2010; LENTZ et al. 2009; MYER et al. 2008; NOYES et al. 1991; ORISHIMO et al. 2010;

PETSCHNIG et al. 1998; REID et al. 2007; ROHMAN et al. 2015; SERNERT et al. 1999; TEGNER & LYSHOLM 1985).

Statistics

Firstly, with Microsoft Office Excel 2013 means and 95% confidence intervals were calculated for the results of the questionnaires, for the LSIs of the functional clinical tests, and the LSIs and absolute values (jumping height in CMJs) of the FPTs. Afterwards, calculations for statistical interferences were conducted with IBM SPSS 22 (IBM, Armonk, NY, USA). First, Kolmogorov-Smirnov, and Mauchly's tests were used to confirm the normality and sphericity of the data distribution. Greenhouse-Geiser estimates were used to correct for violations of sphericity.

Variations in the analyzed parameters for the ACL group over time (T1–T4) were assessed using one-way analysis of variance with repeated measures (RM-ANOVA). If the RM-ANOVA revealed a significant variation, the HOLM-BONFERRONI corrected post-hoc *t*-test for dependent samples was employed to determine statistical differences between the four test sessions (HOLM 1979). Data of T_4 in the ACL group were compared to the results of the control group, by using a *t*-test for independent samples in order to identify differences between control subjects and ACL subjects six months post-reconstruction. Effect sizes were calculated using partial eta squared for the RM-ANOVAs (η_p^2) and COHEN's *d* for the *t*-tests. According to COHEN (1992), large effects are indicated by η_p^2=0.14, medium-sized effects by η_p^2=0.06, and small effects by η_p^2=0.01. In terms of COHEN's *d*, large effects are indicated by *d*=0.8, medium-sized effects by *d*=0.5 and small effects by *d*=0.2. The level of significance for all calculations was set a priori at $P\leq0.05$.

6.4 Results

Questionnaires

KOOS Questionnaire

The KOOS questionnaire was applied to examine the functional knee state from various viewpoints (symptoms & stiffness, pain, ADL, sports and recreational activities, and QoL) from the subjects' self-evaluative view.

RM-ANOVA revealed a significant variation in symptoms & stiffness ($F_{(3,51)}$=8.90, P<0.01, η_p^2=0.34), pain ($F_{(3,51)}$=8.60, P<0.01, η_p^2=0.34), ADL ($F_{(3,51)}$=7.39, P<0.01, η_p^2 = 0.30), sports and recreational activities ($F_{(3,51)}$=20.86, P<0.01, η_p^2 =0.55) and QoL ($F_{(3,51)}$=14.13, P<0.01, η_p^2=0.45). Post-hoc analysis revealed significantly lower scores at T2 than at T3 in all subcategories. The ACL subjects had significantly lower scores at T4 than the control subjects in all subcategories. (Table 4)

Summarized, the ACL subjects evaluated their knee function higher at three months compared to six weeks after reconstruction. However, up to six months no further increase of the score was determined and it remained lower than the healthy control groups' score.

Table 4. Mean results and standard deviations of the Knee Injury and Osteoarthritis Outocme Scores' (KOOS) subcategories.

Subcategory	T1	T2	T3	T4	Control Group	Significant Differences
Symptoms & Stiffness	60.9 ± 19.9	55.0 ± 19.8	70.7 ± 15.0	74.3 ± 18.7	94.8 ± 8.1	T2/T3: $T(17)=1.25$, $P=0.01$, $d=0.92$ T4/CG: $T(38)=4.40$, $P<0.01$, $d=1.39$
Pain	73.3 ± 13.3	70.6 ± 10.9	83.0 ± 7.6	84.1 ± 14.1	98.7 ± 3.7	T2/T3: $T(17)=5.88$, $P<0.01$, $d=1.08$ T4/CG: $T(38)=4.39$, $P<0.01$, $d=1.39$
ADL	79.4 ± 16.5	78.1 ± 16.6	88.4± 16.0	91.4 ± 10.9	100 ± 0.0	T2/T3: $T(17)=3.55$, $P<0.01$, $d=0.72$ T4/CG: $T(38)=3.46$, $P<0.01$, $d=1.09$
Sports & Recreational Activities	41.0 ± 18.2	36.3 ± 23.1	60.4 ± 24.4	69.0 ± 24.0	99.5 ± 1.5	T2/T3: $T(17)=6.45$, $P<0.01$, $d=1.06$ T4/CG: $T(38)=5.53$, $P<0.01$, $d=1.84$
QoL	38.5 ± 15.5	40.3 ± 21.5	56.3 ± 22.8	59.6 ± 22.1	97.8 ± 2.6	T2/T3: $T(17)=5.85$, $P<0.01$, $d=0.79$ T4/CG: $T(38)=7.31$, $P<0.01$, $d=2.31$

Results (means and standard deviations of all subjects) of the subcategories of the KOOS questionnaire of the ACL subjects (T_1–T_4) and the control group (CG). The subcategories are "symptoms & stiffness" (7 items), "pain" (9 items), "activities of daily living" (ADL; 17 items), "sports and recreational activities" (5 items), and "quality of life related to the knee injury" (QoL; 4 items). The maximum possible score in the KOOS was 100, indicating no symptoms. Significant differences ($P \leq 0.05$) with COHEN's d between test sessions are illustrated in the last column.

TAS Questionnaire

RM-ANOVA revealed a significant variation in the TAS ($F_{(4,76)}$=48.87, P<0.01, η_p^2=0.72). The ACL subjects had a significantly lower activity level at T1 than before the tear (T(19)=10.13, P<0.01, d=3.17). After reconstruction (T2), the activity level increased significantly up to T4 (T(19)=4.47, P<0.01, d=1.36). At T4, the activity level was still significantly lower than the pre-injury activity level (T(19)=8.72, P<0.01, d=2.01) and the activity level of the control subjects (T(38)=5.71, P<0.01, d=1.81) (Figure 16).

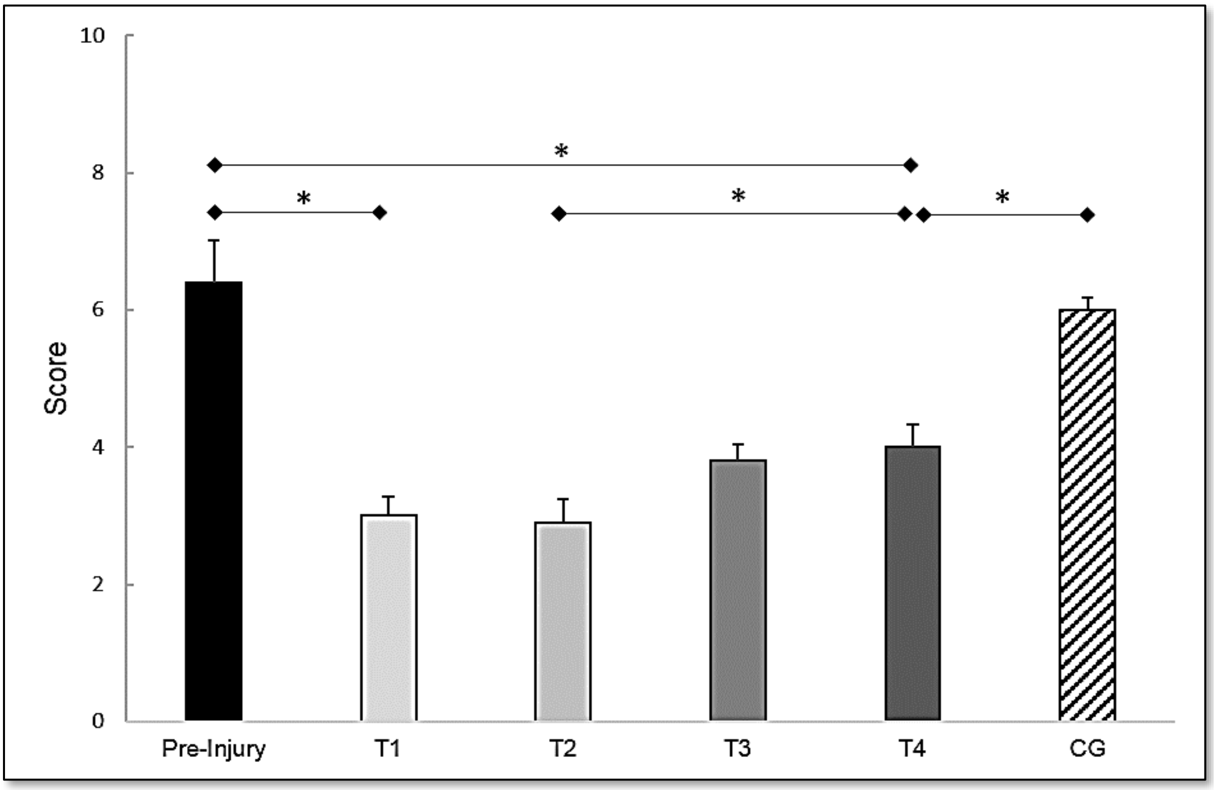

Figure 16. Results of the Tegner Activity Score. *Mean activity level and 95% confidence intervals of the ACL subjects (T1–T4) and the control subjects, assessed with the Tegner activity score (TEGNER & LYSHOLM 1985). Test sessions with significant (P≤0.05) differences are marked with an asterisk (*).*

Functional Clinical tests

Leg Circumference

RM-ANOVA only revealed a significant variation in the LSI_{LC} at S15 (LSI_{LCS15}) ($F_{(3,51)}$=8.42, P<0.01, η_p^2=0.33). The ACL subjects had significantly lower $LSIs_{LCS15}$ at T2 than at T1 (T(19)=4.53, P<0.01, d=1.02) and significantly higher LSI_{LCS15} at T3 than at T2 (T(17)=4.73, P<0.01, d=0.69). At all other landmarks (JL, S5, I5), no significant variations in LC could be found. In addition, the ACL subjects had significantly higher LSI_{LC} values at JL (T(38)=2.29, P=0.03, d=0.73) and I5 (T(38)=2.21, P=0.03, d=0.70) and significantly lower LSI_{LC} at S15 (T(38)=6.07, P<0.01, d=1.92) at T4 than the control subjects. No differences were detected at S5 between the ACL subjects at T4 and the control subjects (Figure 17).

Summarized, at six months post-reconstruction the knee joint area of the reconstructed leg is still thicker compared to the non-injured knee joint and in the middle of the thigh the circumference of the reconstructed leg is clearly reduced compared to the non-injured leg.

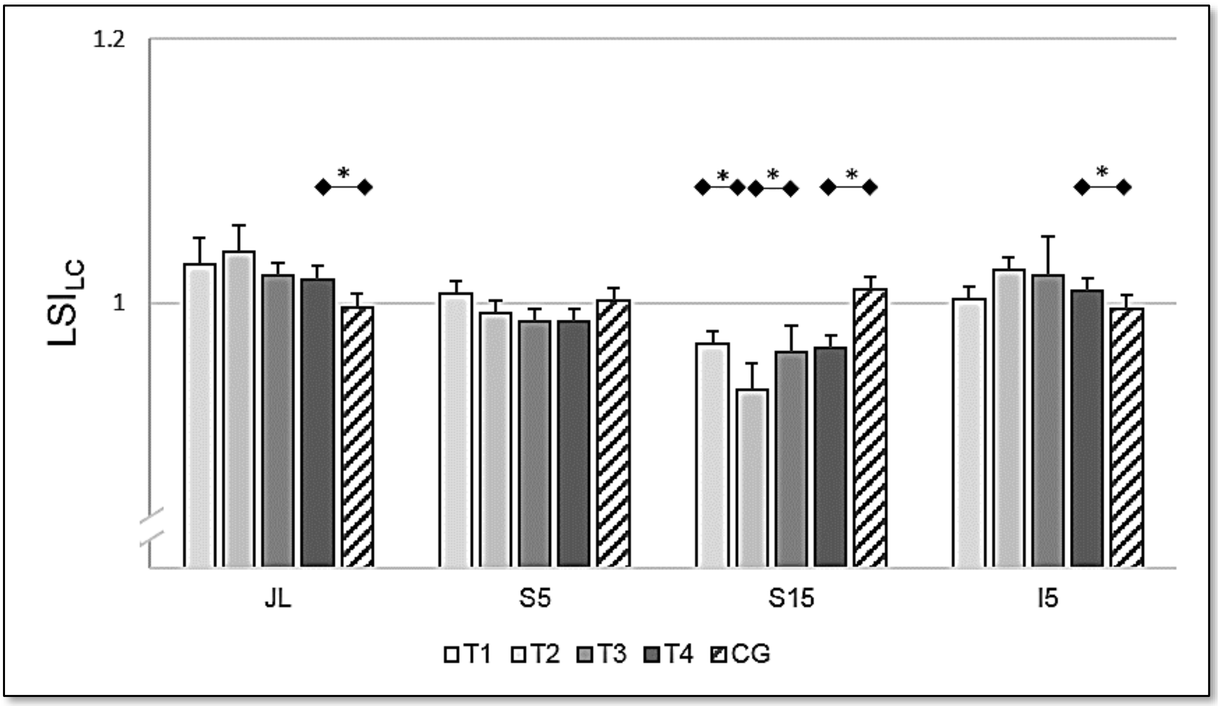

Figure 17. Results of the Leg Symmetry Indices (LSIs) of Leg Circumference Measurements. *Mean LSIs and 95% confidence intervals of leg circumference measurements of the ACL subjects (T1-T4) and the control subjects. All subjects stood upright during the measurements. The legs' circumference were measured at the joint line (JL), and 5cm (S5) and 15cm (S15) superior and 5cm inferior (I5) to the joint line (SØDERBERG et al. 1996). Test sessions with significant (P≤0.05) differences are marked with an asterisk (*).*

Passive ROM

RM-ANOVA revealed a significant variation for knee flexion ($F_{(3,51)}$=31.65, P<0.01, η_p^2=0.65) but no variations for knee extension ($F_{(3,51)}$=3.19, P=0.05, η_p^2=0.16). Post-hoc analysis showed that during knee flexion, the LSI_{ROM} was significantly lower at T2 than at T1 (T(19)=4.59, P<0.01, d=0.99), and significantly higher at T3 than at T2 (T(17)=7.39, P<0.01, d=1.20) and at T_4 than at T_3 (T(17)=3.75, P<0.01, d=0.69). In the ACL subjects at T4, the LSI_{ROM} during flexion (T(38)=3.89, P<0.01, d=1.23) and during extension (T(38)=2.65, P<0.01, d=0.84) was significantly lower compared to the control subjects. At T4, the deficit in the passive ROM of the injured legs was 3.5% in flexion and 2.3% in extension, compared to the non-injured leg (Figure 18). Regarding the passive ROM results, it is apparent that in knee flexion the ROM increases from six weeks post-reconstruction up to six months post-reconstruction. However, the side-to-side deficit in ACL reconstructed subjects remains significant compared to the healthy control subjects at six months post-reconstruction.

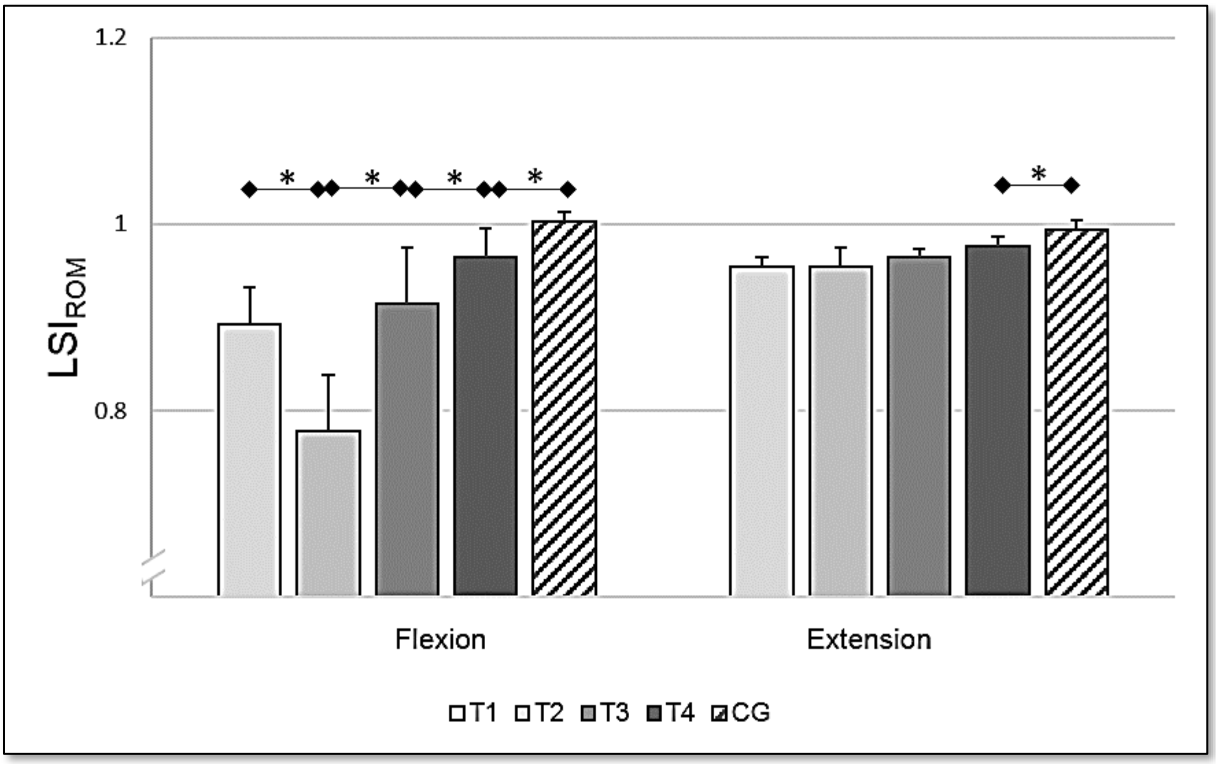

Figure 18. Results of the Leg Symmetry Indices (LSIs) of the Range of Motion Measurements. *Mean LSIs and 95% confidence intervals of the range of motion (ROM) measurements. ROM was measured during knee flexion in prone position and knee extension in supine position in the ACL subjects (T1-T4) and the control subjects (CG) (JANDA 2002). Test sessions with significant ($P \leq 0.05$) differences are marked with an asterisk (*).*

Functional Performance Tests

Counter Movement Jumps (CMJ)

RM-ANOVA revealed a significant variation for jumping heights ($F_{(3,33)}$=5.88, P=0.01, η_p^2=0.35). Jumping heights were significantly higher at T3 than at T2 (T(11)=2.25, P=0.04, d=0.73) and at T4 than at T3 (T(17)=2.77, P=0.01, d=0.35). The jumping heights were significantly higher in the control subjects than in the ACL subjects at T4 (T(38)=2.08, P=0.04, d=0.66). In the ACL subjects, jumping heights increased by 50.8% from T2 to T4. The deficit in jumping heights in the ACL subjects at T4 compared to the control subjects was 22.9% (Figure 19).

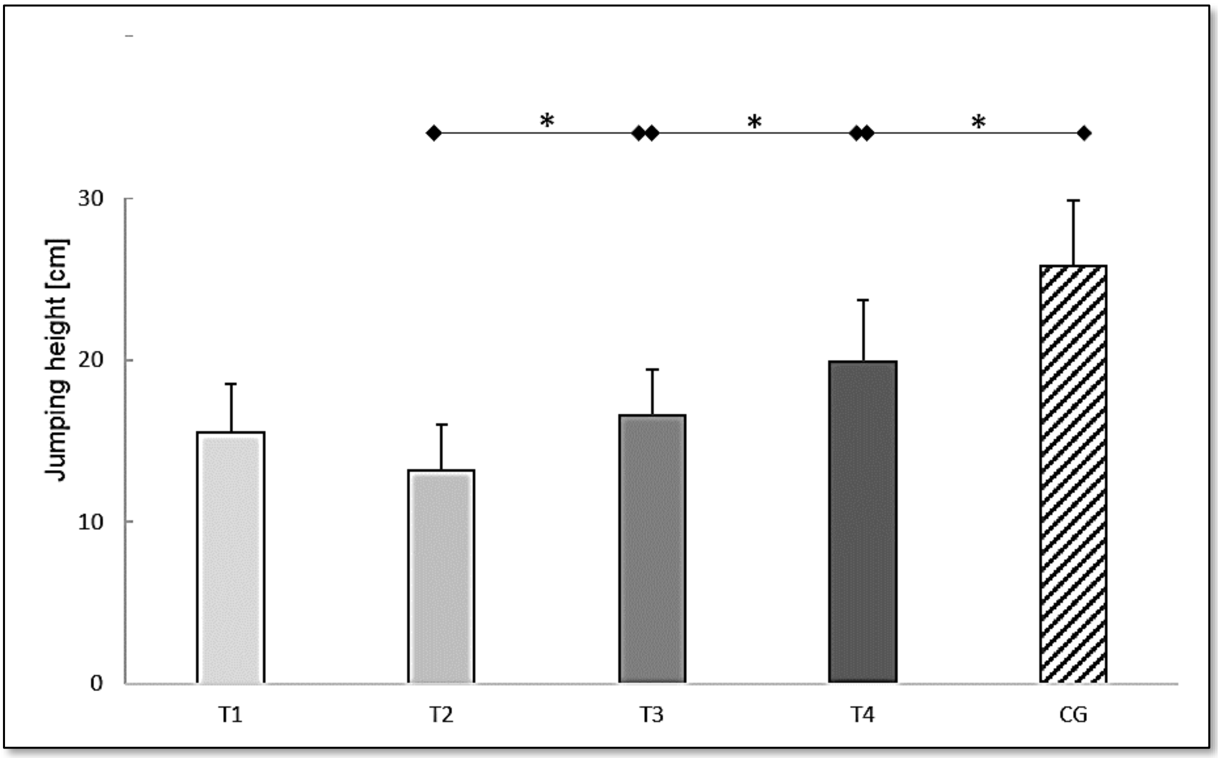

*Figure 19. **Results of the Counter Movement Jumps (CMJs).** Mean jumping heights and 95% confidence intervals of the ACL subjects (T1-T4) and control subjects (CG) of the CMJs. Test sessions with significant (P≤0.05) differences are marked with an asterisk (*).*

RM-ANOVA revealed a significant variation in the LSIs for the acceleration impulse during take-off ($\mathrm{LSI}_{\mathrm{CMJto}}$) ($F_{(3,33)}$=6.33, P=0.01, η_p^2=0.37). The $\mathrm{LSI}_{\mathrm{CMJto}}$ was significantly lower at T2 than at T1 (T(12)=2.21, P=0.05, d=0.50) and significantly higher at T3 than at T2 (T(11)=3.21, P=0.01, d=0.53) and at T4 than at T3 (T(17)=3.10, P=0.01, d=0.45). The ACL subjects had a significantly lower $\mathrm{LSI}_{\mathrm{CMJto}}$ at T4 than the control subjects (T(38)=2.81, P=0.01, d=0.89). The deficit in the acceleration impulse during take-off in the injured leg compared to the non-injured leg was 41% at T4.

RM-ANOVA revealed no significant variation of the LSIs of the deceleration impulse during landing ($\mathrm{LSI}_{\mathrm{CMJla}}$) in the CMJs ($F_{(3,33)}$=1.76, P=0.20, η_p^2=0.14). The $\mathrm{LSI}_{\mathrm{CMJla}}$ of the ACL subjects was significantly lower at T4 than the $\mathrm{LSI}_{\mathrm{CMJl}}$ the of the control subjects (T(38)=3.16, P<0.01, d=1.00). In the ACL subjects, the deceleration impulse during landing was 37% lower in the injured leg than in the non-injured leg at T4. (Figure 20)

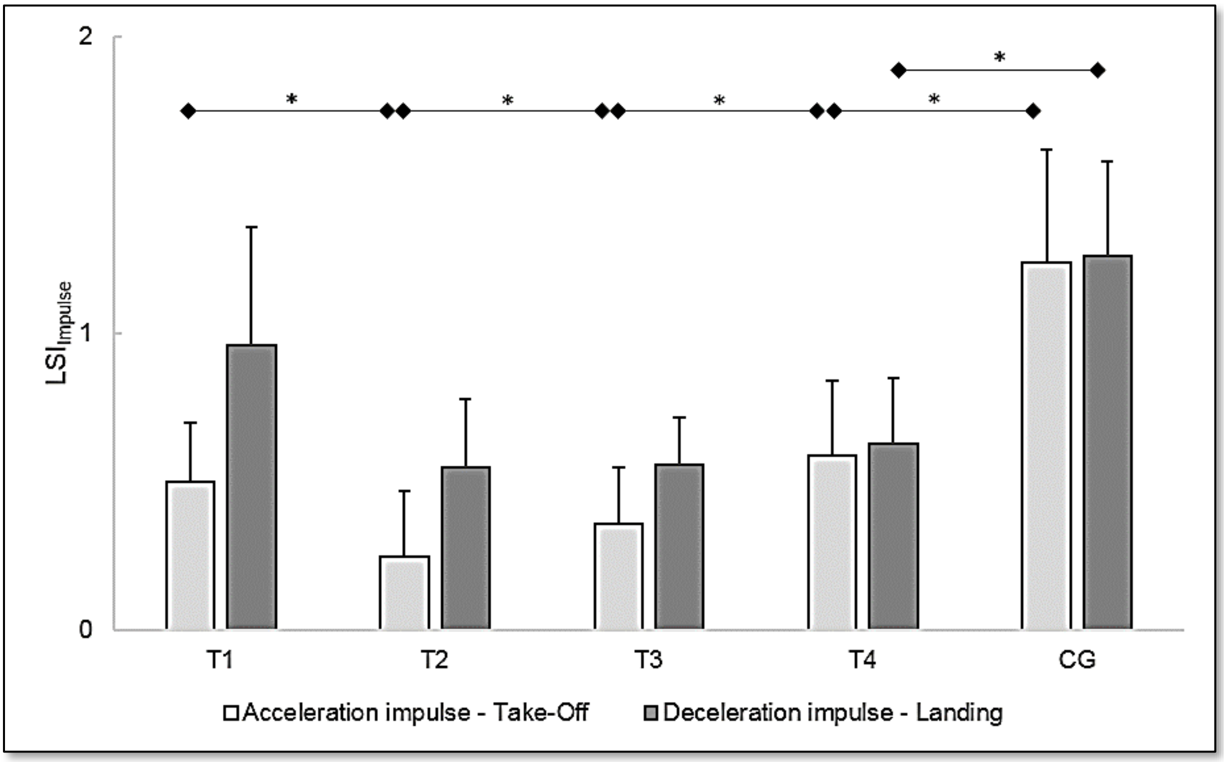

Figure 20. Leg Symmetry Indices (LSIs) of Acceleration Impulses during Take-off and LSIs of Deceleration Impulses during Landing of the Counter Movement Jumps (CMJs). *Mean LSIs and 95% confidence intervals of the acceleration and deceleration impulses of the CMJs. The acceleration impulses were measured during take-off and the deceleration impulses during landing of the ACL subjects (T1-T4) and the control subjects (CG). Test sessions with significant ($P \leq 0.05$) differences are marked with an asterisk (*).*

Summarized, although the jumping height and the LSIs of the acceleration impulse during take-off increased up to six months post-reconstruction, the ACL subjects had not reached the level of the healthy controls in jumping height and the LSIs of the acceleration impulses during take-off and deceleration impulses during landing.

One-Leg Jumps (OLJ)

RM-ANOVA revealed a significant variation of the LSIs of the jumping distances ($F_{(3,45)}=13.43$, $P<0.01$, $\eta_p^2=0.47$). The LSIs of the jumping distance dropped from T1 to T2 ($T(16)=3.32$, $P=0.01$, $d=0.78$). From T2 to T3 ($T(15)=3.56$, $P=0.01$, $d=0.79$) and from T3 to T4 ($T(16)=3.66$, $P<0.01$, $d=0.98$) significant increases of the LSIs for jumping distance were detected. The LSI of the jumping distance was significantly lower in the ACL subjects at T4 compared to the control subjects ($T(38)=2.50$, $P=0.02$, $d=0.79$). In the ACL subjects, the jumping distance of the injured leg was 25.1% lower compared to the non-injured leg at T4 (Figure 21).

RM-ANOVA revealed a significant variation in the LSI for the acceleration impulse during take-off in the ACL subjects (LSI_{OLJto}) ($F_{(3,45)}=12.22$, $P<0.01$, $\eta_p^2=0.45$). The LSIs of acceleration impulse dropped from T1 to T2 ($T(16)=3.32$, $P<0.01$, $d=0.80$). From T2 to T3 ($T(15)=3.56$, $P<0.01$, *d*=0.87) and from T3 to T4 (*T*(16)=3.66, *P*<0.01, *d*=0.99) significant increases of the LSIs of acceleration impulses were detected. However, the $\text{LSI}_{\text{OLJto}}$ in the ACL subjects at T4 was significantly lower compared to the control subjects (*T*(38)=3.30, *P*<0.01, *d*=1.04). The acceleration impulse of the injured leg was 17% lower compared to the non-injured leg at T4 (Figure 22).

Summarized, the LSIs of the jumping distances and of the take-off impulses increased in the ACL subjects up to six months post-reconstruction, however, remained lower than the LSIs of the healthy control subjects.

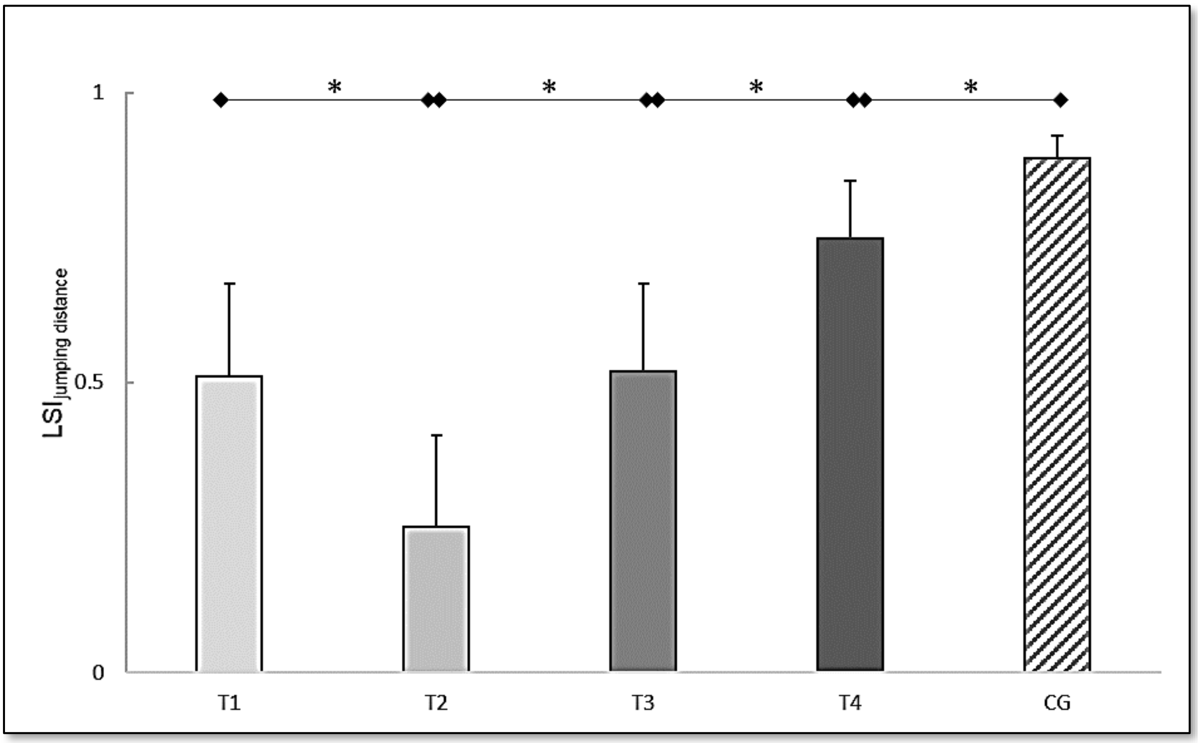

Figure 21. Leg Symmetry Indices (LSIs) of Jumping Distances of the One Leg Jumps (OLJs). *Mean LSIs and 95% confidence intervals of the jumping distances of the OLJs of the ACL subjects (T1-T4) and the control subjects (CG). Test sessions with significant (P≤0.05) differences are marked with an asterisk (*).*

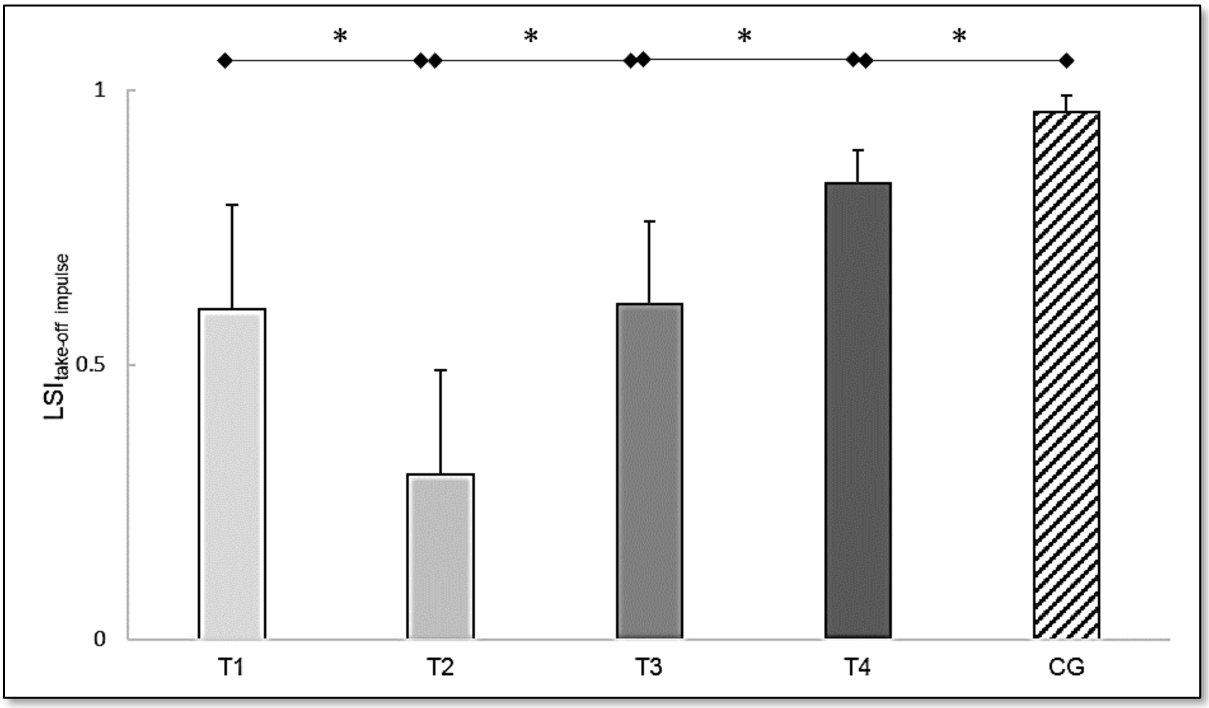

Figure 22.Leg Symmetry Indices (LSIs) of the Acceleration Impulses during Take-off of the One Leg Jumps (OLJs). *Mean LSIs and confidence intervals of the acceleration impulses during take-off of the OLJs of the ACL subjects (T1-T4) and the control subjects (CG). Test sessions with significant (P≤0.05) differences are marked with an asterisk (*).*

Isometric Force Tests

The LSIs of F_{max} (LSI_{Fmax}), RFD_{max} (LSI_{RFDmax}) and RFD_{200max} ($LSI_{RFD200max}$) are given in the Appendix (Table 9 Appendix 10.7). Therein, all conditions where the LSIs differed significantly are listed, including effect sizes of the post-hoc *t*-tests. Figure 23 shows exemplary results of the LSIs for F_{max}, RFD_{max} and RFD_{200max} during knee flexion and knee extension at 90°. The results of the 110° condition showed similar trends.

RM-ANOVA revealed a significant variation in LSI_{Fmax} at 90° flexion ($F_{(3,45)}$=12.11, P<0.01, η_p^2=0.45) and 110° flexion ($F_{(3,33)}$=4.96, P<0.01, η_p^2=0.31) as well as 90° extension ($F_{(3,45)}$=7.38, P<0.01, η_p^2=0.33) and 110° extension ($F_{(3,39)}$=14.06, P< 0.01, η_p^2=0.52). The ACL subjects showed significantly lower values for LSI_{Fmax} in all flexion and extension conditions at T2 compared to T1. Except for 110° flexion from T3 to T4, all other flexion and extension conditions showed significant increases in the LSI_{Fmax} from T2 to T3 and from T3 to T4. The LSI_{Fmax} in the ACL subjects at T4 were significantly lower than those of the control subjects at 90° and 110° knee flexion as well as 90° and 110° knee extension. The deficit of F_{max} in the injured leg compared to the non-injured leg was between 25% (110° extension) and 51% (110° flexion) at T4.

RM-ANOVA revealed a significant variation in LSI_{RFDmax} in the ACL subjects at 90° flexion ($F_{(3,57)}$=3.28, P=0.03, η_p^2=0.16) as well as at 90° extension ($F_{(3,57)}$=3.28, P=0.01, η_p^2=0.29) and 110°

extension ($F_{(3,51)}$=4.45, P=0.01, η_p^2=0.21). The LSI_{RFDmax} was significantly lower in all tested conditions at T2 compared to T1 (Table 9; Section 10.6). At 110° and 90° knee extension, significantly higher LSI_{RFDmax} was found at T4 compared to T3. The LSI_{RFDmax} in the ACL subjects at T4 were significantly lower than those of the control subjects at 90° and 110° knee flexion as well as 90° and 110° knee extension. The deficit in RFD_{max} in the injured leg compared to the non-injured leg was between 18% (90° extension) and 44% (110° flexion) at T4.

RM-ANOVA revealed a significant variation in $LSI_{RFD200max}$ at 110° knee flexion ($F_{(3,48)}$=3.28, P=0.03, η_p^2=0.17) and 110° knee extension ($F_{(3,51)}$=4.19, P=0.02, η_p^2=0.20). $LSI_{RFD200max}$ was significantly lower at T1 compared to T2 as well as significant higher at T4 compared to T3. The $LSI_{RFD200max}$ in the ACL subjects at T4 were significantly lower than those of the control subjects at 90° and 110° knee flexion as well as 90° and 110° knee extension (Table 9; Section 10.6). The deficit in RFD_{200max} in the injured leg compared to the non-injured leg was between 19% (90° extension) and 40% (90° flexion) at T4.

Summarized, the LSIs of all parameters of the isometric tests dropped from pre- to post-reconstruction time. Afterwards the LSIs increased in the knee flexion and extension conditions up to six months post-reconstruction. This was especially seen in the $LSIs_{Fmax}$ over all testing conditions, but not in all testing conditions for $LSIs_{RFDmax}$ and $LSIs_{RFD200max}$. All LSIs of the analyzed strength parameters were lower six months after reconstruction compared to the healthy control subjects.

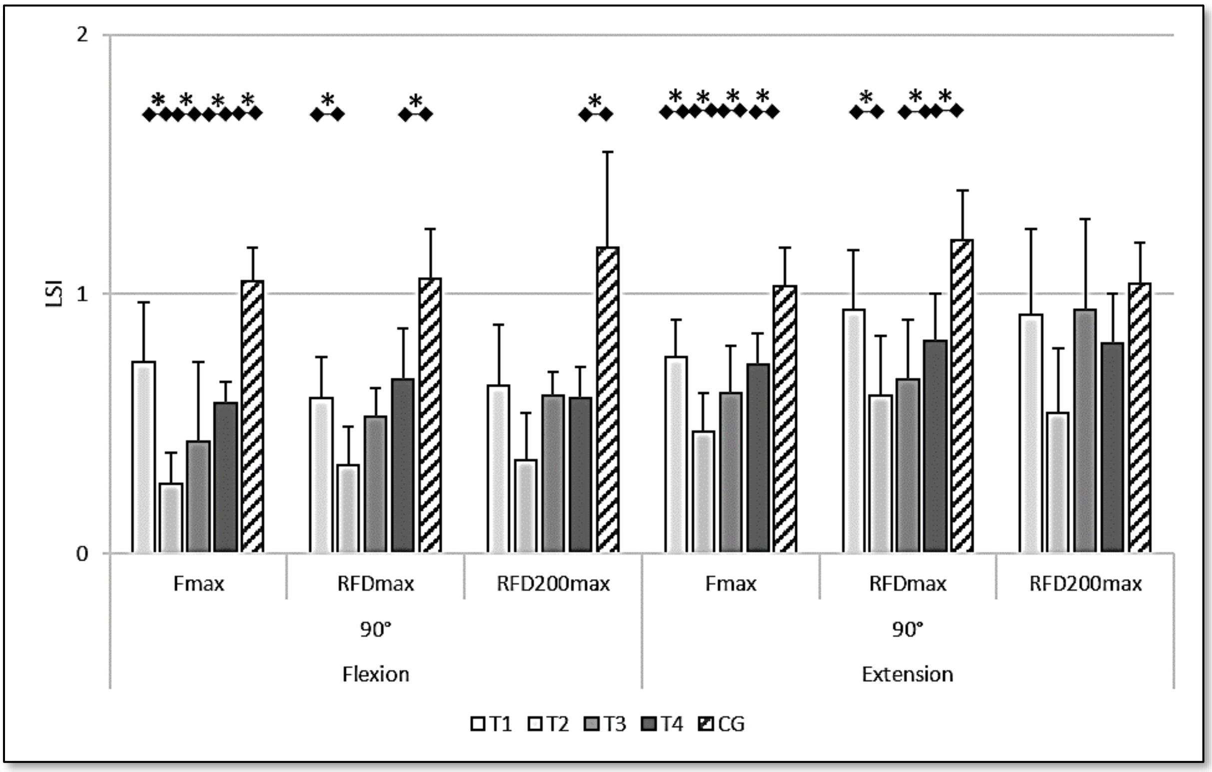

Figure 23. Leg Symmetry Indices (LSIs) of the isometric force parameters in 90° flexion and 90° extension condition. *Exemplary results of mean LSIs 95% confidence intervals of the maximum force (F_{max}), maximum rate of force development (RFD_{max}) and maximum rate of force development of the initial 200ms of contraction (RFD_{200max}) in 90° knee flexion and 90° knee extension conditions. Detailed results of the LSIs of all analyzed parameters and significant differences of all parameters between the test sessions are given in the Appendix (Table 9 Appendix 10.7). Test sessions with significant ($P \leq 0.05$) differences are marked with an asterisk (*) in Fig. 22 and are mentioned in the Results section of the manuscript.*

6.5 Discussion

This was the first study investigating specific components, determining and limiting knee function, after ACL reconstruction. This was implemented by the combination of self-evaluating questionnaires, functional clinical tests as well as static and dynamic functional FPTs from pre- to six months post-reconstruction with four test sessions. With this study design a more detailed understanding of the course of the functional state of the knee during the rehabilitation process was enabled. On a macroscopic level this study revealed three main findings: Firstly, the LSIs decreased after the ACL tear and reconstruction, indicating that the injured leg loses functionality from pre- to post-reconstruction. Secondly, the LSIs increased from six weeks post-reconstruction up to six months post-reconstruction, and thirdly, the LSIs of the ACL group subjects remained lower compared to the LSIs of the control subjects at six months post-reconstruction.

The reduction of the LSIs from pre- to post-reconstruction was significant in almost all tested parameters. This primarily shows the influence of the ACL tear and reconstruction on joint function in clinical tests and FPTs as well as the impact of the ACL tear of the individuals' QoL, which could be derived by the low self-evaluated knee function. Besides the low self-evaluated state, the low performance in the functional clinical tests and FPTs are not unexpected as the important role of the ACL for knee joint functionality is undeniably described (MYER et al. 2008; RUDOLPH et al. 2000; THE MARS GROUP 2010). The increase of functionality, according to the rising LSIs, in almost all parameters from six weeks post-reconstruction up to three and six months post-reconstruction shows that the analyzed rehabilitation programs enhance functionality in the reconstructed leg although the ACL group subjects did not reach the level of the control subjects in nearly all of the conducted tests. These results are discussed in details in the subsequent sections.

Functional Clinical Tests

Despite the enhancement of the LSIs, they remained on a lower level in nearly all parameters at six months post-reconstruction compared to the healthy control group subjects. These lower LSIs were seen in the functional clinical tests and the FPTs. The reduced LSIs of the LC measurements at S15 show, that the thigh musculature was still atrophied in the ACL group. Such thigh atrophy was described before and can be explained by the traumatic rupture and the subsequent neuromuscular changes in the injured leg (MCHUGH et al. 2002; THOMAS et al. 2016; LORENTZON et al. 1989). Additionally, the ACL subjects show reduced LSIs for passive ROM in knee extension and flexion compared to the control subjects six months post-reconstruction independently of the increasing LSIs in passive ROM over the four test sessions. Such knee ROM deficits in dynamic and static conditions were described previously (GOKELER et al. 2009; ORISHIMO et al. 2010), as well as the importance of full ROM recovery, especially in knee flexion, for full knee joint recovery in dynamic movements (HEWETT et al. 2005; WALDÉN et al. 2011). As both parameters have not recovered up to six months post-reconstruction, it is not surprising that the ACL group subjects show pronounced LSI deficiencies in the FPTs.

One-Legged and Bilateral Jumps

LSI deficiencies were apparent in the dynamic jumping FPTs compared to the control subjects, at six months post-reconstruction. Although the LSIs of jumping distances in the OLJs increased up to six months post-reconstruction, the ACL subjects showed pronounced LSI deficits for jumping distance compared to the control subjects. The ACL subjects could only realize a jumping distance with the injured leg of 74.9% of the non-injured leg. As it is described that a minimum of 85% should get reached before the performance of the reconstructed leg is declared normal (BARBER et al. 1990; DE FONTENEY et al. 2015; GUSTAVSSON et al. 2006; KUBO et al. 2004; LENTZ et al. 2009; MYER et al. 2008; ORISHIMO et al. 2010; REID et al. 2007; PETSCHNIG et al. 1998; RUDOLPH et al. 2000; TEGNER & LYSHOLM 1985; WILK et al. 1994), the results of our study yielded remarkable deficits in one-legged jumping performance in the reconstructed leg and therewith no normal symmetry level of the ACL reconstructed subjects.

These one-legged movement deficits were underlined by the bilateral CMJs performance, where the jumping height was reduced by 23.9 % compared to the control subjects. In contrast to unilateral OLJs for distance or height (BARBER et al. 1990; DE FONTENEY et al. 2015; GOKELER et al. 2009; GUSTAVSSON et al. 2006; KUBO et al. 2004; ORISHIMO et al. 2010; PETSCHNIG et al. 1998; REID et al. 2007; RUDOLPH et al. 2000; TEGNER & LYSHOLM 1985; WILK et al. 1994), bilateral CMJs are underrepresented in studies evaluating the functional outcomes after ACL tears. However, the evaluation of CMJs provides important information about the injured leg influences to the performance of bilateral movements. Especially, by the consideration of the acceleration impulse during take-off and the deceleration impulse during landing. These impulses provide general information about the ability to generate, apply and compensate for forces over a specific time in order to realize a specific task.

Although, the LSIs of the impulse parameters of the ACL subjects also improved over time, the LSIs of the acceleration impulse during take-off and the deceleration impulse during landing were lower than the LSIs of the control subjects at six months post- reconstruction, indicating a clear asymmetrical loading pattern. This asymmetrical load pattern was seen as a 41% lower acceleration impulse during take-off in the injured leg compared to the non-injured leg. This demonstrates a shift of load generation to the non-injured leg during take-off. This results also in a reduced overall take-off impulse, which explains the reduced jumping heights in the CMJs. During bilateral landing of the CMJs the deceleration impulse in the injured leg was 37% lower than in the non-injured leg, implying as well a shift of load compensation to the non-injured leg. Surprisingly, in the OLJs, the ACL subjects showed only a 17% deficit in the acceleration impulse during take-off in the injured compared to the non-injured leg. This deficit in acceleration impulse during take-off was lower in the OLJs than in the CMJs. This demonstrates that during take-off in bilateral CMJs, the ACL subjects shifted more load to their non-injured leg than the relative leg deficit was in the unilateral OLJs.

Collectively, the results of these parameters lead to the conclusion that besides deficits between the legs in the functional clinical tests in dynamic performance remarkable deficiencies, especially in bilateral jumping, in the injured leg compared to the non-injured leg at six months post-reconstruction exist. Similar compensation strategies involving the non-injured leg in jumps have been described in OLJs before, but not in CMJs (GOKELER et al. 2009; ORISHIMO et al. 2010). The results implicate that for comprehensive evaluation and monitoring of knee joint functionality one leg movement tasks should be supplemented by bilateral movement tasks, such as CMJs. The results of the functional clinical tests and the FPTs demonstrate how essential comprehensive test batteries are, including clinical tests and FPTs, for determining leg deficiencies more graduate and for providing a comprehensive state of the knee functionality.

Isometric Force Tests

The deficiencies in the reconstructed leg in the jumping tasks are underlined by deficiencies of the reconstructed leg in the isometric force tests. Herein, the LSIs improved from about six weeks post-reconstruction up to six months post-reconstruction. However, the LSIs of the ACL subjects were reduced compared to the control subjects' LSIs in F_{max}, RFD_{max} and RFD_{200max} at six months post-reconstruction.

RFD_{200max} is important for the rehabilitation process evaluation because during movements such as postural balance corrections in everyday life or jumping in intense sports, contraction times of up to 200ms are required. These contraction times are shorter than the time normally needed to reach maximal isometric force, which is between 300 and 500ms (AAGAARD et al. 2002; THOMAS et al. 2016).

The developments of F_{max} in comparison to RFD_{max} and RFD_{200max} indicate that neuromuscular adaptation processes recover on a higher level in comparison to adaptations of the legs' muscle volume up to six months post-reconstruction. In flexion and extension condition, F_{max} shows a stepwise increase of the leg strength with every test session, without reaching the level of the control group at six months post-reconstruction. Especially in knee extension, the RFD does not show such a time effect. In particular in RFD_{200max} there is no difference in the ACL group compared to the control group in test sessions three and four. As RFD is in general strongly related to efferent neuromuscular capacities, it appears that the RFD deficits are not that pronounced than the deficits in maximum force generation (AAGAARD et al. 2002). In contrast, the maximum force, which is substantially reduced in the ACL group compared to the healthy control group, is strongly related to the muscle volume. This result is in accordance to the analyses of the LCs. It was found, that at the fourth test session the circumference of the thigh in the area of the biggest muscle belly (S15) stayed reduced in the injured leg compared to the non-injured leg and additionally the relative circumference of the injured leg in the ACL group was reduced compared to the control subjects.

Deficits between the ACL subjects and the control subjects six months post-reconstruction were observed under knee flexion and extension conditions and at knee angles of 90° and 110°. The injured leg deficits compared to the non-injured leg of the ACL group subjects were between 25% (110° extension) to 51% (110° flexion) in F_{max}, between 18% (90° extension) to 44% (110° flexion) in RFD_{max}, and between 19% (90° extension) to 40% (90° flexion) in RFD_{200max}. These deficiencies are higher than those reported in the literature (LENTZ et al. 2009).

The deficits in comparison to the control group could be explained by a deficiency of the hamstrings muscles, which could be caused by the graft removal of tendons of hamstrings muscles. This was underlined by the more prominent deficiency in the injured leg during flexion than during extension. Thus, the deficient passive ROM during flexion was associated with deficiencies in isolated flexion force generation in the injured leg along with deficiencies in the FPTs. Due to the importance of flexion capabilities in dynamic performance tasks and the agonistic function of the hamstrings to the ACL (HEWETT et al. 2005; WALDÉN et al. 2011), it appears that these limitations in ROM in knee flexion and in generating forces could be an explanation for the shift of load to the non-injured side in bilateral CMJs and the performance discrepancy in the unilateral OLJs (GOKELER et al. 2009; ORISHIMO et al. 2010) and the generally reduced functionality compared to the control group subjects even at six months post-reconstruction.

Limitations

The sample consisted of subjects of both genders with a wide range of age and different pre-injury activity levels. Additionally, depending on the functional state, the subjects could perform activities beyond institutional therapeutical rehabilitation to a variable extent. The ability to perform autonomous therapeutic-independent training is strongly associated with the functional status and the intrinsic motivation of ACL reconstructed individuals. Higher training loads typically result in a higher functional state, due to the fact that the structures determining functionality, get positively influenced by an increased amount of training. Depending on the purposes, these issues need to be controlled in future studies. Due to the reason that this study aimed to draw a general picture of the functional outcome after ACL reconstruction we did not restrict the inclusion criteria of the sample in relation to the mentioned criteria. Nonetheless, more homogenous samples could lead to more specific results in relation to the drawn sample.

Practical Implications

The results of this study imply that detailed analyses of specific components, determining and limiting knee function, monitored repetitively after ACL reconstruction, improves the understanding of the recovery process of knee functionality. Therefore, the applied test battery enables clinicians and therapists to detect functionality very detailed, which provides a quantitative base for adapting the rehabilitation program more individually in relation to the respective individual functional state. This helps to achieve the best rehabilitative outcome of the ACL reconstructed individuals. In contrast, functional performance testing at one specific time point after reconstruction, as well as placing reliance only on functional clinical testing or the time period after reconstruction seems not adequate for determining functionality of ACL reconstructed individuals (PETERSEN & ZANTOP 2013). Moreover, the results of this study show that clinicians and therapists have to be aware of limited restoration of knee functionality of ACL reconstructed subjects in comparison to healthy control subjects up to six months after reconstruction. Therefore, caution is advised before individuals get released in pre-injury sports and further training recommendations are essential.

Conclusions

Summarized it can be stated that functionality of the ACL reconstructed subjects follows a uniform course, with a decrease from immediately pre-reconstruction time to six weeks post-reconstruction and a subsequent increase of functionality up to three and six months post-reconstruction. This shows that the applied common rehabilitation program enhances knee joint functionality up to six months post-reconstruction. However, at six months post-reconstruction the ACL reconstructed subjects have not reached the functional state of healthy control subjects in hardly any parameter, not even in their self-evaluated functional knee state and their self-determined activity level.

Accordingly, our general hypothesis was confirmed, namely, that the functionality of the ACL reconstructed subjects of this study could not be called ‘normal’ from subjective and objective viewpoints at six months post-reconstruction.

7 Study III:

Analyses of Daily Occurring Turns in ACL Reconstructed Subjects from Pre- to Six Months Post-ACL Reconstruction.

Unpublished manuscript. In preparation for publication.

KRAFFT FC, STETTER BJ, STEIN T, ELLERMANN A, FLECHTENMACHER J, EBERLE C, SELL S & POTTHAST W. (2018). ACL Reconstructed Subjects Show a Variety of Functional Adaptations in 90° and 180° Turns from Pre- to Six Months Post-ACL Reconstruction.

7.1 Abstract

Objective. Functional adaptations in sagittal joint kinematics and kinetics were detected in straight locomotion tasks, such as gait, in ACL reconstructed subjects. These aim to increase knee joint stability and reduce loads to the implanted autograft. However, manifestations of such functional adaptations could contribute to the framework of accelerated onset and progression of musculoskeletal disorders and chronic degenerative joint diseases. Therefore, the purpose of this study was to examine potential functional adaptations strategies of ACL reconstructed subjects in 90° and 180° turns by analyzing general locomotion strategies, and sagittal plane kinematics and kinetics. **Methods.** 20 subjects with unilateral tears of the ACL ((32 ± 13.3 yrs.; ACL group), reconstructed with the same reconstruction technique, and 20 matched healthy controls (33.3 ± 13.4 yrs.; CG) performed 90° and 180° turns at four test sessions: T_1 (6 wks. pre-reconstruction), T_2 (7 wks. post-reconstruction), T_3 (3 mos. post-reconstruction), and T_4 (6 mos. post-reconstruction). Kinetics were detected by two 3D force plates (1000Hz). Kinematics were sampled with a 3D Motion Capture-System (200Hz). Inverse kinematics and dynamics were computed using the full-body Dynamicus 9 model. The subjects were free in the turning strategy (step or spin turn strategy) to perform the respective turns and free in the selection of the leading and trailing leg (injured or non-injured leg). **Results.** The general locomotion strategy showed a preference of the step turn strategy in the ACL group and to prefer the injured/reconstructed legs as leading legs with increasing time after the reconstruction. Increased knee flexion was found in most turning locomotion conditions in the ACL group at T4 compared to the CG. Additionally, tendencies of kinetic adaptations were detected in increased knee flexion and increased knee extension moments in various characteristics. These appeared mostly in turning conditions, wherein tendencies of kinematic adaptations were found. In the leading legs of the spin turns solely knee extension moments were detected over the whole stance phase, which appeared to be increased by 130% compared to the peak knee extension moments detected in the leading and trailing legs of the step turns and the trailing legs of the spin turns. **Conclusions.** The general locomotion strategy seemed to have recovered on an acceptable level, as the ACL group showed a preference of the step turn strategy like the CG and healthy subjects. However, tendencies of isolated and accompanied functional kinematic and kinetic adaptations were found in the ACL group even at three and six months after reconstruction similar to those detected in straight ahead gait. Due to the large individual variances, appearing in various characteristics of functional adaptations in turning locomotion, it was concluded that more specific consideration of individual functional adaptations in activities of daily living should be taken into account in the rehabilitation process. This should support a comprehensive rehabilitation process to receive fully recovered knee joints and to prevent manifestations of such functional kinematic and kinetic adaptations.

7.2 Introduction

Gait analyses with the objective to examine functional adaptations of ACL reconstructed individuals were conducted in various studies during straight locomotion tasks, as straight gait and stair ascent and descent (ANDRIACCHI & DYRBY 2005; BERCHUCK et al. 1990; HALL et al. 2012; KNOLL et al. 2004b; LEWEK et al. 2002; WEXLER et al. 1998; ZABALA et al. 2013). Therein, specific functional adaptations were detected in ACL reconstructed subjects. These adaptations occurred during straight ahead gait in ACL reconstructed subjects in terms of load reductions to the reconstructed knee by reducing the activity of the M. quadriceps. Such adaptation processes were found in the immediate post-reconstruction phase, at six months after reconstruction and up to two years after reconstruction (BERCHUCK et al. 1990; DEVITA et al. 1997; HOOPER et al. 2002; TIMONEY et al. 1993; WEXLER et al. 1998). This phenomenon was designated as quadriceps avoidance gait (BERCHUCK et al. 1990). Loads shall get reduced to the implanted graft straight gait by the quadriceps avoidance gait (BERCHUCK et al. 1990; WEXLER et al. 1998; ZABALA et al. 2013). Such load reductions are beneficial in the immediate subsequent phase after the ACL reconstruction, to protect the implanted graft of inappropriate stress. However, unbalanced loading situations even long-term after the reconstruction (ZABALA et al. 2013), led to the assumption that compensation strategies could generally manifest prospectively. If so, adaptation processes would lead to chronic pathologic overloading processes of the non-injured leg alongside with a concomitantly chronic load reduction of the reconstructed leg or a complete transformation of the load compensation strategies (OBERLÄNDER et al. 2012). Imbalanced load situations are generally disadvantageous during movements and lead inevitably to an accelerated onset of joint cartilage degeneration and chronic knee osteoarthritis (ANDRIACCHI & DYRBY 2005; DANIEL et al. 1994; HALL et al. 2012; HAWKINS et al. 1986; LOHMANDER et al. 2007; MCDANIEL & DAMRON 1983; SCHIPPLEIN & ANDRIACCHI 1991; SHARMA et al. 1998).

However, ADLs contain various locomotion tasks besides the widely examined straight locomotion tasks. Such movements can be characterized by different locomotion characteristics (e.g. walking turns) compared to the cyclic alternating locomotion in straight locomotion tasks (COURTINE & SCHIEPPATI 2003; HASE & STEIN 1999; HICHEUR et al. 2005; IMAI et al. 2001; SREENIVASA et al. 2008). As various types of turns occur frequently throughout the day and due to the versatile characterization of the general turning locomotion strategies (COURTINE & SCHIEPPATI 2003; HASE & STEIN 1999; HICHEUR et al. 2005; IMAI et al. 2001; SREENIVASA et al. 2008), it was assumed that analyses of daily turns would provide valuable knowledge about potential adaptation strategies of ACL reconstructed subjects. Due to the specific characterization of turns, with their typical changing of the movement direction, turning locomotion requires different demands to the locomotion system, as those required for straight locomotion tasks (COURTINE & SCHIEPPATI 2003; HASE & STEIN 1999; MUELLER et al. 1995; SALSICH & MUELLER 2000). In particular, these variations occur in terms of differed head and trunk orientations to initiate and realize a turn (COURTINE & SCHIEPPATI 2003). Such differed head and trunk movements influence the general locomotion of the lower body, as for example the inner leg of a turn has a reduced stride length compared to the outer leg and one leg acts as leading leg, meanwhile the contralateral leg acts as trailing leg (COURTINE & SCHIEPPATI 2003). Therefore, turns represent a different kind of movement class, where naturally imbalanced locomotion demands between the legs occur. This leads to the fact that each leg provides different contributions and has separate locomotion and loading demands for the realization of turns (COURTINE & SCHIEPPATI 2003; HASE & STEIN 1999).

These facts outline the clear difference in the general locomotion compared to consistently balanced, alternating straight locomotion tasks. This led to the assumption that locomotion altering injuries, as ACL tears, could lead to functional adaptations in the general turning locomotion, which could potentially diverge from those described for straight ahead movements.

Therefore, to enlarge a comprehensive approach of functional analysis in ACL reconstructed subjects, adaptations and compensations due to ACL tears should not only concentrate on straight locomotion tasks. Additionally, existing studies, which investigated functionality in straight gait (BERCHUCK et al. 1990; WEXLER et al. 1998) or walking stairs (ZABALA et al. 2013), were designed as cross-sectional studies, analyzing functionality at a specific time-point after the reconstruction. Longitudinal studies, analyzing potential functional adaptations in turns, with a close monitored design from pre- to six months post-reconstruction, are missing.

Therefore, the purpose of the study was to analyze turning locomotion of 90° and 180° turns in ACL reconstructed subjects from pre- to six months post-ACL reconstruction and in comparison to a matched healthy control group (CG), with the aim to examine:

1. The influence of ACL tears and reconstructions on the general locomotion strategy.
2. The sagittal plane joint kinematics of ACL reconstructed subjects, who performed the turns with a uniform locomotion strategy at a respective test session.

(3) The sagittal plane joint kinetics of ACL reconstructed subjects, who performed the turns with a uniform locomotion strategy at a respective test session.

7.3 Methods

Sample

Subjects with ACL tears (n = 20) and healthy control subjects (n = 20), without any history of leg injuries, participated in the study (Table 5). Subjects were included, who sustained unilateral tears and underwent uniform ACL reconstruction techniques with a combined semitendinosus and gracilis autograft, via the double-bundle technique (SCHMIDT-WIETHOFF & DARGEL 2007). Exclusion criteria were concomitant severe injuries of the Menisci or the collateral ligaments in the knee joint. Inclusion criteria of the control subjects were the absence of any leg injuries and the fulfillment of the matching criteria to the respective ACL injured subject. The control subjects were matched to the ACL subjects according to: sex, age, height, mass and pre-injury activity level (Tegner Activity Score). The study was approved by the ethics committee of the State Medical Council of Baden-Württemberg (Stuttgart, Germany). All subjects provided written informed consent for their study participation.

Table 5. Sample Characteristics.

	Age [yr]	Height [cm]	Mass [kg]	Body-mass index [kg/m^2]	Activity Level (TAS)
ACL group	32.0 ± 13.3	174.7 ± 9.0	73.2 ± 8.7	24.1 ± 3.4	6.4 ± 1.4
Control group	33.3 ± 13.4	175.4 ± 10.4	74.7 ± 8.2	24.4 ± 2.6	6.0 ± 1.4

Mean values and standard deviations (SD) of the age, the anthropometric parameters body height [cm], body mass [kg], the Body-Mass-Index [kg/m^2], and the activity level determined with the Tegner Activity Score (TAS) of the ACL group subjects and the matched healthy control group subjects. TAS in the ACL group subjects is related to the pre-injury activity level.

Rehabilitation Program

All subjects received a standardized post-surgical rehabilitation program, according to the German health insurance system. This consists of three stages:

(1) Low-intensity (passive) activities up to six weeks post-reconstruction. Including physiotherapy with lymphatic drainage, passive movement exercises (by machine or therapist), sensorimotor training, weight-bearing exercises, and isometric training under therapists' supervision.

(2) Medium-intensity activities with muscular and balance training up to three months post-reconstruction. Including physiotherapy with lymphatic drainage, passive movement

exercises, independent strength training, balance training, and activities and sports without pivoting movements (e.g. cycling, swimming, (nordic) walking).

(3) Medium-to-high-intensity activities. Including intense strength training (if possible) up to six months post-reconstruction. Sports training (without pivoting movements) and slight return to pre-injury sports and sports-level with jumps, intense cycling, and strength training.

All stages were adaptable according to the rehabilitation state of the individuals' knee joint. Such a stepwise, three-staged structure is commonly applied in the rehabilitation cycle after ACL reconstructions (WHITING & ZERNICKE 2008). The summarized rehabilitation program of the ACL subjects, including the applied exercises and training as well as the performable activities and sports, is presented in the Appendix 10.5.

Study Design

The study was designed as a longitudinal non-randomized controlled trial to evaluate an existing and commonly applied rehabilitation program after ACL reconstruction in a chronologically and functionality detailed manner under the considerations of daily occurring turns. Therewith, possible time effects between or within parameters determining knee function and in comparison with healthy subjects should be detected. Accordingly, the ACL reconstructed subjects were tested at four different test sessions over a period of seven to eight months (Figure 24). The first test was performed preoperatively, immediately before the reconstruction and about seven weeks after the ACL tear (T1). All following tests were postoperative (T1-T4). T2 was about seven weeks, T3 was approximately three months and T4 approximately six months after ACL reconstruction. The test design was aligned to the three main stages of the rehabilitation process. The control subjects attended one test session.

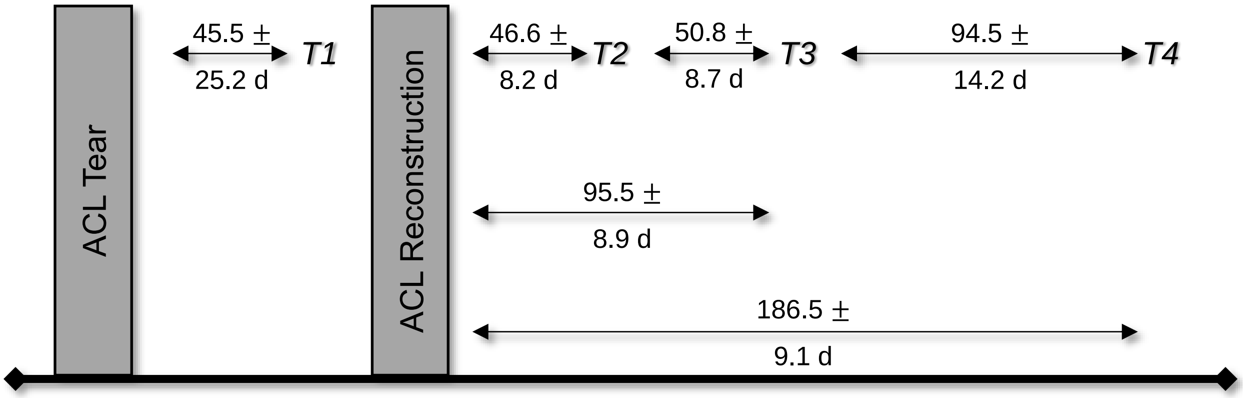

Figure 24. Study Design. *Mean days (d) and standard deviations between the test sessions of the ACL reconstructed subjects. T1 was at about six to seven weeks after the ACL tear, immediately before the ACL reconstruction surgery. T2 was at about six to seven weeks after the ACL reconstruction surgery. T3 was about three months and T4 was about six months after the ACL reconstruction surgery.*

Testing Task

According to KRAFFT et al. (2015), two daily occurring turns (Figure 25) were analyzed. All subjects had to perform 90° and 180° turns in clockwise (right orientated) and counter-clockwise (left orientated) direction at a self-selected gait velocity (Figure 25). This methodological setting resulted in four turning conditions:

- 180° turn left (counter-clockwise)
- 180° turn right (clockwise)
- 90° turn left (counter-clockwise)
- 90° turn right (clockwise)

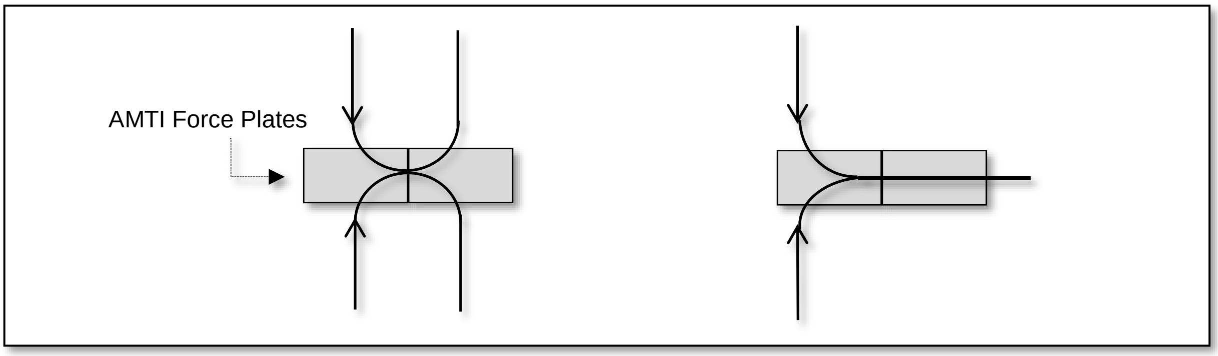

Figure 25. Types of Analyzed Turning Conditions. *Left: 180° turn clockwise and counter-clockwise. Right: 90° turn clockwise and counter-clockwise. Arrows mark both tested walking directions. The subjects had to walk with a self-selected gait velocity and with their own locomotion strategy.*

The performance of these types of turns had been proven reliable in healthy subjects, in terms of the general locomotion strategy (Step/spin turn; leading/trailing leg), the ground contact times of the turning steps, as well as the vertical and medio-lateral GRFs (Chapter 5) (KRAFFT et al. 2015).

Data Acquisition and Data Processing

The turning gait pathways (Figure 25) were marked on the floor of the movement analysis laboratory, BioMotion Center at the Institute of Sports and Sports Science at the Karlsruhe Institute of Technology. All turns had to be walked clockwise (right orientated) and counter-clockwise (left orientated) to determine eventual effects to the locomotion strategies depending on the walking direction. All subjects had to walk at a self-selected gait velocity to analyze the turning gait in a setting, which represents daily life conditions as appropriate as possible. Self-selected gait velocities were applied to reduce influential effects of external study conditions, which could change an individual's locomotion behavior in their turning movements. All subjects had to complete three valid trials for each turn. Validation was defined by placing each foot fully on one FP. Failing in the defined performance led to a repetition of the failed trial. Subjects had been free in their choice, which foot acted as leading leg and as trailing leg for the realization of the turns. The subjects had to walk the four turning conditions in a block randomized order to exclude learning effects from one condition to another.

Data were captured with the 3D motion analysis system (200 Hz; Vicon®, Oxford, UK; 12 MX13 cameras and 1 MX3 camera), which was linked to two 3D FPs (1000 Hz; AMTI®, Watertown, Massachusetts, USA). For an optimal tracking of the subjects' movements, 42 retro-reflective spherical markers (Diameter 19 mm, lightweight super-spherical markers; Qualisys AB, Gothenburg, Sweden) were attached to model-specific anatomical landmarks using double-sided tape, according to a modified version of the multi-body model, ALASKA Dynamicus 9 (HÄRTEL & HERMSDORF 2006). (Figure 7; Table 9 Appendix 10.4) Data were pre-processed with the software Vicon Nexus® (Version 1.8.5, Oxford, UK) to receive gap-free trajectories of the attached markers. Before the calculation of the kinematics and the inverse dynamics were enabled, data were post-processed with Matlab (Version R2017a; The MathWorks® Inc., Natick, Massachusetts, USA). Subsequently, kinematics and joint kinetics were employed by the multi-body model of ALASKA Dynamicus 9 (HÄRTEL & HERMSDORF 2006). This modelling process enables the subjects-specific calculation of loads in each joint during movements by the inverse dynamics approach (ROBERTSON et al. 2004).

Data Analyses

For analyses of the general locomotion strategies, firstly, it was determined if the subjects performed the turns with a step turn or with a spin turn strategy (HASE & STEIN 1999). In the performance of the step turn strategy the outer leg acts as leading leg, while the inner leg acts as trailing leg (Figure 26A, 26B). Performing the spin turn strategy, the inner leg acts as leading leg while the outer leg acts as trailing leg (Figures 26C, 26D).

For analyses of the locomotion strategies in relation to foot placement, all trials with the same foot placement strategy were summed up at each test session. Because the subjects could freely decide to walk each turn with a spin or a step turn strategy, subjects could arbitrary choose the turning strategy at each test session. This led to the fact that a differing quantity and a differing selection of subjects performed the respective turns with the same locomotion technique at each test session. Therefore, the results were analyzed in relation to homogenous foot placement strategies in the 90° and 180° turn, leading to four potential turning strategies (Figure 26).

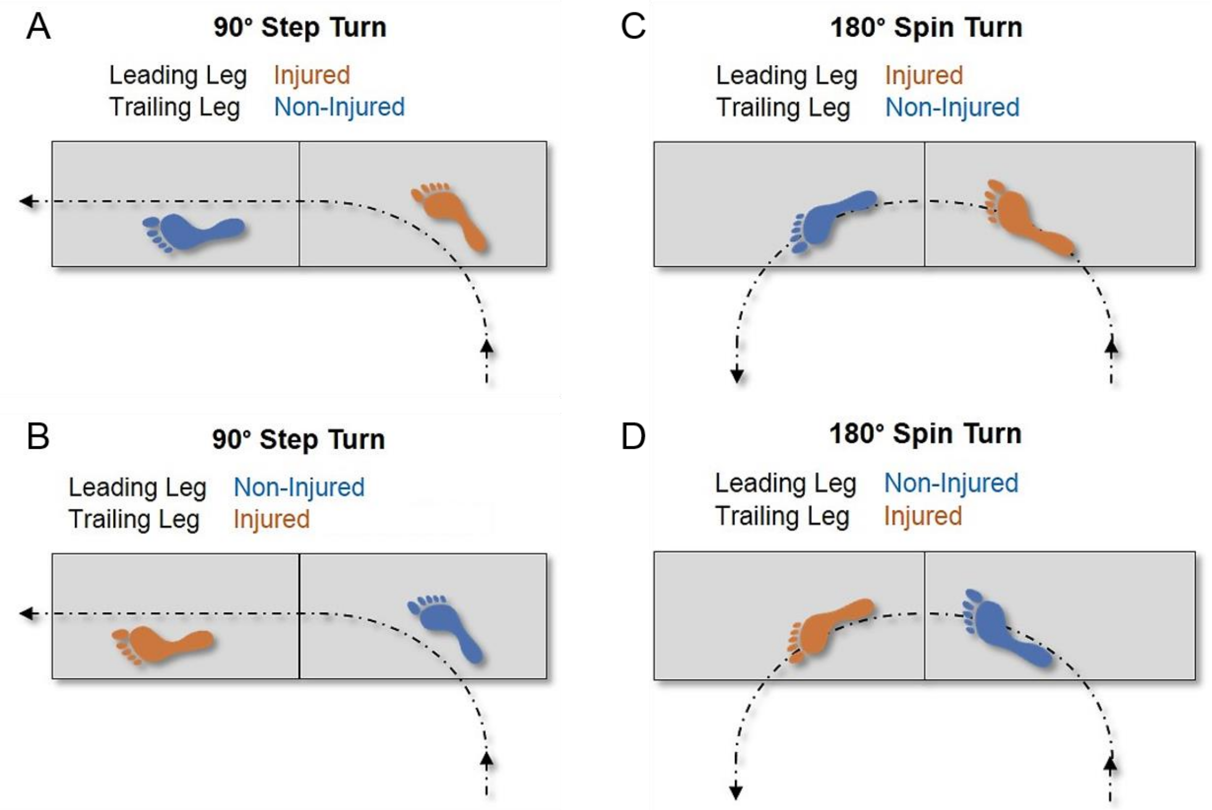

Figure 26. Turning Strategies. *Feasible turning locomotion strategies during the 90° and 180° turning conditions. A: 90° turn performed with the step turn strategy and the injured leg as leading leg. B: 90° turn performed with the step turn strategy and the non-injured leg as leading leg. C: 180° turn performed with the spin turn strategy and the injured leg as leading leg. D: 180° turn performed with the spin turn strategy and the non-injured leg as leading leg. Both turns could have been performed with a step or a spin turn strategy by the ACL reconstructed and healthy control subjects.*

Parameters

Gait velocities and ground contact times of the leading and trailing leg were determined as spatio-temporal parameters.

For examination of functional adaptations, sagittal plane kinematics (knee flexion angles) and kinetics (internal knee flexion moments and internal knee extension moments) were analyzed in the injured/reconstructed and non-injured legs of the ACL group and compared to the non-dominant and dominant legs of the CG, respectively.

Specifically, in kinematics, the mean local maximum (peak) in the early stance phase, the loading response phase, and the mean local minimum knee flexion angles in the terminal stance phase were analyzed (KIRTLEY 2006; PERRY 2003). Furthermore, the mean knee flexion excursion was examined, as a measure of the range of sagittal knee joint movement throughout the stance phase. The sub-phases of the stance phase were defined according to PERRY (2003) (Figure 27). In kinetics, the maximum knee flexion and knee extension moments were analyzed in the stance phase. Knee angles and knee moments were normalized to 100% of the stance phase for each leg.

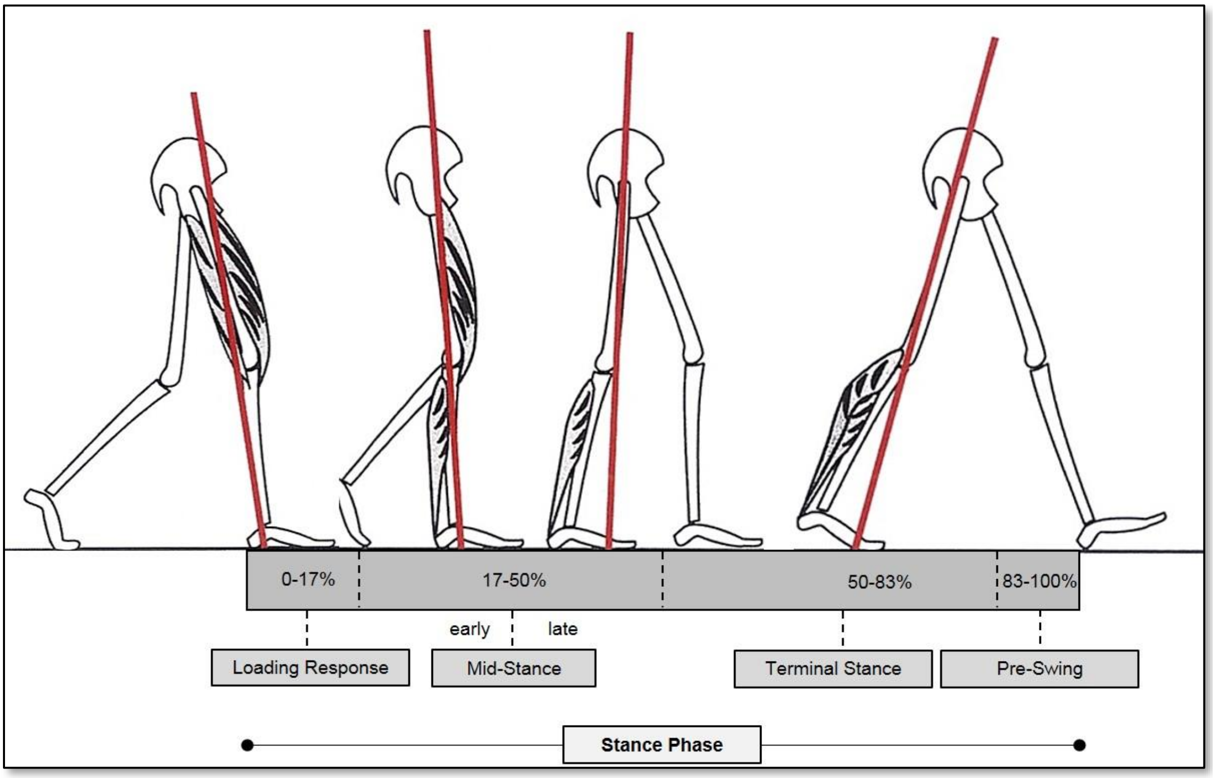

Figure 27. Gait Events in Straight Gait. *In this figure the different phases of the whole stance phase are illustrated. First phase, loading response, is composed of the heel-strike situation and the loading response of the leg, wherein the load acting after placing the foot is absorbed. The mid-stance phase is characterized by a unipedal situation, wherein a forward movement is performed by the load-bearing foot. In the terminal stance phase the unipedal stance phase ends and the heel is lifted from the ground. During the whole phase the main load is accepted by the forefoot. The pre-swing phase indicates the finalization of the stance phase by lifting the toes off the ground, whereas the contralateral leg is in the loading response phase. The red line indicates the resultant ground reaction force vector. (Figure modified according to PERRY 2003)*

Data analyses with focus on the sagittal plane, were considered as one major adaptation parameter in the immediate pre- and post-reconstruction phase, because with these parameters stress and load to the implanted autograft can be operationalized. This method was established through studies, which detected functional adaptations in terms of reduced quadriceps activations during straight ahead gait of ACL reconstructed subjects, concluding that these functional adaptations reduce stresses and loads to the reconstructed ACL (ANDRIACCHI & DYRBY 2005; BERCHUCK et al. 1990; WEXLER et al. 1998).

Statistical Analysis

Microsoft Office Excel 2013 was used for the calculation of means and SDs. Means of knee angles and knee moments in the sagittal plane were calculated for all subjects, who performed the respective turn with the same locomotion strategy at each test session. Exemplary, all subjects who performed the 90° turn with the step turn strategy using the injured/reconstructed leg as leading leg, were grouped for the calculation of means. Thus, because the subjects were free in their choice, how to perform the turns, exceedingly few subjects performed the turns with a uniform locomotion strategy throughout all test sessions. Therefore, the subjects, included in a specific group with a uniform locomotion strategy, varied at each test session. This led to the fact, that calculations of inferential statistics were unfeasible with the standard methods normally used for the computation of potential statistical differences (RM-ANOVA, *t*-test), as it was for instance applied to the results of the FPTs (Chapter 6).

7.4 Results

General Locomotion Strategy

Initially, the general locomotion strategies of the turns were analyzed. Therein it was distinguished, if the subjects performed the turns with a step or a spin turn strategy. Additionally, it was examined if the performed turning strategy was exerted with the injured/reconstructed leg or the non-injured leg as leading or trailing leg. Furthermore, the spatio-temporal parameters, mean gait velocities of the different turning locomotion conditions and the mean ground contact times of the turning steps, were taken under consideration in the analyses of the general locomotion strategy.

90° Turns

Analyzing the distributions (in counts) of the general locomotion strategies (Figure 28), it was found that the ACL group and the CG performed the 90° turns at each test session more often with the step turn strategy than with the spin turn strategy. Preference of the step turn strategy reached 60% at T1, 62.5% at T2, 53% at T3, 55% at T4, and 57.5% in the CG. Applying the step turn strategy, the injured/reconstructed legs (ACL group: T1: 54%; T3: 68%; T4: 64%) and the non-dominant legs (CG: 56%) were used more often as leading legs at most test sessions. Solely at T2, the ACL group performed the step turns equally with the injured/reconstructed or the non-injured legs as leading legs. Accordingly, in the spin turns the injured/reconstructed legs were used more often as leading legs at T1 (56%), T3 (59%), and T4 (67%) than the non-injured leg. Except at T2, where the spin turns were performed equally with the reconstructed or non-injured legs as leading legs. The CG showed a preference of 67% to perform the spin turns with the non-dominant legs as leading legs. This led to a uniform trend, determined in both locomotion strategies: after the ACL group subjects performed the step and spin turn strategies equally with the injured/reconstructed and non-injured legs as leading legs at T2, it appeared that the ACL group subjects increasingly used the injured/reconstructed legs as leading legs at T3 and T4. This resulted in a majority of two-thirds in favor to perfrom the 90° turns with the injured/reconstructed legs as leading legs at T3 and T4. Similar distributions were found in the CG in favor to perform the turns with the non-dominant legs as leading legs.

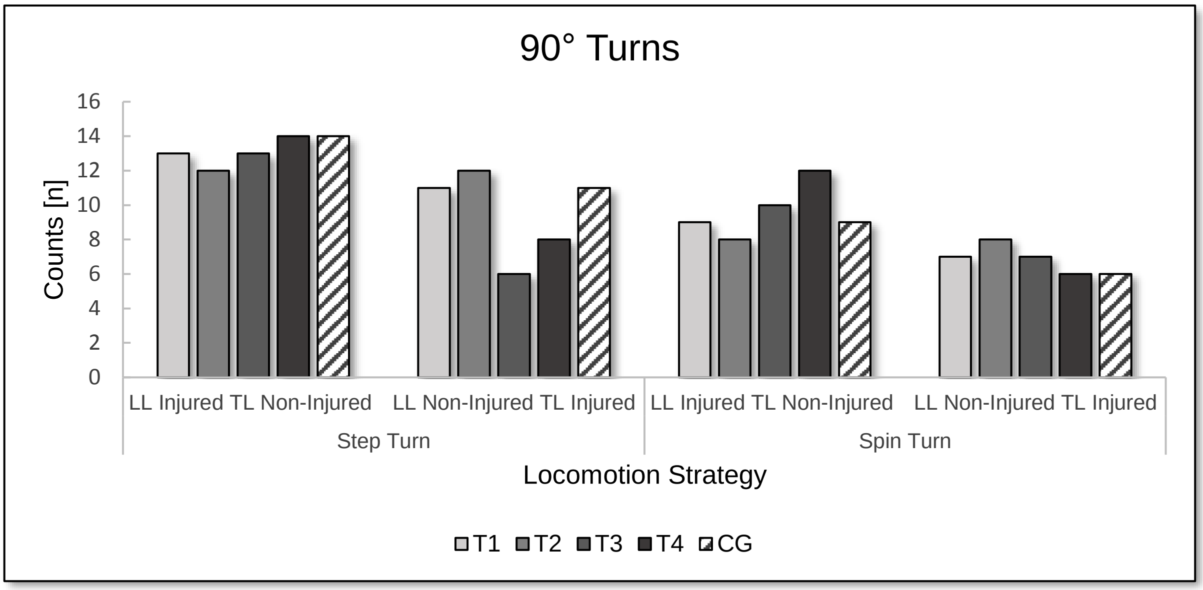

Figure 28. General Locomotion Strategy in 90° Turns. *Distributions (in counts) of the turning locomotion strategies (step or spin turn strategy) in the 90° turns. LL = leading leg; TL = trailing leg. T1 (light grey), T2 (medium grey), T3 (grey), and T4 (dark grey) represent the test sessions of the ACL group. The cross-striped bars indicate the distributions of the control group.*

180° Turns

Analyzing the general locomotion strategies in the 180° turns (Figure 29), as in the 90° turns, preferences of the step turn strategy compared to the spin turn strategy occurred at most test sessions in the ACL group and as well in the CG. The ACL group showed a preference of the step turn strategy of 65% at T1, of 61% at T3, of 52.5% at T4, and of 62.5% in the CG. At T2, the ACL group performed the 180° equally with the step and the spin turn strategy.

In the 180° step turns it was found that the ACL group performed the turns equally or more often with the non-injured legs as leading legs at T1 (50%) and at T2 (55%). However, the ACL group preferred the injured/reconstructed legs as leading legs at T3 (65%) and T4 (70%). The CG showed a slight preference to perform the 180° step turns with the dominant legs as leading legs (52%).

In the spin turn strategy the same pattern occurred. The ACL group showed equal or preferred use of the non-injured legs as leading legs at T1 (50%) and at T2 (55%). In contrast, the ACL group performed the 180° spin turns more often with injured/reconstructed legs as leading legs at T3 (64%) and at T4 (63%). The CG showed a slight preference to perform the 180° spin turns with the non-dominant legs as leading legs (53%). As in the 90° turns, the ACL group subjects increased the preference to perform the 180° turns with the injured/reconstructed legs as leading legs with increasing time after the reconstruction. This resulted in a 70% majority to perform the step turn strategy with the injured/reconstructed legs as leading legs and a 63% majority to perform the spin turn strategy with the injured/reconstructed legs as leading legs. In contrast, the proportion regarding the selection of the leading legs was nearly balanced in both turning locomotion strategies in the CG.

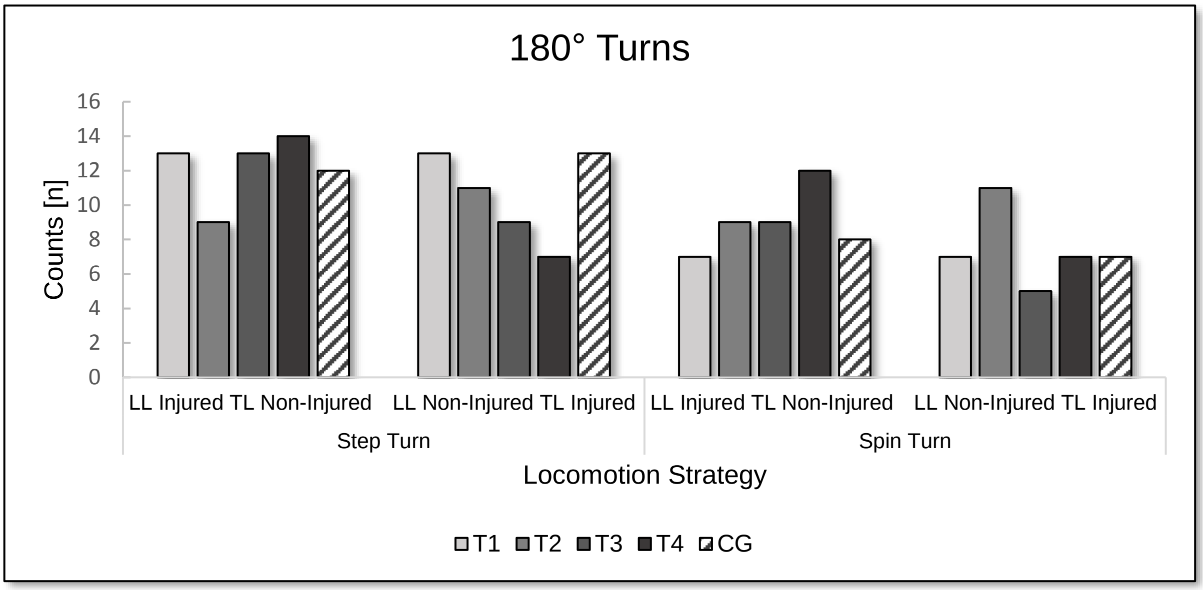

Figure 29. General Locomotion Strategy in 180° Turns. *Distributions (in counts) of the turning locomotion strategies (step or spin turn strategy) in the 180° turns. LL = leading leg; TL = trailing leg. T1 (light grey), T2 (medium grey), T3 (grey), and T4 (dark grey) represent the test sessions of the ACL group. The cross-striped bars indicate the distributions of the control group.*

Gait Velocities

90° Turns

Gait velocities increased in the step turn and the spin turn strategy from T1 to T4. The 90° step turns were performed with a mean gait velocity of 4.26 km/h, if the injured/reconstructed legs acted as leading legs and with a mean gait velocity of 3.97 km/h, if the non-injured legs acted as leading legs at T1. The gait velocities increased up to 4.71 km/h (leading leg injured/reconstructed) and 4.99 km/h (leading leg non-injured) at T4. The CG performed the 90° step turns slightly slower, with gait velocities ranging in average between 4.52 km/h (leading legs non-dominant) and 4.50 km/h (leading legs dominant).

If the 90° turns were performed with the spin turn strategy, average gait velocities of 4.43 km/h (leading legs injured/reconstructed) and 4.09 km/h (leading legs non-injured) were reached in the ACL group at T1. The gait velocities increased up to 4.49 km/h (leading legs injured/reconstructed) and 4.83 km/h (leading legs non-injured) at T4. The CG showed in the 90° spin turns slightly reduced mean gait velocities compared to the ACL group. The mean gait velocities of the CG ranged between 4.56 km/h (leading legs non-dominant) and 4.35 km/h (leading legs dominant). (Figure 30)

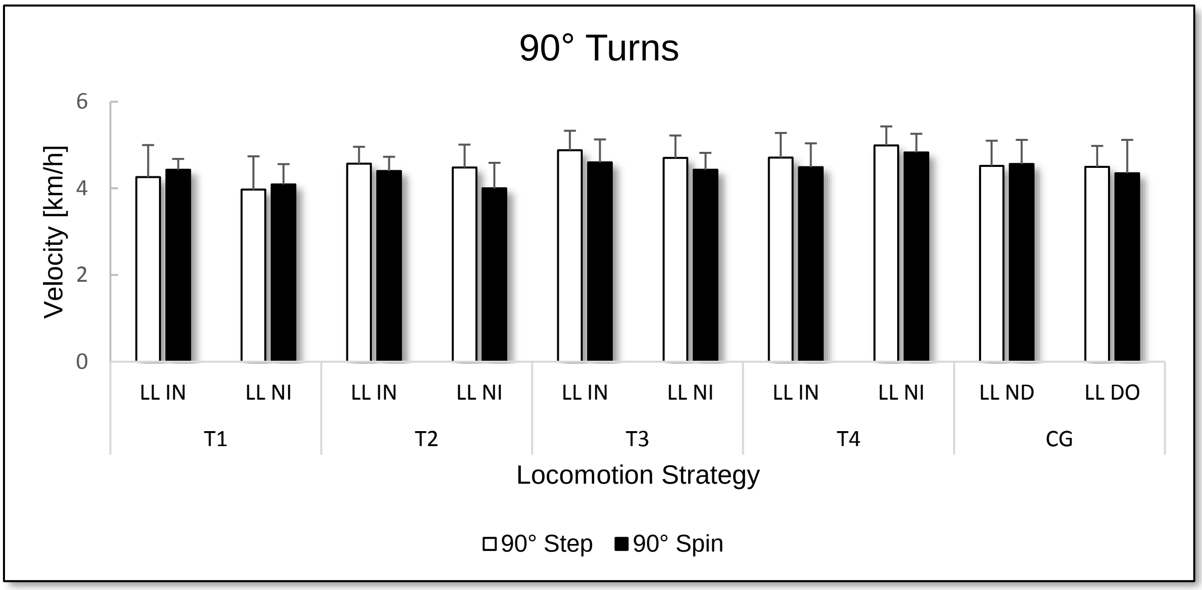

Figure 30. Mean Gait Velocities [km/h] with standard deviations of the 90° Turns. *Test sessions T1 to T4 represent the mean gait velocities with standard deviations of the ACL group and the control group (CG), while performing the 90° turns with step (white bars) or spin (Black Bars). LL = leading leg; LL IN = Leading leg injured/reconstructed; LL NI = leading leg non-injured; LL ND = leading leg non-dominant; LL DO = leading leg dominant.*

180° Turns

In the 180° turns, the gait velocities increased, as in the 90° turns, in the ACL group from T1 to T4 (Figure 31). Performing the 180° turns with the step turn strategy, the mean gait velocities ranged in the ACL group between 3.74 km/h (leading legs non-injured) and 4.02 km/h (leading legs injured/reconstructed) at T1. The gait velocities increased over the subsequent test sessions up to 4.55 km/h (leading legs injured/reconstructed) and 4.45 km/h (leading legs non-injured) at T4. The CG performed the 180° step turns slightly higher mean gait velocity, ranging between 4.61 km/h (leading legs non-dominant) and 4.71 km/h (leading legs dominant).

If the ACL group performed the 180° turns with the spin turn strategy, increases of the gait velocities were found similar as for the step turn strategy with increasing time after the ACL tears. The mean gait velocities of the ACL group ranged between 3.95 km/h (leading legs non-injured) and 4.12 km/h (leading legs injured/reconstructed) at T1 and increased up to 4.43 km/h (leading legs non-injured) and 4.58 km/h (leading legs injured/reconstructed) at T4. Accordingly, the CG performed the 180° spin turns with mean gait velocities, ranging between 4.19 km/h (leading legs dominant) and 4.39 km/h (leading legs non-dominant).

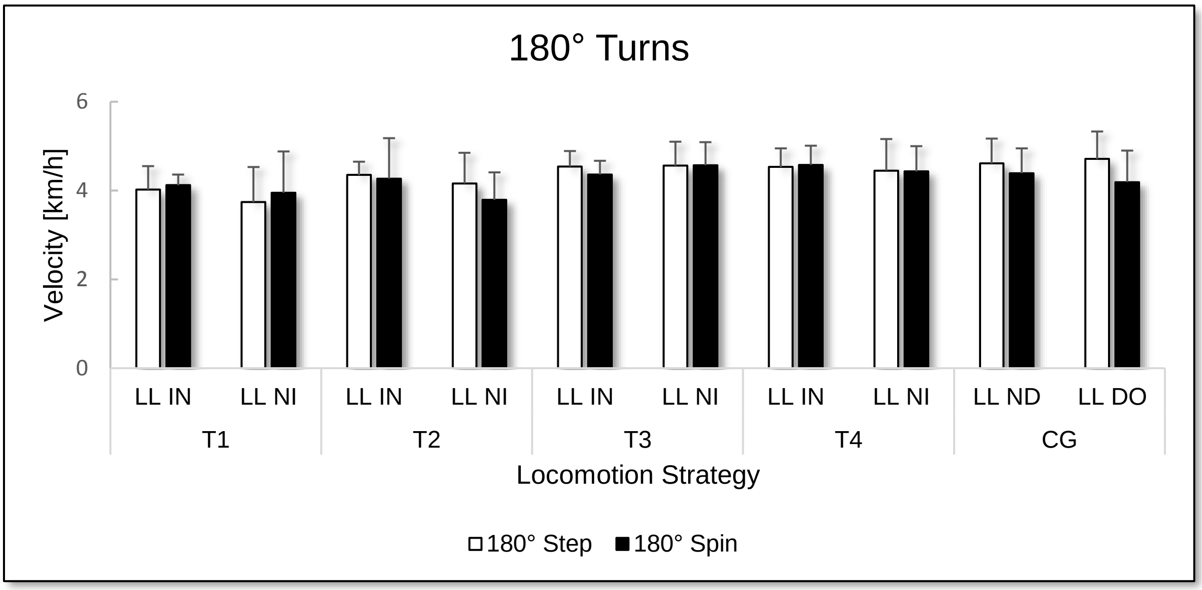

Figure 31. ***Mean gait velocities [km/h] with standard deviations of the 180° turns****. Test sessions T1 to T4 represent the gait velocities of the ACL group. CG the gait velocities of the control group. LL = leading leg; TL = trailing leg; LL IN = Leading leg injured/reconstructed; LL NI = leading leg non-injured; LL ND = leading leg non-dominant; LL DO = leading leg dominant.*

Ground Contact Times

90° Turns

Considerations of the mean ground contact times showed a relative homogenous pattern in the ACL group, especially at T3 and T4 and in the CG (Figure 32). At these test sessions, the mean ground contact times of the leading and the trailing legs ranged between 700 ms and 800 ms. However, tendencies of prolonged ground contact times were found in the trailing leg at T1, performing the step turn strategy, independently if the injured/reconstructed or non-injured leg acted as trailing leg. Furthermore, prolonged ground contact times of the trailing legs were found at T2, performing the spin turn strategy. Additionally, it appeared that the ground contact times were slightly reduced during the performance of the step turn strategy compared to the spin turn strategy in the leading and trailing legs in the ACL group from T2 to T4 and as well in the CG.

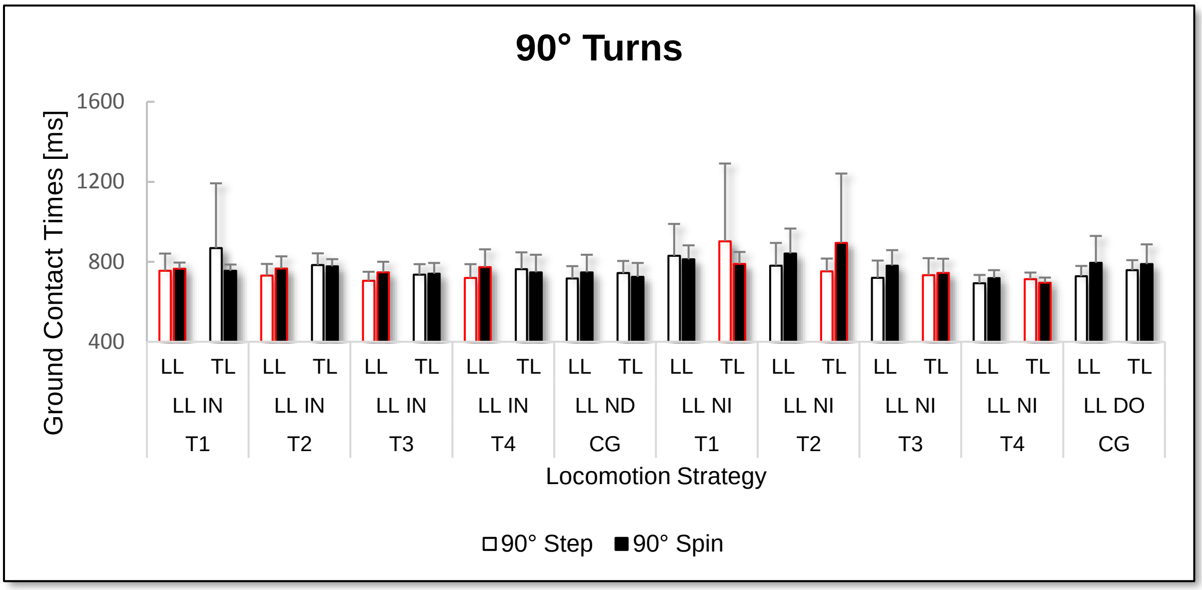

Figure 32. Mean ground contact times (GCT) in milliseconds [ms] with standard deviations of the 90° turns. *Test sessions T1 to T4 represent the GCTs of the ACL group. CG the GCTs of the control group. LL = leading leg; TL = trailing leg; LL IN = Leading leg injured/reconstructed; LL NI = leading leg non-injured; LL ND = leading leg non-dominant; LL DO = leading leg dominant. Red framed bars and red letters indicate the injured/reconstructed legs.*

180° Turns

In the 180° turns, tendencies of prolonged mean ground contact times appeared, performing the step turn strategy at T1 and T2 (Figure 33). Afterwards, in contrast, the ground contact times showed more homogenous characteristics with lower variances at T3 and T4. However, across all test sessions and both turning strategies, it was found that the mean ground contact times of the leading legs appeared to be reduced performing the step turn strategy than the spin turn strategy. It appeared that the mean ground contact times of the trailing legs were prolonged, performing the step turn strategy at T4. The CG showed in the 180° turns lower mean ground contact times in the leading legs, performing the step turn strategy compared to the spin turn strategy. The mean ground contact times of the trailing legs appeared to be on the same level in the step as in the spin turn strategy in the CG.

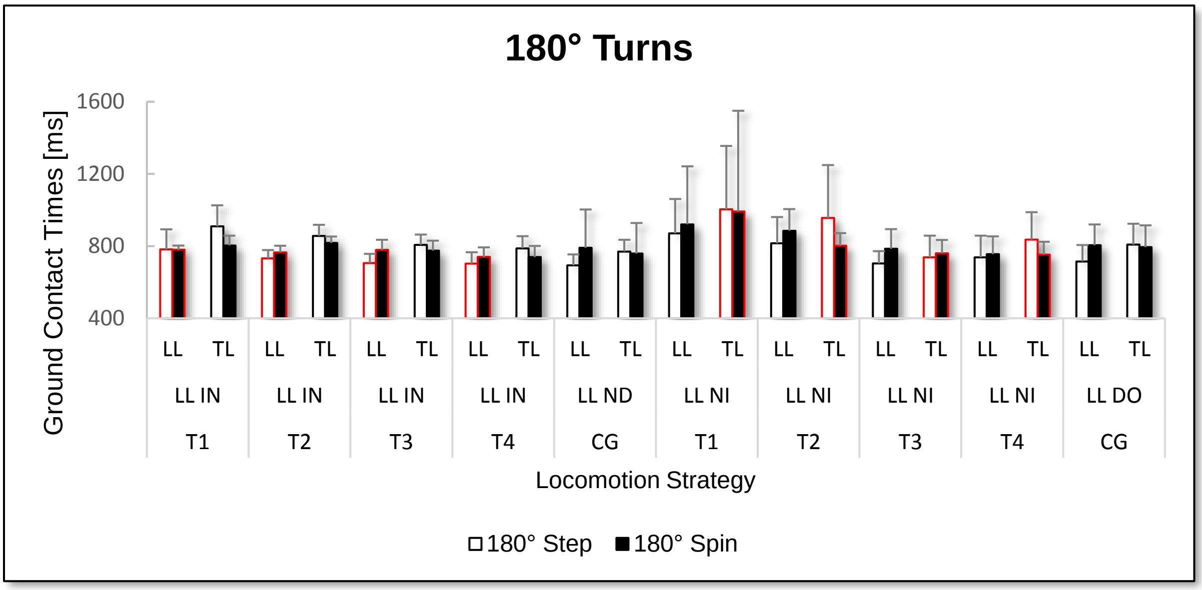

Figure 33. Ground contact times (GCT) in milliseconds [ms] with standard deviations of the 180° turns. *Test sessions T1 to T4 represent the GCTs of the ACL group. CG the GCTs of the control group. LL = leading leg; TL = trailing leg; LL IN = Leading leg injured; LL NI = leading leg non-injured; LL ND = leading leg non-dominant; LL DO = leading leg dominant. Red framed bars indicate the injured/reconstructed legs.*

Kinematics

General Findings

The descriptive analyses of the sagittal plane kinematics were focused on distinctive features in relation to peak knee flexion angles in the early stance up to 50% of the stance phase as well as in the late mid-stance phase. An exemplary illustration of a knee flexion angle curve over the stance phase is presented in Figure 34.

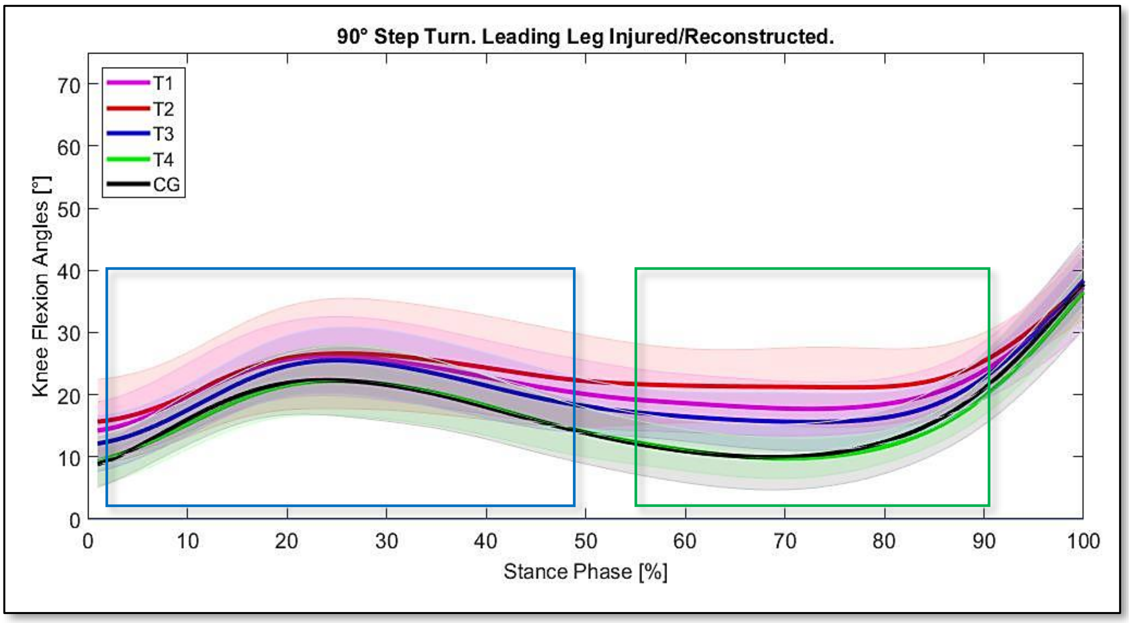

Figure 34. Knee Flexion Angles of the Injured/Reconstructed Legs in the 90° Step Turns. *Mean graphs of the knee flexion angles of the injured/reconstructed legs of the ACL group acting as leading legs in the 90° step turns. The knee flexion angles of the injured/reconstructed legs were compared to the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line represents the knee flexion curve of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles. The blue box illustrates the early stance phase up to 50% of the stance phase. The green box illustrates the terminal phase (According to PERRY et al. 2003).*

Increased knee flexions appeared in 50% of all analyzed turning locomotion conditions. These occurred over the whole stance phase or pronounced in the early stance phase up to 50% of the stance phase. These increased knee flexions appeared in the injured/reconstructed and non-injured legs and when acting as leading or trailing legs. Furthermore, these increased knee flexions showed tendencies to appear in the ACL group at all test sessions compared to the CG. The tendencies of kinematic adaptations are described in detail, according to their various specific characteristics.

In particular, the ACL group subjects showed tendencies of increased knee flexions over the whole stance phase at all test session, in the:

- Injured legs, acting as trailing legs in 90° step turns and the 180° step turns. (Figure 37 Appendix 10.8)

Tendencies of increased knee flexions were found in the ACL group subjects in the early stance phase up to 50% of the stance phase, but not in the terminal phase, at all test sessions, in the:

- Injured legs, acting as leading and trailing legs in 90° spin turns. (Figure 38 Appendix 10.8)
- Non-Injured legs, acting as leading legs and trailing legs in 90° step turns (Figure 39 Appendix 10.8).
- Non-Injured legs, acting as leading and trailing legs in the 90° spin turns (Figure 40 Appendix 10.8).

Furthermore, the ACL group showed tendencies of increased knee flexions over the whole stance phase from T1 to T3, which diminished up to T4 compared to the CG. These characteristics were found in the:

- Injured legs, acting as leading legs in 90° and 180° step turns (Figure 41 Appendix 10.9).
- Injured legs, acting as trailing legs in the 180° spin turns (Figure 42 Appendix 10.9).

The remaining analyzed turning locomotion conditions showed a congruent course of knee flexion over the whole stance phase at all test sessions compared to the CG:

- Non-injured legs, acting as leading and trailing legs in 180° step turns. (Figure 43 Appendix 10.10)
- Non-injured legs, acting as leading and trailing legs in 180° spin turns. (Figure 44 Appendix 10.10)
- Injured legs, acting as leading legs in 180° spin turns. (Figure 45 Appendix 10.10)

According to the presented overview of the kinematic findings, some results are, subsequently, described in detail. Especially, these results, wherein tendencies of functional adaptations appeared in the ACL group at all four tests sessions compared to the CG. This detailed analyses were divided, on the one side in the adaptations of the injured/reconstructed leg and on the other side in the adaptations of the non-injured leg.

Tendencies of Increased Knee Flexions at all Test Sessions

Injured/Reconstructed Legs

The ACL group showed tendencies of kinematic adaptations in the injured/reconstructed legs, when acting as leading legs, in the 90° spin turns, at all test sessions compared to the CG. Furthermore, tendencies of kinematic adaptations occurred in the injured/reconstructed legs, when acting as trailing legs in the 90° and 180° step turns and the 90° spin turns.

In the 90° and 180° step turns, increased knee flexions occurred in the trailing legs over the whole stance phase. Specifically, the ACL group subjects showed in the injured/reconstructed legs, acting as trailing legs, mean peak knee flexion angles in the early stance phase, which ranged from 22.8° to 29.4° from T1 to T3. At T4, the mean peak flexion angles appeared to be 27.2° in the 90° step turns and 22.7° in the 180° step turns. These knee flexion angles tended to be increased compared to the non-dominant legs, acting as trailing legs, in the CG (90° step turn: 18.4°; 180 step turn: 22.7°). Additionally, mean peak knee flexion angles in the terminal stance phase ranged in the injured/reconstructed legs of the ACL group in both turning conditions from 14.2° to 21.9° from T1 to T3. At T4, the mean peak knee flexion angles showed the lowest mean knee flexion angles of all test sessions in the 90° step turns (13.9°) and the 180° step turns (16.0°). However, these knee angles remained on a higher level as the mean peak knee flexion angles detected in the CG (90° step turn: 8.6°; 180° step turn: 10.5°). (Table 6; Figure 37 Appendix 10.8)

In the 90° spin turns, tendencies of increased knee flexions occurred in the early stance phase up to 50% of the stance phase at all test sessions, equally if the injured/reconstructed legs acted as leading or as trailing legs. In contrast, in the late terminal stance phase, no mentionable differences of the mean knee flexion angles were found. The analyses of the leading leg situations in the early stance phase revealed tendencies of increased mean peak knee flexions, ranging from 31.5° (T1) to 39.9° (T3) and 36.3° (T4). These mean peak knee flexion angles occurred to be increased compared to the non-dominant legs of the CG (26.5°). In the trailing legs, the mean peak knee flexion angles of the early stance phase ranged from 38.9° (T1) to 44.9° (T3) and 36.1° (T4), which tended to be increased compared to the CG (25.2°). (Table 6; Figure 38 Appendix 10.8)

Non-Injured Legs

Additionally, tendencies of kinematic adaptations occurred in the non-injured legs during turning locomotion at all test sessions compared to the CG. These appeared in the ACL group in the 90° step turns and in the 90° spin turns, in the leading and trailing legs. Specifically, these kinematic adaptations occurred in the early stance phase up to 50% of the stance phase, but not in the terminal stance phase.

In the 90° step turns, the mean peak knee flexion of the leading legs ranged from 21.7° (T1) to 28.9° (T2) and 26.6° (T4). These appeared to be increased compared to the dominant legs of the CG (20.9°), acting as leading legs. Additionally, the mean peak knee flexion angles of the trailing legs ranged from 26.8° (T1) to 25.0° (T3) and 23.8° (T4). These knee flexion angles appeared to be increased compared to the trailing legs of the CG (19.8°) in the 90° step turns. (Table 6; Figure 39 Appendix 10.8)

In the 90° spin turns, the mean peak knee flexion of the trailing legs ranged from 33.4° (T1) to 41.6° (T3) and 31.9° (T4). These appeared to be increased compared to the dominant legs of the CG (21.9°), when acting as leading legs. Additionally, the mean peak knee flexion angles of the trailing legs ranged from 34.9° (T1) to 39.6° (T3) and 40.5° (T4). These knee flexion angles appeared to be increased compared to the trailing legs of the CG (25.2) in the 90° spin turns. (Table 6; Figures 40 Appendix 10.8)

Tendencies of Increased Knee Flexion from T1 to T3

Besides the described adaptations, which occurred at all test sessions, there occurred three turning locomotion conditions, wherein tendencies of increased knee flexion were detected over the entire stance phase from T1 to T3. These increased knee flexions diminished at T4 and approached the level of the CG at T4. These phenomena were detected isolated in the injured legs, when acting as leading legs in the 90° and 180° step turns and when acting as trailing legs in the 180° spin turns. (Table 6; Figures 41 and 42 Appendix 10.9)

Tendencies of Equal Knee Flexions from T1 to T4 and Compared to the CG

The analyses of the remaining turning locomotion conditions revealed homogeneous knee flexion angle courses over the whole stance phase in the ACL group at all test sessions and compared to the CG. These tendencies of unaffected sagittal kinematics appeared in the ACL group solely in the non-injured legs, in the leading and trailing legs. Therein, no increased knee flexion angles were found in the early stance or the terminal stance phase in the ACL group at all test sessions compared to the CG. (Table 6; Figures 43 to 45 Appendix 10.10).

Table 6. Mean Knee Flexion Angles in the Early Stance and Terminal Stance Phase in the Analyzed Turning Locomotion Conditions.

Turning Condition		Stance Phase	T1	T2	T3	T4	CG
90° Step Turn	LL injured/reconstructed	ES	26.2 (6.4)	26.6 (8.9)	25.5 (5.3)	22.2 (5.5)	22.3 (5.6)
		TS	17.7 (4.2)	21.2 (6.4)	15.6 (4.6)	9.7 (3.2)	9.9 (5.3)
	LL non-injured	ES	21.7 (5.0)	28.9 (5.3)	26.2 (5.9)	26.6 (5.1)	20.9 (3.2)
		TS	8.9 (5.5)	10.3 (4.7)	9.2 (4.1)	9.3 (4.3)	7.3 (5.6)
	TL injured/reconstructed	ES	22.8 (7.1)	29.4 (4.4)	25.0 (7.1)	27.2 (4.8)	18.6 (7.1)
		TS	16.0 (8.2)	20.3 (7.0)	14.2 (6.8)	13.9 (6.6)	8.5 (8.3)
	TL non-injured	ES	26.8 (13.9)	26.6 (4.4)	25.0 (5.5)	23.8 (5.1)	19.8 (6.2)
		TS	11.6 (12.3)	9.1 (4.5)	8.8 (3.9)	8.2 (3.7)	8.5 (5.3)
90° Spin Turn	LL injured/reconstructed	ES	32.3 (21.3)	33.4 (18.8)	39.9 (22.5)	36.3 (26.1)	26.5 (12.8)
		TS	17.5 (7.3)	18.2 (5.9)	18.5 (8.2)	11.4 (4.8)	12.6 (4.4)
	LL non-injured	ES	33.4 (29.3)	28.5 (21.9)	41.6 (28.6)	31.9 (25.2)	21.9 (5.5)
		TS	8.5 (2.8)	8.0 (2.7)	10.2 (2.6)	8.4 (3.3)	9.7 (5.6)
	TL injured/reconstructed	ES	38.9 (24.6)	34.3 (16.1)	44.9 (21.6)	36.1 (24.6)	25.2 (6.3)
		TS	17.5 (7.0)	18.2 (6.9)	15.8 (4.6)	11.2 (5.5)	10.9 (8.2)
	TL non-injured	ES	34.9 (17.2)	35.7 (23.8)	39.6 (19.7)	40.5 (21.5)	26.8 (5.4)
		TS	8.1 (4.5)	8.8 (3.9)	9.8 (4.2)	8.3 (2.9)	8.3 (5.9)
180° Step Turn	LL injured/reconstructed	ES	27.0 (6.1)	30.9 (13.1)	26.4 (5.8)	24.3 (4.8)	26.4 (13.1)
		TS	18.9 (5.3)	18.4 (6.6)	17.9 (5.8)	12.6 (3.9)	13.0 (4.5)
	LL non-injured	ES	22.5 (5.7)	27.5 (4.6)	25.6 (5.2)	25.8 (5.4)	23.7 (4.7)
		TS	10.8 (5.5)	11.7 (6.0)	8.8 (2.1)	10.7 (4.2)	10.8 (4.9)
	TL injured/reconstructed	ES	24.7 (15.3)	26.8 (4.7)	23.0 (5.8)	22.7 (6.4)	18.7 (7.6)
		TS	20.4 (8.5)	21.9 (6.1)	17.0 (3.9)	16.0 (6.8)	10.5 (6.3)
	TL non-injured	ES	20.8 (5.5)	28.0 (15.2)	22.6 (6.0)	22.5 (6.0)	30.1 (21.5)
		TS	13.4 (4.7)	12.7 (5.1)	12.9 (5.3)	11.7 (3.2)	12.2 (5.0)
180° Spin Turn	LL injured/reconstructed	ES	23.4 (7.1)	30.4 (12.7)	23.4 (7.3)	22.8 (5.3)	21.7 (6.8)
		TS	16.2 (6.4)	22.1 (6.5)	16.3 (7.6)	16.6 (5.7)	14.6 (5.7)
	LL non-injured	ES	24.4 (7.9)	25.2 (6.8)	31.4 (18.0)	23.9 (5.8)	21.5 (6.0)
		TS	14.0 (8.1)	16.5 (6.8)	14.5 (3.5)	14.1 (4.3)	13.4 (5.6)
	TL injured/reconstructed	ES	25.4 (9.5)	27.4 (4.4)	27.0 (13.5)	23.3 (6.5)	23.6 (4.6)
		TS	17.1 (10.1)	22.7 (6.4)	14.1 (5.6)	15.9 (6.5)	11.4 (6.9)
	TL non-injured	ES	24.7 (7.1)	25.6 (8.6)	24.9 (4.1)	24.4 (5.9)	22.5 (7.1)
		TS	8.7 (5.1)	9.7 (5.0)	11.7 (3.7)	7.6 (3.5)	11.8 (5.0)

Mean peak flexion angles with standard deviations in brackets of the turning locomotion conditions. In the first column the analyzed turning locomotion condition is mentioned (LL = Leading leg; TL = Trailing leg). The second column presents the respective analyzed stance phases (ES=Early stance phase; TS = Terminal stance phase). The third (T1) to sixth column (T4) represents the mean peak flexion angles at ES or LMS of the ACL group at all test sessions. The latter column (CG) contains the mean peak knee flexion angles in ES and LMS of the Control Group. All values represent means in degrees [°]. Rows marked in red indicate the turning locomotion conditions with increased knee flexions compared to the CG at all test sessions. Rows marked yellow indicate turning locomotion conditions with increased knee flexions from T1 to T3, but balanced knee flexions compared to the CG at T4. Rows marked in green indicate the turning locomotion conditions with no stronger differences in the ACL group compared to the CG at all test sessions.

Kinetics

General Findings

In the descriptive analyses of the sagittal plane kinetics, two main characteristics of the moment-time curves emerged: firstly, moment-time curves, showing knee flexion moments in the early stance, which switched in the mid-stance phase to knee extension moments (Figure 35A). These characteristic appeared in the leading and trailing legs of the step turns and in the trailing legs of the spin turns. The second emerging characteristic of the moment-time curves was characterized by appearing solely knee extension moments in a double-peaked pattern over the whole stance phase (Figure 35B). These characteristics of the moment over time curves, were determined solely for the spin turns in the leading legs.

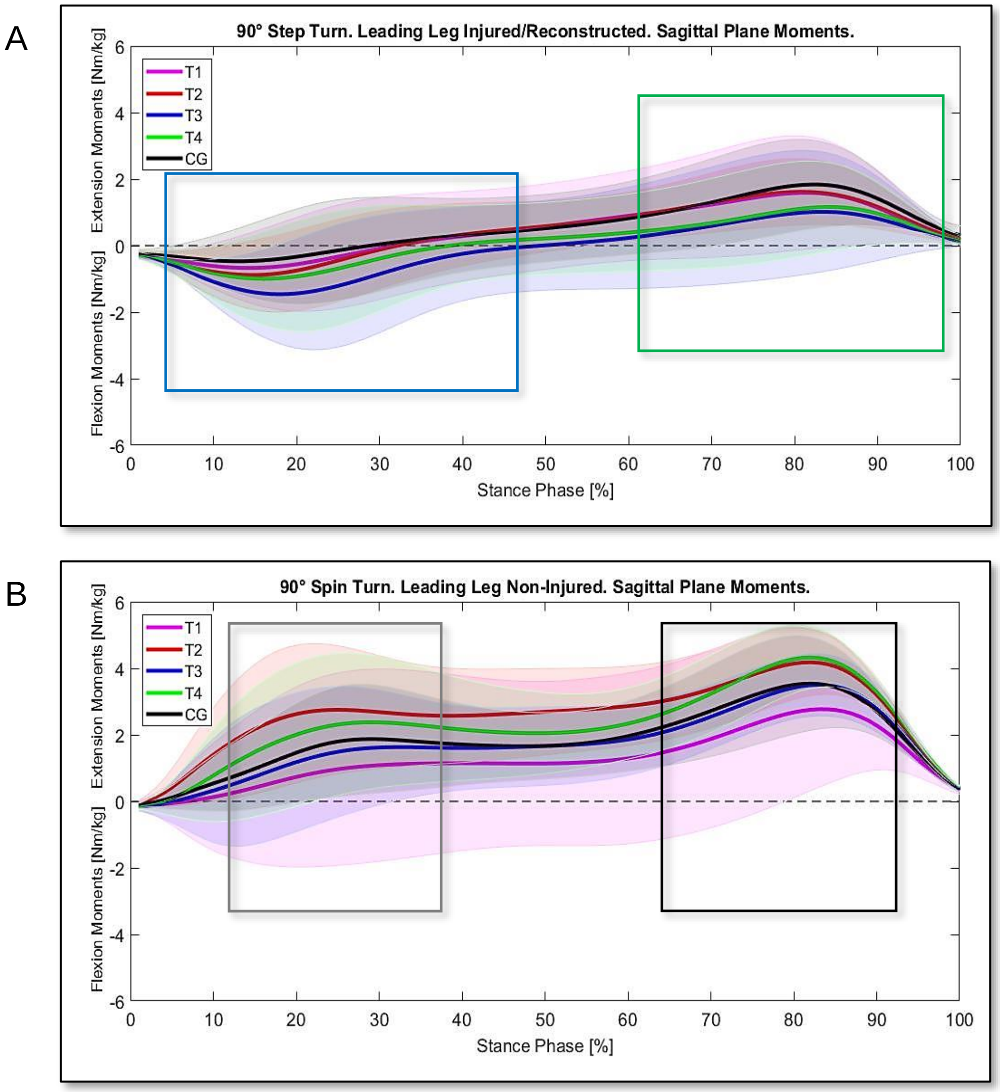

Figure 35. Exemplary Moment-Time Curves with Alternating Knee Flexion Moments in Early Stance and Knee Extension Moments in Terminal Stance (A) and Double-Peaked Pattern Knee Extension Moments (B). *Herein, 90° step turn locomotion performed with the injured/reconstructed legs as leading legs (A) and 90° spin turn locomotion performed with the non-injured legs as leading legs (B) are presented. Mean graphs of the knee moments normalized to bodyweight, of the injured/reconstructed legs of the ACL group at the four test sessions (T1 to T4) and the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.Positive values indicate knee extension moments, negative values indicate knee flexion moments. Shaded areas represent the standard deviations. In the left graph, the blue box illustrates the early stance phase, the green box the terminal stance phase (According to PERRY 2003). In the right graph, the grey box illustrates the first peak in the early stance phase and the black box illustrates the second peak in the terminal stance phase of the double-peaked moment-time curves, appearing in the leading legs of the spin turns.*

Therefore, the analyses of the kinetics in the turning locomotion situations were focused on distinctive features in relation to peak knee flexion moments in the early stance phase as well as peak knee extension moments in the terminal stance phase in all step turn locomotion conditions and in the trailing leg situations of the spin turn strategy (Figure 35A). In the leading legs of the spin turns, the analyses were focused on both appearing peaks of the mean knee extension moment curves during the stance phase (Figure 35B).

Besides the differed characteristics of the moment-time curves of the leading legs, in the spin turns compared to all other tested turning locomotion conditions, higher mean knee extension moments were detected in the leading legs of the spin turns. In the spin turns, mean peak knee extension moments appeared to be in the ACL group in average 1.8 Nm/kg BW (Range = 1.3-2.4 Nm/kg BW) in the early stance phase and 3.2 Nm/kg BW (Range = 2.7-4.3 Nm/kg BW) in the terminal stance phase at T4. This revealed increased mean knee extension moments in average of 29% in the early stance phase and of 129% in the terminal stance phase in the leading legs during the spin turns compared to the peak mean knee extension moments detected in the leading and trailing legs in the step turns or the trailing legs in the spin turns.

To reach the purpose to detect potential functional adaptation strategies in turning locomotion, the kinetic data were clustered according to specific characteristics of functional adaptations and according to kinematic findings previously detected. Generally, the subsequently described tendencies of kinetic adaptations were obtained in the leading and trailing legs in the tested turning locomotion conditions:

- Tendencies of kinetic adaptations in turning locomotion conditions, showing also kinematic adaptations.
- Tendencies of no kinetic adaptations in turning locomotion conditions, showing kinematic adaptations.
- Tendencies of kinetic adaptations in turning locomotion conditions, showing no kinematic adaptations.
- Tendencies of no kinetic adaptations in turning locomotion situations, showing also no kinematic adaptations.

According to the presented overview of the kinetic findings, the results are, subsequently, described in detail. Therein, special focused lied on results, where tendencies of functional kinetic adaptations appeared in the ACL group at six months post-ACL reconstruction (T4) compared to the CG.

Kinetic Adaptations in Turning Locomotion Conditions, Showing also Kinematic Adaptations

Overall, it was found that two thirds of the analyzed turning locomotion conditions, showing kinematic adaptations at all test sessions or in the first three test sessions, additionally, showed tendencies of kinetic adaptations at six months post-ACL reconstruction compared to the CG. These tendencies of kinetic adaptations occurred in both legs and appeared in the following turning locomotion conditions:

- Injured legs, acting as leading legs in the 90° and 180° step turns.
- Injured legs, acting as trailing legs in the 90° step turns and 90° spin turns.
- Non-injured legs, acting as leading legs in the 90° step turns.
- Non-injured legs, acting as trailing legs in the 90° and 180° spin turns.

These listed turning locomotion conditions showed different characteristics of the sagittal knee moments in comparison to the CG. Therefore, the subsequent analysis was separated according to the detected characteristics of kinetic adaptation.

Tendencies of kinetic functional adaptations appeared in increased knee flexion moments in the early stance phase accompanied by reduced knee extension moments in the terminal stance phase in the:

- Injured legs, acting as leading and trailing legs in the 90° step turns (Figure 46; Appendix 10.11).
- Non-injured legs, acting as trailing legs in the 180° spin turns (Figure 47; Appendix 10.11).

Therein, the ACL group subjects showed mean knee flexion moments in the early stance phase, ranging from 0.7 Nm/kg BW (Injured legs as trailing legs in 90° step turns) to 1.8 Nm/kg BW (Non-injured legs as trailing legs in 180° spin turns) at T4. These mean knee flexion moments were increased by 50% (Non-injured legs as trailing legs in 180° spin turns) to 250% (Injured legs as trailing legs in the 90° step turns) compared to the CG. The knee extension moments, acting in the terminal stance phase, ranged in the ACL group between 0.5 Nm/kg BW (Non-injured legs as trailing legs in 180° spin turns) and 1.3 Nm/kg BW (Injured legs as trailing legs in 90° step turns) at T4. These mean knee extension moments were reduced by 33% (Injured legs as leading and trailing legs in the 90° step turns) to 45% (Non-injured legs as trailing legs in the 180° spin turns) compared to the CG. (Table 7; Figures 46 and 47 Appendix 10.11)

Furthermore, tendencies of kinetic adaptations occurred at T4 compared to the CG, in terms of no differences in the knee flexion moment in the early stance, but tendencies of increased knee extension moments in the terminal stance phase. These appeared in the following conditions:

- Injured legs, acting as leading legs in the 180° step turns (Figure 48; Appendix 10.11).
- Injured legs, acting as trailing legs in the 90° spin turns (Figure 49; Appendix 10.11).

- Non-injured legs, acting as leading legs in the 90° step turns (Figure 48; Appendix 10.11).

In these turning locomotion conditions the mean knee flexion moments in the early stance phase were on an equal level in the ACL group at T4 (Mean = 0.5 Nm/kg BW; Range = 0.4-0.6 Nm/kg BW) compared to the CG (Mean = 0.6 Nm/kg BW; Range = 0.4-0.8 Nm/kg BW). The mean knee extension moments in the terminal stance phase ranged from 1.6 Nm/kg BW (Injured legs as leading legs in the 180° step turns) to 2.1 Nm/kg BW (Non-injured legs as leading legs in 90° step turns) in the ACL group at T4. These mean knee extension moments were increased compared to the CG by 33% (Injured legs as leading legs in the 180° step turns) to 54% (Injured legs, acting as trailing legs in the 90° spin turns). (Table 7; Figures 48 and 49, Appendix 10.11).

Lastly, the non-injured legs, acting as trailing legs in the 90° spin turn showed yet another tendency of kinetic adaptations that were accompanied by kinematic adaptations at T4 compared to the CG. Therein, the ACL group subjects showed mean knee flexion moments of 0.7 Nm/kg BW and mean knee extension moments of 1.7 Nm/kg BW. These mean knee flexion moments in the early stance phase appeared to be increased compared to the CG by 250%. In the knee extension moments in the terminal stance phase, however, tendencies of no differences occurred in the ACL group at T4 compared to the CG. (Table 7; Figure 50, Appendix 10.11)

No Kinetic Adaptations in Turning Locomotion Conditions, Showing Kinematic Adaptations

There also occurred turning locomotion conditions, where no form of kinetic adaptations were found in the sagittal plane, although kinematic adaptations were found in these respective turning locomotion conditions. These phenomena occurred in the:

- Injured legs, acting as leading legs in the 90° spin turns (Figure 52; Appendix 10.12).
- Injured legs, acting as trailing legs in the 180° step turns (Figure: 51, Appendix 10.12) and the 180° spin turns (Figure 52, Appendix 10.12).
- Non-injured legs, acting as trailing legs in the 90° step turns (Figure 51; Appendix 10.12).

Therein, mean knee flexion moments of the early stance phase appeared to be 1.5 Nm/kg BW in the ACL group at T4 and 1.6 Nm/kg BW in the CG. In the ACL group the mean knee flexion moments ranged between 0.9 Nm/kg BW (Non-injured legs as trailing legs in 90° step turns) and 1.8 Nm/kg BW (Injured legs as leading legs in the 90° spin turns). The mean knee extension moments in the terminal stance phase reached 1.8 Nm/kg BW in the ACL group at T4 and as well in the CG. The mean knee extension moments ranged between 0.7 Nm/kg BW (Injured legs as trailing legs in 180° step turns) and 3.2 Nm/kg BW (Injured legs as leading legs in the 90° spin turns) in the ACL group at T4. (Table 7; Figures 51 and 52, Appendix 10.12)

Tendencies of Kinetic Adaptations in Turning Locomotion Conditions, Showing no Kinematic Adaptations

Tendencies of kinetic adaptations were found in turning locomotion conditions, wherein the kinematic analyses revealed no tendencies of adaptations. These phenomena occurred solely in the leading legs in two spin turning conditions:

- Injured legs, acting as leading legs in the 90° spin turns (Figure 53, Appendix 10.13).
- Non-injured legs, acting as leading legs in the 180° spin turns (Figure 53, Appendix 10.13).

In one condition (Non-injured legs as leading legs in the 90° spin turns) both peaks of the mean extension moments (Peak 1 = 2.4 Nm/kg BW; Peak 2 = 4.3 Nm/kg BW) were increased in the ACL group at T4 compared to the CG (Peak 1 = 1.9 Nm/kg BW; Peak 2 = 3.5 Nm/kg BW). In the other turning locomotion condition (Injured legs as leading legs in the 180° spin turns), both peaks of the mean knee extension moment curves (Peak 1 = 1.7 Nm/kg BW, Peak 2 = 2.7 Nm/kg BW) were reduced in the ACL group at T4 compared to the CG (Peak 1 = 3.0 Nm/kg BW; Peak 2 = 3.7 Nm/kg BW). (Table 7; Figure 53, Appendix 10.13).

Tendencies of no Kinetic Adaptations in Turning Locomotion Conditions, Showing also no Kinematic Adaptations

The last group of turning locomotion conditions is gathered under the finding that, besides the analyses of the kinematics revealed no tendencies of adaptations, the analyses of the kinetics also revealed no tendencies of adaptations in the ACL group at T4 compared to the CG. These findings appeared solely in the non-injured legs, when:

- Acting as leading legs in the 180° step turns (Figure 54, Appendix 10.14) and the 180° spin turns (Figure 55 Appendix 10.14).
- Acting as trailing legs in the 180° step turns (Figure 54 Appendix 10.14).

In detail, in both step turn locomotion conditions, mean knee flexion moments in the early stance phase reached 0.8 Nm/kg BW in the ACL group at T4. The same mean knee flexion moments were detected in the CG in the early stance phase. The mean knee extension moments in the terminal stance phase reached 1.9 Nm/kg BW in the leading legs and 1.2 Nm/kg BW in the trailing legs of the 180° step turns. Accordingly, the CG showed mean knee extension moments on a similar level (leading legs: 1.7 Nm/kg BW; trailing legs: 1.4 Nm/kg BW). In the 180° spin turn locomotion conditions, both peaks of the mean knee extension moments curves were on an equal level between the ACL group at T4 and the CG. The first peak appeared to be 1.3 Nm/kg BW in the ACL group as in the CG. The second peak reached 2.7

Nm/kg BW in the ACL group and 2.9 Nm/kg BW in the CG. (Table 7; Figures 54 and 55, Appendix 10.14).

Table 7. Results of the Mean Knee Flexion Moments (M_{KF}) and the Mean Knee Extension Moments (M_{KE}) in the Analyzed Turning Locomotion Conditions in the ACL Group and the Control Group.

	Turning Condition	Moments	T1	T2	T3	T4	CG
90° Step Turn	LL injured/reconstructed	M_{KF}	0.7 (1.0)	0.9 (1.1)	1.5 (1.5)	1.0 (1.4)	0.5 (1.0)
		M_{KE}	1.6 (1.7)	1.6 (1.0)	1.0 (1.8)	1.2 (1.3)	1.8 (1.3)
	LL non-injured	M_{KF}	0.7 (1.0)	0.8 (0.8)	0.5 (0.6)	0.6 (0.9)	0.4 (1.1)
		M_{KE}	1.5 (1.2)	1.6 (0.6)	1.6 (1.4)	2.1 (1.1)	1.5 (1.5)
	TL injured/reconstructed	M_{KF}	0.5 (0.7)	0.4 (0.5)	0.5 (1.0)	0.7 (1.1)	0.2 (0.1)
		M_{KE}	1.8 (1.4)	2.1 (1.8)	1.6 (1.2)	1.3 (1.2)	1.9 (1.3)
	TL non-injured	M_{KF}	0.2 (0.9)	1.0 (1.0)	0.6 (0.6)	0.9 (0.8)	0.8 (0.9)
		M_{KE}	1.6 (1.2)	1.5 (1.4)	1.8 (0.8)	1.4 (0.9)	1.2 (1.0)
90° Spin Turn	LL injured/reconstructed	M_{KE1}		2.5 (2.3)	2.3 (2.3)	1.7 (2.1)	1.9 (2.6)
		M_{KE2}	2.6 (0.3)	3.8 (1.6)	3.5 (1.4)	3.2 (1.1)	3.4 (2.2)
	LL non-injured	M_{KE1}	1.2 (2.6)	2.8 (1.9)	1.6 (1.6)	2.4 (2.0)	1.9 (1.6)
		M_{KE2}	2.8 (2.4)	4.2 (1.0)	3.5 (0.9)	4.3 (0.9)	3.5 (1.4)
	TL injured/reconstructed	M_{KF}	0.9 (0.6)	0.5 (0.7)	0.7 (0.5)	0.4 (0.4)	0.7 (0.7)
		M_{KE}	1.0 (1.0)	2.4 (2.1)	1.3 (0.3)	1.9 (0.9)	1.3 (1.0)
	TL non-injured	M_{KF}	1.0 (0.5)	0.5 (0.4)	0.8 (0.6)	0.7 (0.7)	0.2 (0.4)
		M_{KE}	1.1 (0.6)	2.1 (0.6)	1.7 (0.7)	1.6 (0.6)	1.9 (1.8)
180° Step Turn	LL injured/reconstructed	M_{KF}	0.9 (0.9)	1.6 (1.3)	0.5 (0.5)	0.6 (0.7)	0.8 (1.1)
		M_{KE}	1.2 (0.8)	1.7 (1.8)	1.7 (1.2)	1.6 (0.7)	1.2 (0.8)
	LL non-injured	M_{KF}	0.5 (0.7)	0.3 (0.7)	0.4 (0.4)	0.3 (0.3)	0.2 (0.5)
		M_{KE}	1.1 (0.9)	1.5 (0.5)	1.9 (0.7)	1.9 (0.9)	1.7 (1.1)
	TL injured/reconstructed	M_{KF}	1.5 (1.8)	0.8 (1.0)	0.7 (0.9)	0.5 (0.7)	0.9 (1.0)
		M_{KE}	0.8 (1.4)	0.6 (1.0)	1.4 (1.0)	1.3 (1.2)	1.3 (0.9)
	TL non-injured	M_{KF}	1.5 (1.4)	1.9 (1.7)	0.9 (1.0)	1.2 (0.9)	1.4 (1.5)
		M_{KE}	0.8 (0.9)	0.5 (0.8)	1.0 (0.7)	0.7 (0.5)	0.8 (1.1)
180° Spin Turn	LL injured/reconstructed	M_{KE1}	3.1 (2.1)	1.8 (2.0)	2.0 (2.5)	1.7 (1.4)	3.0 (1.8)
		M_{KE2}	4.1 (1.2)	3.1 (1.4)	3.0 (1.6)	2.7 (1.1)	3.7 (2.0)
	LL non-injured	M_{KE1}		1.7 (2.2)	1.7 (2.5)	1.2 (2.4)	1.3 (2.2)
		M_{KE2}	1.0 (1.4)	3.1 (1.7)	3.0 (2.1)	2.7 (1.9)	2.9 (2.2)
	TL injured/reconstructed	M_{KF}	3.2 (1.1)	1.7 (0.9)	1.7 (1.1)	2.2 (1.6)	2.2 (1.9)
	TL non-injured	M_{KF}	0.9 (0.6)	1.8 (0.7)	1.8 (1.0)	1.8 (0.7)	1.2 (0.9)
		M_{KE}	1.1 (1.3)	0.3 (0.7)	0.3 (0.7)	0.5 (0.8)	0.9 (0.8)

In the first column the analyzed turning locomotion condition is shown (LL = Leading leg; TL = Trailing leg). The second column presents the respective moments that acted throughout the stance phases (M_{KF} = Knee flexion moment; M_{KE} = Knee extension moment) in Newtons per bodyweight [N/kg BW] If solely knee extension moments with a double-peaked pattern acted over the stance phase, the first peak knee extension moment is indicated by M_{KE1} and the second peak mean extension moment by M_{KE2}. The third (T1) to sixth column (T4) represents the mean peak flexion angles at ES or LMS of the ACL group at all test sessions. The latter column (CG) contains the mean peak knee flexion angles in ES and LMS of the Control Group. All values represent means in degrees [°]. Rows marked in red indicate the turning locomotion conditions with tendencies of kinetic adaptations in the ACL group at T4 compared to the CG, where also kinematic adaptations were found. Rows marked in orange indicate turning locomotion conditions with tendencies of kinetic adaptations in the ACL group at T4 compared to the CG, where no tendencies of kinematic adaptations were found. Rows marked yellow indicate turning locomotion conditions with no tendencies of kinetic adaptations in the ACL group at T4 compared to the CG, although tendencies of kinematic adaptations were found. Rows marked in green indicate the turning locomotion conditions with no tendencies of kinetic adaptations in the ACL group at T4 compared to the CG, where also no kinematic adaptations were detected.

7.5 Discussion

The purpose of this study was to analyze potential functional adaptations in 90° and 180° turns in ACL reconstructed subjects from pre- up to six months post-ACL reconstruction and in comparison to a healthy CG. In order to determine functional adaptations during turning steps, general turning locomotion strategy, as well as sagittal plane kinematic and kinetic parameters were analyzed.

In particular, it was examined, if the ACL tears and reconstructions generally affected the selection of the locomotion strategy (step or spin turn). Furthermore, if the knee flexion angles, the internal knee flexion moments and the internal knee extension moments showed tendencies of functional adaptations during the stance phase.

Special focus was placed on the sagittal plane, due to previously described functional plane in ACL teared and reconstructed subjects in straight locomotion tasks (BERCHUCK et al. 1990; DEVITA et al. 1997; HOOPER et al. 2002; TIMONEY et al. 1993; WEXLER et al. 1998). These adaptations purposed to reduce loads to the reconstructed knee joints and were described beneficial short-term after the reconstruction (GARDINIER et al. 2012). However, mid- and long-term manifestations of unequal load situations could contribute to imbalances in the legs, which prospectively can result in an accelerated onset and progress of musculoskeletal disorders and chronic degenerative joint diseases (ALTMAN et al. 1986; HURWITZ et al. 2000; SHARMA et al. 1998). This originates due to overloading of one leg and, thus, the inevitably load reduction of the contralateral leg.

General Locomotion Strategy

The analyses of the general locomotion strategies showed that the 90° and the 180° turns were performed more frequently with the step turn strategy than with the spin turn strategy in the ACL group at the test sessions and as well in the CG.

Therefore, it appeared that the general locomotion was not strongly affected by the ACL tears and reconstructions. This was suggested, because a preference of the step turn strategy seems rather normal. As HASE & STEIN (1999) described that healthy subjects generally perform turns more often with a step turn strategy than with a spin turn strategy. General preference of the step turn strategy was assumed to originate in its easier performance and more stable realization (HASE & STEIN 1999). The easier and more stable characteristics of the step turn strategy is provided by a wider base of support, while changing the movement direction, compared to the spin turn strategy (HASE & STEIN 1999). Therewith, control of the COM is maintained easier during step turns (HASE & STEIN 1999), which was suggested as one major reason to prefer the step turn strategy over the spin turn strategy in the ACL group before and after reconstruction. Recovery of normal turning locomotion was also strengthened by the turning gait velocities and the mean ground contact times of the turning steps. Therein, the velocities and ground contact times tended to be increased at T2, however, decreased up to T3 and T4 onto the level of the CG.

Conspicuously, the ACL group acted in the 90° and 180° turns, in the step as in the spin turn strategy, more often with the injured/reconstructed legs as leading legs in all but one test session. This was an unexpected finding, as it was described that in the leading legs higher demands are required during turning locomotion compared to the trailing legs (HASE & STEIN 1999). Only in the 180° spin turns, the ACL group performed the turns more often with the non-injured legs as leading legs at the test session short-term after the reconstructions (T2). However, this characteristic diminished up to three (T3) and six (T4) months after ACL reconstruction, where the ACL group again acted more often with the injured/reconstructed legs as leading legs.

However, the reduction to perform the 180° spin turns with the reconstructed legs as leading legs in the 180° spin turns at about seven weeks after reconstruction (T2) was suggested beneficial to reduce demands to the recently reconstructed ACL. This was assumed, because in the spin turn strategy demands to the leading legs are higher compared to the step turn strategy (HASE & STEIN 1999). These higher demands are defined by the fact that in the spin turn strategy the body spins on the leading legs, while simultaneously producing breaking forces (HASE & STEIN 1999). Furthermore, the orientation into the new direction of the turn is mainly conducted by an axial rotation of the leading legs (HASE & STEIN 1999). Due to these higher demands to the leading legs, it was suggested beneficial to perform 180° spin turns more frequently with the non-injured legs as leading legs short- and mid-term after the reconstruction, instead of exposing the reconstructed legs to unbeneficial high demands. In contrast, the injured/reconstructed legs were used again more frequently as leading legs in the 180° spin turns at three and six months after reconstruction. Therefore, although higher demands are required of the leading legs (HASE & STEIN 1999), it did not seem to pose a general hindrance to use the injured/reconstructed legs as leading legs. Consequently, this could put the injured/reconstructed legs at higher risks to get overloaded in turning locomotion. However, activities of daily living, such as turning, do not to provoke loads comparable to high-intensity movements, as jumping. Therefore, it was suggested that the use of the injured/reconstructed legs as leading legs might not lead to any kind of unbeneficial symptoms that could induce a general prevention to perform 180° spin turns with the injured/reconstructed legs as leading legs. Nonetheless, the high repetition of daily locomotion tasks could accumulate slight overloading in single steps to high overloading at the end of the day.

In conclusion, although the injured/reconstructed legs were used as leading legs and the ACL group subjects generally returned to a normal turning locomotion, it was assumed that the ACL reconstructed subjects have not fully recovered their turning locomotion up to six months post reconstruction. Therefore, analyses of the kinematics and kinetics were essential for deeper analyses of potential functional adaptations during turning locomotion.

Tendencies of Kinematic Adaptations

The analyses of the sagittal kinematics revealed tendencies of kinematic adaptations in increased knee flexions in the early stance phase up to 50% of the stance phase or even over the entire stance phase. These appeared in half of all analyzed turning locomotion conditions and at all test sessions. These findings occurred in the injured/reconstructed and the non-injured legs and almost exclusively in the 90° step and spin turn conditions. Such generally increased knee flexions led to low knee flexion excursions in the sagittal plane over the whole stance phase. In three further conditions, deeper flexed knee joints appeared from T1 to T3 but recovered up to T4 onto the level of the CG.

Such deep flexed knee joints throughout the stance phase were described to be caused by heavy intra-articular knee joint effusions, joint-tissue derangements, or muscle inhibitions due to pain, induced by the tear and the reconstruction (DEVITA et al. 1997; GARDINIER et al. 2012; KNOLL et al. 2004a; TORRY et al. 2000). Consequently, these symptoms can lead to increased hamstring activity and decreased quadriceps activity, which induces generally more flexed knee joint positions (CHILDS et al. 2004; KNOLL et al. 2004a; TORRY et al. 2000). In line, increased knee flexion in the early stance was also described as potential adaptation strategy due to adaptations in the step prior to the turning step. This step is described as a complex and demanding situation, as meanwhile demands are required, which are similar to those of stopping movements (HASE & STEIN 1999; LYON & DAY 1997). Such demands require high stability of the knee joint, what, consequently is maintained by increased knee joint flexion. Furthermore, such bended knee positions during gait were also described in patients with knee OA (CHILDS et al. 2004). Consequently, these strategies seem to reduce stresses and loads to the reconstructed ACL and alongside seem to increase stability to the reconstructed knee joints by preventing pivoting movements in the knee joint with these stabilization strategies (BERCHUCK et al. 1990; KNOLL et al. 2004a; WEXLER et al. 1999).

Due to the beneficial function of these adaptations to reduce loads and increase stability to the knee joints, this adaptation strategy seems indicated in ACL injured and reconstructed subjects, especially short-term after the tear or the reconstruction. However, as these tendencies of kinematic adaptations only recovered in three conditions to the level of the healthy CG at six months after reconstruction, it was suggested that such kinematic adaptations bear the risk to manifest. As increased knee flexions also emerged in gait adaptations of individuals with knee osteoarthritis (CHILDS et al. 2004), it may be of crucial interest to prevent manifestations of these adaptation strategies. This is underlined by the fact that it was assumed that such functional kinematic adaptation strategies in straight locomotion tasks should recover up to six months after reconstruction (DEVITA et al. 1997; KNOLL et al. 2004b).

In contrast, the kinematic analyses of the 180° step and spin turns revealed in all but one condition no kinematic differences in the ACL group at T4 compared to the CG. Resulting into the same general characteristics of the knee flexion courses and the same peak mean knee flexion angles in the early stance and the late-mid stance phase between the ACL group and the CG. This was an oppositional finding compared to the increased knee flexions detected in the 90° turns.

However, concordant to the analyses of the general locomotion strategy, it was concluded that, although some results could lead to the interpretation of full knee joint recovery, some other results showed still kinematic adaptations at six months after ACL reconstruction. This was an indication for a very task-specific and individual recovery of knee joint functionality after ACL reconstructions, because subjects showed, for instance, a recovered general locomotion strategy, but beyond functional adaptations in the knee joint kinematics.

Tendencies of Kinetic Adaptations

Besides tendencies of functional kinematic adaptations, there occurred also tendencies of kinetic adaptations. These appeared in terms of differed knee flexion and knee extension moments in the ACL group compared to the CG in both legs in the step turns and in the trailing legs of the spin turns. In the leading legs of the spin turns, a generally differed characteristic of the knee moments emerged, with exclusively acting knee extension moments over the whole stance phase. Therein, as well tendencies of kinetic adaptations occurred, alongside with generally higher detected peaks in the moment-time characteristics. Mean peak knee extension moments in the leading legs during the spin turns appeared to be increased up to 130%. As internal knee extension moments produce high stress to the implanted autograft (BERCHUCK et al. 1990; GARDINIER et al. 2012; ZABALA et al. 2013), the detected increase of the knee extension moments during spin turns could produce high stress to the implanted graft. Therefore, it was assumed unbenenficial to perform the spin turns with the injured/reconstructed legs as leading legs short- and mid-term after ACL reconstruction. However, as these knee extension moments lead to high tension in the thigh’s musculature, they could contribute to increase the knee joint stability to withstand the occurring loads to the leading legs, especially the axial rotational loads, in the 180° turns (HASE & STEIN 1999). In contrast, by stiffening the knee joint the rotational movement as the rotational loads are mainly transferred to and accepted by the adjacent joints, especially the hip joint (OBERLÄNDER et al. 2012). Consequently, this bears the risk to overload the hip joints (DEVITA et al. 1992). As the characteristics of the mean knee extension moments appeared in the contralateral non-injured legs as well as in the CG, it was assumed that these findings are no functional kinetic adaptation of the ACL reconstructed subjects, it rather seems to be a task-specificity of the sagittal kinetics in the leading legs during the performance of spin turns.

Furthermore, specific kinetic adaptations of the trailing legs can occur due to the fact that in turning locomotion, movement velocity is slowed down in the turning steps performed by the leading legs (HASE & STEIN 1999). In the subsequent trailing steps, the velocity is increased again, which requires segmental accelerations in the lower limbs (HASE & STEIN 1999). These accelerations require inevitably high demands of the trailing legs. Such high acceleration demands tend to provoke higher loads to the knee joint. Therefore, the subjects seemed to reduce stress to the reconstructed ACL by a deeper flexed knee joint position throughout the stance phase to withstand the higher loads by a concomitant activation of the quadriceps and hamstrings musculature (GARDINIER et al. 2012; TORRY et al. 2000).

Generally, the kinetic adaptations were categorized, according to previously detected tendencies of kinematic adaptations. Therefore, tendencies of kinetic adaptations were detected in turning locomotion conditions, wherein also tendencies of kinematic adaptations were detected. Furthermore, tendencies of kinematic adaptations occurred in turning locomotion conditions, wherein no tendencies of kinematic adaptations occurred. Additionally, in some turning locomotion conditions no tendencies of kinetic adaptations occurred, although tendencies of kinematic adaptations were detected previously and, finally, turning locomotion conditions were found, wherein neither tendencies of kinetic adaptations nor tendencies of kinematic adaptations were found.

In the largest part (nearly 50%) of all analyzed turning locomotion conditions, tendencies of kinetic adaptations were detected at six months post-reconstruction, wherein also tendencies of kinematic adaptations were found. These tendencies of kinetic adaptations appeared in comparison to the CG, in increased knee flexion moments in the early stance accompanied by reduced knee extension moments in the terminal stance, in equal knee flexion moments in the early stance accompanied by increased knee extension moments in the terminal stance, and in increased knee flexion moments in the early stance accompanied by equal knee extension moments in the terminal stance.

The reductions of the knee extension moments support the suggestion of persistent reductions of quadriceps activations after ACL reconstruction to reduce loads to the implanted autograft and increase knee joint stability, as it was described in straight locomotion tasks (BERCHUCK et al. 1990; GARDINIER et al. 2012; WEXLER et al. 1998).

Although, in most turning locomotion conditions combined functional kinetic and kinematic adaptations were found in the ACL group at T4 compared to the CG, it additionally appeared that functional kinetic adaptations can also occur with the absence of kinematic adaptations and vice versa. Furthermore, there appeared some turning locomotion conditions, wherein neither kinetic nor kinematic adaptations occurred in the ACL group at T4 compared to the CG. Alongside, tendencies of notable prolongations of the knee flexion moment phases and shortening of the knee extension moment phases were found at three and six months after reconstruction compared to the CG. Because a concomitant activity of the quadriceps and hamstrings musculature provides higher stability to the knee joint (GARDINIER et al. 2012; TORRY et al. 2000), the prolongation of acting knee flexion moments seem to be an additional adaptation strategy, aiming to increase the duration of knee flexion moments and therewith to shorten the duration of knee extension moments in the stance phase, resulting in load reductions to the reconstructed ACL. However, this bears the risk to overload adjacent joints, as the hip or ankle joints of the ipsilateral leg or the joints of the contralateral leg (OBERLÄNDER et al. 2012).

Additionally, a general transformation of the locomotion process by changing the direction of the ground reaction force vectors could lead to higher risks of prospective injuries or deficiencies of the injured and non-injured legs (OBERLÄNDER et al. 2012).

These kinetic findings underlined the complexity and variety of functional knee joint recovery in ACL reconstructed subjects, which ranged between clear tendencies of kinetic and kinematic adaptations and the full absence of any tendencies of kinetic and kinematic adaptations. This strengthens the conclusion of a highly task-specific and individually-centered recovery of knee joint functionality in ACL reconstructed subjects. Such heterogeneous functional adaptations after ACL tears were also described by GARDINIER et al. (2012). Therefore, it was assumed that the functional outcome might be highly associated by potential concomitant injuries, and/or an inadequate morphologic and functional recovery in the rehabilitation process. Therefore, adaptation of rehabilitation programs, according to individual functional deficiencies and task-specific deficiencies should be implemented in ACL rehabilitation.

Conclusions and Practical Implications

Depending on the descriptive analyses of the data of this study, it can be stated that ACL reconstructed subjects showed tendencies of functional kinematic and kinetic adaptations in the reconstructed leg even at three and at six months after the ACL reconstruction. Although, it was found that functional adaptations can show large individual variances, it was assumed that the general purpose of the detected functional kinematic and kinetic adaptations aimed to reduce loads to the injured and reconstructed knee joints in the performance of turns, similar as it was detected in straight locomotion tasks (BERCHUCK et al. 1990; GARDINIER et al. 2012; WEXLER et al. 1998).

It appeared that these adaptations occurred in both, 90° and 180° turns, performed with the step and the spin turn strategy. However, the findings of this study revealed that the spin turn strategy in general seemed to be more disadvantageous and unbeneficial for ACL injured and reconstructed knee joints. This is due to the high internal knee extension moments detected in the leading legs in this turning strategy. Therefore, the practical implication of these results is to sensitize the ACL reconstructed subjects in avoiding the spin turn strategy and to encourage and train them to perform turns by applying the step turn strategy at least up to six months after ACL reconstruction.

Furthermore, it was found that functional adaptations, in terms of increased knee flexions over the stance phase, also occurred in patients with knee osteoarthritis (CHILDS et al. 2004). Hence, the reduction of functional adaptations in ADLs is indicated to reduce onset and process of degenerative joint diseases, which are caused by an imbalanced or unfunctional loading of the knee joints during the movements (ANDRIACCHI & MÜNDERMANN 2006). The kinetic data of this study support these findings, as certain imbalanced loadings of the injured/reconstructed and non-injured knee joints have been detected in various characteristics in this study.

It was assumed that these functional adaptations have certain grades of specificity. In particular, the injured/reconstructed legs showed wide ranged standard deviations occurred for most of the kinematic and kinetic variables. In contrast, in the non-injured legs, reduced standard deviations appeared in the 90° and 180° turns compared to the injured/reconstructed legs.

In association, as the general rehabilitation programs after ACL reconstructions are focused on maximizing neuromuscular and strength recovery aiming for a most likely return to pre-injury sports (WHITING & ZERNICKE 2008), the findings of this study additionally imply that exercises, specifically aiming to reduce imbalances in locomotion strategies of ADLs should also find inclusion in generally applied post-surgical rehabilitation programs.

Limitations

In this study, the ACL injured and reconstructed subjects could freely choose the respective locomotion strategy to perform the turns at each test session. Consequently, this led to a varying amount of subjects performed the same locomotion strategy at each test session, with only a little amount of subjects performing all turns with the same locomotion strategy over all four test sessions. The varying amount of subjects within a specific group, performing the same turn with the same turning strategy at a test session, led to limited generalization of the data. Due to this, additionally, no inferential statistics could be calculated, which reduced the level of statistical interpretation of the analyzed data. Therefore, in future studies more standardized study protocols should be conducted.

Nonetheless, by the results and findings of this study, general and specific descriptions of potential functional adaptations due to ACL tears and subsequent ACL reconstructions, in non-straight locomotion tasks of daily life, here specifically of daily occurring turns, were described for the first time. This study, especially, the embedded methodological approach, as well as, the results and deduced findings, can provide the basis further investigations in the field of daily living activities.

8 General Discussion, Summary, and Conclusions

Due to the conducted research in the field of ACL reconstructions and rehabilitation, ACLs can get reconstructed successfully with high odds and a good rehabilitative outcome (IRELAND 2002). The level and progress of recovery, however, depends on a variety of concomitant circumstances, as potential concomitant injuries of other biological structures of the knee joint (BIEN & DUBUQUE 2015). Moreover, wide-spread individual functional adaptations and imbalances were detected in motions even long time after the injury (BIEN & DUBUQUE 2015; KOSTOGIANNIS et al. 2007; LOHMANDER et al. 2004). Manifested functional imbalances represent a crucial fact to accelerate the onset and progression of chronic degenerative diseases at the involved joint after an ACL tear (BIEN & DUBUQUE 2015; CASTANHARO et al. 2011; DE FONTENEY et al. 2014; DECKER et al. 2002; ERNST AL. 2000; ORISHIMO et al. 2010; PATERNO et al. 2007). In some cases people even had to generally reduce their activity level or suffered from a strong quality of life reduction after sustaining an ACL tear and a subsequent surgical reconstruction (KVIST et al. 2005; TE WIERKE et al. 2013). Others suffered from secondary ruptures of the ACL, injuries of the sound contralateral leg, or severe concomitant injuries (BIEN & DUBUQUE 2015; PATERNO et al. 2010; PINCZEWSKI et al. 2007; SALMON et al. 2005; WRIGHT et al. 2007). These concomitant circumstances and developments can highly influence the framework of adequate or inadequate functional knee joint rehabilitation. Consequently, a complete return to pre-injury sports is generally not achieved and the injury can lead to a decremental reduction of sports activities, recreational activities and the overall quality of life.

Therefore, as the present thesis purposed, it is indicated to determine and examine functionality at various time points after ACL tear and reconstruction in the best possible comprehensive way. This approach aims to detect functional deficiencies or adaptations more individual and to deduce more adequate individual-based rehabilitation programs in relation to the subjects' individual deficits. This more individualized rehabilitation programs of ACL reconstructed individuals aim to reach a better individual functional outcome (BIEN & DUBUQUE 2015; FITZGERALD et al. 2000; GARDINIER et al. 2012; GUSTAVSSON et al. 2006; HEWETT et al. 2005; MANDELBAUM et al. 2005).

A comprehensive determination of functional adaptations and deficits is enabled by comprehensive test batteries, which are applied at various time points. As different movements require a variety of demands to the locomotion system, it may not be sufficiently to determine functionality or, especially, return-to-sports criteria by one specific test (i.e. One leg jumps) or a specific movement class (i.e. different types of jumps, strength tests) at one specific time point after the ACL reconstruction (BIEN & DUBUQUE 2015; NARDUCCI et al. 2011).

Hence, the present thesis purposed to add and provide important knowledge in terms of functional adaptations during the post-surgical half-year rehabilitation phase by a comprehensive test battery, which combined (1) the determination of subjects' self-administered evaluation of functionality, (2) the determination of functionality in functional clinical tests, (3) the determination of functionality in dynamic high-demanding tasks, and (4) the determination of functionality in activities and movements of daily life. To reach this purpose, results and findings of self-administered questionnaires and scores, specifically the Knee Injury and Osteoarthritis Outcomes Score (KOOS) and the Tegner Activity Score (TAS), two functional clinical tests (Knee ROM, Leg circumference), various functional performance tests (Counter movement jumps (CMJ), One leg jumps for distance (OLJ), isometric force tests), and the analyses of two daily, occurring turns (90° and 180° turns) were included in this thesis. The test-specific developments over the rehabilitation cycle up to six months after ACL reconstruction are subsequently discussed, starting with the functional clinical tests, followed by the functional performance tests (FPTs), the activities of daily living (ADLs), and finalized by the injury related self-concept of the subjects.

8.1 Deficits in Functional Clinical Tests

Functional clinical tests are applied to assess the functionality of a joint by passive physical examination of a joint or a structure's function (HIRSCHMANN & MÜLLER 2015). Therefore, in this thesis, leg circumference measurements were conducted according to SØDERBERG et al. (1996) to generally measure potential atrophies of the thigh's musculature. Furthermore, examination of passive ROM measurements of knee flexion and knee extension were conducted according to JANDA (2002) to assess potential impairments and limitations of the joint capsule.

Passive knee joint ROM measurements are established in screening procedures of clinicians and therapists to determine knee joint functionality and before individuals can get released in pre-injury sports and activities (PETERSEN & ZANTOP 2013). In terms of knee joint functionality it was described that a recovery of the knee joint's ROM is decisive for full recovery of the knee joint functionality in all dynamic movements (HEWETT et al. 2005; MAYR et al. 2004; WALDÉN et al. 2011). Furthermore, recovery of full knee joint ROM is essential for the prevention of early onset of degenerative joint diseases (MAYR et al. 2004). Thus, it is indicated to include ROM measurements in a comprehensive functional testing after ACL tears and reconstructions.

The passive ROM measurements in the study of this thesis revealed ROM flexion deficits on a higher level than during passive knee extension situation. Moreover, the LSIs of knee flexion did not recover on the level of the CG up to six months after ACL reconstruction. Impaired knee joint ROMs were described recently in ACL reconstructed individuals short- and mid-term after the reconstruction (BIAU et al. 2006; HARNER et al. 1992; GOKELER et al. 2009; LI et al. 2011; ORISHIMO et al. 2010).

The detected more pronounced deficit of the knee flexion ROM could be explained by an impaired function of the knee flexion musculature due to the removal of the semitendinosus and gracilis tendon graft at the harvest site (MOHTADI et al. 2011). As these tendons add valuable work in the knee flexion force generation, removal of these tendon parts seem to lead to pronounced flexion deficits (BIAU et al. 2006). Nonetheless, despite no differences occurred in post-operative knee joint stability after reconstructing the torn ACL with a hamstring tendon (HT) or a bone patellar-tendon bone (BPTB) autograft, reconstructions with a HT autograft seemed to result in fewer post-surgical symptoms, especially in a reduction of knee pain (BIAU et al. 2006). However, knee joint ROM deficits were described in general as one predetermination for reduced functions of thigh's flexion musculature and were also described as prerequisite for limitations of the knee joint during dynamic movements (HURLEY 1997). As it was also found that the knee extension ROM was impaired, this led to the assumption that the knee joint capsule was still deficient at six months after ACL reconstruction.

In conclusion, due to the ACL tear and the subsequent reconstruction the joint capsule was impaired in its function. This could be caused by knee joint swelling, joint tissue derangement, or muscle inhibition due to pain, which all together reduced the ROM of the knee joint (BIAU et al. 2006; HURLEY 1997; KNOLL et al. 2004a; MAYR et al. 2004). Thus, in relation to the data of the underlying study, it was concluded that the knee joints were not fully recovered in their passive motion function compared to the CG at six months post-reconstruction. Therefore, this reduced knee joint function might predetermine deficiencies in dynamic movements or movement components, due to the knee joints function in maintaining and transmitting loads in low- and high-intensity locomotion tasks (HURLEY 1997).

Alongside, the atrophy of the thighs' muscular bulks underlined that the femoral musculature showed in general an incomplete morphologic recovery at six months post-reconstruction. This thigh atrophy was described already and can be explained by the traumatic rupture, the subsequent neuromuscular changes in the injured leg, and the impaired knee joint capsule (HURLEY 1997; KNOLL et al. 2004a; MAYR et al. 2004; MCHUGH et al. 2002; THOMAS et al. 2016; LORENTZON et al. 1989). Therefore, out of the conducted functional clinical tests it was concluded that well morphologic prerequisites are essential for a symptom-free and safe return in pre-injury activities on a recreational or competitive level. Hence, from the viewpoint of the functional clinical tests, the ACL group of this study did not reach the functional clinical level of the CG at six months after ACL reconstruction. This incomplete recovery on a morphologic level, can inevitably lead to incomplete general functional recovery and as well result in higher predispositions of prospective impairments and chronic degenerative changes at the injured and reconstructed knee joint.

8.2 Reduced Functionality in Functional Performance Tests

Overall applied tests to determine functionality in specific FPTs a general tendency was found, which was characterized as follows: The leg symmetry level dropped in all FPTs from the pre-reconstruction test session to the test session at seven weeks after the ACL reconstruction under the level of the pre-reconstruction state. Afterwards, an increase of the leg symmetry was found in all applied functional tests. Nonetheless, the established leg symmetry level of 85% to 90%, which was considered relevant to declare full knee joint recovery and for a safe return in pre-injury sports on pre-injury level, especially in jumping tasks (BARBER et al. 1990; JURIS et al. 1997; GUSTAVSSON et al. 2006; ÖSTENBERG et al. 1998; RISBERG et al. 1995), was hardly reached in means of any analyzed parameter. The respective results of each applied FPT are subsequently discussed separately.

Reconstructed Leg Deficiencies in One Leg Jumps for Distance

OLJs for distance or the combination of various one-legged jumping tasks are the FPTs most frequently conducted and most widely accepted in studies determining functionality at various time points after the reconstruction and as criteria for determination of return-to-sports in ACL reconstructed subjects (ALMANGOUSH & HERRINGTON 2014; BARBER et al. 1990; ERNST et al. 2000; GUSTAVSSON et al. 2006; KVIST 2004; LENTZ et al. 2009; MYER et al. 2008; NARDUCCI et al. 2011; NOYES et al. 1991; RUDOLPH et al. 2000; TEGNER et al. 1986). Out of the conducted studies, LSIs of 85% (BARBER et al. 1990; NOYES et al. 1989) to 90% (JURIS et al. 1997; PETSCHNIG et al. 1998; RISBERG et al. 1995) of the performance of the reconstructed legs compared to the performance of the non-injured legs have established as criteria for full recovered knee joint functionality and to release ACL reconstructed subjects back in pre-injury sports. This convention was deduced of studies by analyzing functionality in isolated or combined one-legged jumping tasks (BARBER et al. 1990; NOYES et al. 1991).

Following the 85% or 90% convention, this thesis showed that the ACL group did not reach in average a jumping distance of at least 85% with the injured/reconstructed legs compared to the non-injured legs, in the OLJs at none of the test sessions up to six months after ACL reconstruction. In average, the ACL group reached in the reconstructed legs only a jumping distance 75% compared to the non-injured legs at six months after ACL reconstruction. Although in average 85% could not get reached, some subjects reached even higher LSIs. Moreover, enhancement of the LSIs could get shown in the ACL group with increasing time after the ACL reconstruction up to six months post-reconstruction. These findings indicated that the applied rehabilitation programs enhanced the level of functionality in OLJs with increasing time after the reconstruction, but not up to the level of a healthy CG. Due to the general acceptance of OLJs to determine functional recovery, this finding alone could have led to the suggestion that the knee joints of the ACL reconstructed subjects are not fully recovered in dynamic one-legged movements at six months after ACL reconstruction.

Besides the detected deficits in jumping distance, analyses of the LSIs of the acceleration impulse during take-off in the OLJs revealed further deficits in the leg functionality of the ACL group compared to the CG. These results underlined the findings of the jumping distance deficits in the ACL reconstructed subjects. Considering these results, again, an increase of the mean LSI of the acceleration impulse was detected in the ACL group. However, it remained significantly lower in the ACL group at six months post-reconstruction compared to the CG, although the ACL group reached an acceleration impulse of about 80% in the reconstructed leg compared to the non-injured leg. The CG reached nearly a balanced level of the acceleration impulses during take-off in the OLJs between the non-dominant and dominant legs.

Both results implied that the ACL group of this study, could generally not reach the symmetry level of the healthy CG in the analyzed parameters of the OLJs. Furthermore, the symmetry level, which is established in literature as return-to-sports criteria or achievable functional recovery, could also not get reached (BARBER et al. 1990; JURIS et al. 1997; NOYES et al. 1989; PETSCHNIG et al. 1998; RISBERG et al. 1995).

Therefore, as practical implication of the OLJ results, it was concluded that in relation to the jumping distance data, the ACL group subjects did not recover on a symmetry level as the healthy CG. Therefore, due to these functional adaptations, this might indicate that releasing the subjects on pre-injury activity levels at six months post-reconstruction could bear high risks of prospective impairments, diseases and knee joint limitations. Nonetheless, some subjects reached even higher LSIs than the average scores of the ACL group, which provided a first indication that the functional rehabilitation did not follow a uniform course. Instead, it rather seemed that functional rehabilitation and recovery proceeded very individually, depending on concomitant injuries, age while tearing the ACL and adherence to the rehabilitation program.

Reconstructed Leg Deficiencies in Bilateral Counter Movement Jumps

The results and findings of the OLJs were underlined by the analyses of the bilateral CMJs. Moreover, the examination of the CMJs revealed results that supported the suggestion that the ACL reconstructed subjects did not reach the leg symmetry, the knee joint functionality and the performance level of matched healthy controls up to six months after ACL reconstruction. These findings confirmed the consideration that releasing the ACL reconstructed subjects to pre-injury activity level should not only depend on the time period after the reconstruction and functional clinical tests. Instead, it is recommended to include dynamic FPTs, to determine the level of dynamic knee joint functionality, in a return-to-sports decision at six months after ACL reconstruction.

This assumption was deduced, because in the bilateral CMJs, it was found that the general performance parameter (jumping height) remained about 23% lower in the ACL group at six months after reconstruction compared to the matched healthy CG, although an increase of the jumping height was found in the ACL group from seven weeks to six months after ACL reconstruction.

Besides the overall reduced jumping heights in the ACL group, the deficiencies of the reconstructed legs in the analyses of the LSIs of the acceleration impulses during take-off and the deceleration impulses during landing appeared to be remarkable in the CMJs. The leg-to-leg deficits reached in the reconstructed legs in the acceleration impulse during take-off and the deceleration impulse during landing about 40% at six months after ACL reconstruction. Although, the LSIs of the acceleration and deceleration impulses increased over time after the ACL reconstruction, the ACL group showed remarkable deficits in the LSIs of the take-off and landing impulses compared to the CG.

These results showed that there occurred strong shifts of loading to the non-injured leg, in terms of force generation, in the take-off situation and, in terms of load acceptance, in the landing situation during the bilateral movement of the CMJs. As a result, the main load during take-off and landing was generated and accepted by the non-injured legs. Interestingly, the shift of general loading during take-off to the non-injured leg appeared to be appreciably higher during the CMJs than the deficit appeared in the isolated one-legged jumping situation during the OLJs. In the OLJs, where the subjects had to generate a one-legged take-off impulse for maximizing jumping distance, the reconstructed legs showed a take-off impulse deficit of about 20% at six months after reconstruction. In contrast, in the CMJ situation, where the main work is characterized by a simultaneous bilateral vertical take-off impulse, the ACL group subjects showed in the reconstructed leg a deficit of 40% in load generation in the take-off situation at six months after reconstruction, including an immense overloading of the non-injured leg. Therefore, these findings indicated that in bilateral movements the ACL group subjects showed strong functional adaptations in the CMJs at six months after reconstruction. This led to the assumption that these adaptation strategies could be one decisive factor to highly increase the risk of injuries of the sound contralateral leg. This was supported by the findings that load asymmetries in the legs during bilateral jumping are a crucial factor for an increased risk of injuries (ARENDT & GRIFFIN 2000; HERZOG et al. 1989) and in healthy subjects, normally, none or only slight leg asymmetries exist in bilateral vertical jumping (STEPHENS et al. 2007).

In conclusion, the presented data of the CMJs confirmed and supported the functional deficits found in the analyses of the OLJs. Even more, by the simultaneous separate analyses of both legs during the bilateral CMJs, it was found that during simultaneous bilateral movements the ACL reconstructed subjects showed a strong shift of load to the non-injured leg, which inevitably leads to severe overloading of the non-injured leg.

Out of both jumping analyses it can be stated that the ACL group subjects did in average not recover on the functional level of the healthy CG subjects although an enhancement of the knee joint functionality was detected with increasing time after the ACL reconstruction. Therefore, due to the findings of the unilateral and bilateral jumping analyses it can be stated that it is not indicated to release the ACL reconstructed subjects back to pre-injury sports and intensity level. Especially, in sports with high repetitions of jumping and landing situations, such strong shifts of load bear and increase the risk of prospective injuries or degenerative damage at the reconstructed and/or non-injured legs (ROOS 2005).

This led to the practical implication that further training programs are necessitated to increase the level of functionality in the reconstructed legs in sport-specific movements, as one-legged or bilateral jumping and, furthermore, functional testing over the rehabilitation cycle is essential to detect potentially pronounced functional deficits of the legs. By detecting specific data of functionality repetitively over the post-surgical rehabilitation cycle, a more-individualized adaptation of rehabilitation programs would be enabled.

Reconstructed Leg Deficiencies in Isometric Force Tests

Alongside to the before discussed findings of the jumping tasks, the examination of the maximum voluntary force generation under isometric conditions revealed, as well, reconstructed leg deficiencies in the ACL group compared to the healthy CG: These appeared to be on a comparable level or even more pronounced as the results of the jumping tests. Hence, these results further confirmed and strengthened the findings deduced from the jumping tests.

As in the jumping tests, the LSIs of the mean force capabilities (peak voluntary force generation and peak rate of force developments) dropped clearly from pre- to post-reconstruction. Afterwards, the LSIs of the force capabilities enhanced with increasing time after the reconstruction. However, none of the LSIs of the analyzed parameters reached in average the level of the healthy CG. It was concluded that, in line with the deficits of the force generating and load compensation deficits under dynamic conditions, the force capabilities of the ACL reconstructed subjects, as representatives of isolated static force generation situations, did not reach the side-to-side level of the CG as well. In the CG, the side-to-side ratio of the analyzed force components (F_{max}, RFD_{max}, and RFD_{200max}) of the legs was balanced or slightly increased, in favor of the non-dominant side. Moreover, these detected reconstructed leg deficits of the ACL group in this study appeared to be higher than those detected in previous studies, especially in the flexion condition (LENTZ et al. 2009; NEETER et al. 2006).

The ACL group in this study showed reconstructed legs deficits compared to the non-injured legs, ranging in average between 42% and 51% in peak voluntary force generation (F_{max}) during flexion and between 25% and 27% during extension condition at six months post-reconstruction (Table 11 Appendix 10.7). In the RFD_{max}, reconstructed leg deficits ranged compared to the non-injured leg between 34% and 44% during flexion conditions and between 18% and 31% during extension conditions at six months post-reconstruction (Table 11 Appendix 10.7). Finally, in the RFD_{200max}, reconstructed leg deficits compared to the non-injured legs ranged between 39% and 40% in flexion conditions and between 19% and 34% in extension conditions at six months after the ACL reconstruction (Table 11

Appendix 10.7). However, as the ACL group subjects were reconstructed with a HT autograft and they showed pronounced deficits in the knee flexion ROMs compared to the extension ROM deficits, it was plausible that in the isolated isometric flexion force generation more pronounced deficits occurred compared to the knee extension situation.

Moreover, as the static circumference measurements of the thighs' muscular bulks revealed pronounced morphologic side-to-side deficits of the thighs' musculature in the ACL group and compared to the CG, the results of the isometric force tests led to the assumption that the force generating capabilities, which are mainly determined by neuromuscular components (HERZOG 2006), were deficient on a multi-modal level in the ACL group compared to the CG at six months after ACL reconstruction.

Due to the fact that in sports fast movements, as sprint running and cutting, occur, which require rapid contraction times of 50 ms to 250 ms, recovery of the RFD up to the level of the healthy CG subjects seems absolutely relevant before indicating that an ACL reconstructed subject is fully recovered in force generating capabilities, which are essential for sports participation (AAGAARD et al. 2002; THOMAS et al. 2016). As the ACL group did not reach the side-to-side ratio of the CG in RFD_{max} and especially in RFD_{200max}, which is realized during the initial 200ms of maximum voluntary contraction, it was assumed that in relation to the examination of the isometric force tests in this study, a return to pre-injury sports is in general not indicated at this time after the ACL reconstruction. This was concluded, because the muscular capabilities of the thigh did not recover on a morphologic (thigh circumference) and a force generating level (isometric force tests and impulse during jumping) as the healthy CG up to six months after ACL reconstruction.

As the analyzed parameters of the dynamic FPTs also revealed clear deficits in the side-to-side ratio of the dynamic muscular capabilities in the ACL group compared to CG, it was concluded that the ACL group subjects showed in general clear functional deficiencies on a multi-modal muscular level (morphologically and in dynamic and static situations) compared to the CG in the conducted FPTs and the functional clinical tests at six months after ACL reconstruction. Therefore, it was suggested that more time is needed to recover static and dynamic force generating and load accepting muscular capabilities in ACL reconstructed subjects. Additionally, it was assumed that rehabilitation programs should be adapted more precisely and individually, according to persistent functional deficits. This should achieved by the standardized implementation of dynamic FPTs into post-surgical ACL rehabilitation. Summarized, by the results and findings of the functional clinical tests and the FPTs, it was stated that the ACL reconstructed subjects of this study did not recover their muscular capabilities up to six months after ACL reconstruction on a level to recommend release and participation in pre-injury sports on pre-injury intensity level.

Surely, these findings of functional adaptations are closely related to the examined FPTs. Nonetheless, as the muscular and neuromuscular capabilities can be detected by these static and dynamic

FPTs (ALEXANDER 2000; WANK & HEGER 2009) and because the jumping tasks represent movement components and types of movements, which are required in intense ADLs and, especially, in sports (WANK & HEGER 2009), these performance related results provide important knowledge about the state of the functional recovery of the knee joint and of the biological structures (e.g. musculature, tissue etc.) of the legs over the post-surgical rehabilitation process.

These findings, moreover, led to the implication and recommendation to include functional testing in the post-surgical rehabilitation phase more standardized, to detect the individual deficits throughout the rehabilitation cycle more precisely, and to deduce more individual-based adaptations of the rehabilitation program. Specifically, pronounced deficits in the maximum strength capacities should be addressed by an increase of maximum strength and neuromuscular training programs. Distinct deficits of postural stability should be compensated by an increase of sensorimotor training. Deficits in complex high-demanding movements, as jumping, should be restored by a rehabilitation program that includes the relevant components of these movements. That is: maximum strength training of the legs, strength training of the whole body, agility training, and postural stability training in complex demanding movements, as landing, variations in training programs to adapt the neuromuscular systems to a complex variety of demanding tasks again. This approach was motivated due to the fact that wide ranges of the state of morphologic recovery and the state of the recovery of the functional performance level were detected at the different test sessions of this study.

8.3 Tendencies of Functional Adaptations in Daily Occurring Turns

The analyses of the 90° and 180° turns, as representatives of daily occurring turns, revealed in terms of the general locomotion strategy that the majority of the subjects showed generally locomotion strategies as healthy subjects before and after the ACL reconstruction. In particular, the ACL group subjects performed more often the step than the spin turn strategy in both 90° and 180° turns at nearly all test sessions. As healthy individuals also perform turns more often with a step turn strategy (HASE & STEIN 1999; KRAFFT et al. 2015), the detected locomotion pattern was considered normal in the ACL group. Thus, it seemed that the ACL tear had no general influence in the selection of the general turning locomotion strategy. These findings were underlined by the fact that, generally, the ACL group performed both turns more often with the injured/reconstructed legs as leading legs. Due to the fact that the leading leg has to accept higher demands during the turning process (HASE & STEIN 1999; KRAFFT et al. 2015), contrary results were expected. However, these unexpected findings showed that the ACL group could withstand the general demands required to the injured/reconstructed leg in its function as leading leg and did not lead to any general avoidance strategy to expose the injured/reconstructed legs to the demands of the leading leg situations.

Nonetheless, it was assumed that the ACL injured/reconstructed subjects would show kinematic and kinetic adaptation processes during turning gait due to the ACL tears and reconstructions, as it was described during straight locomotion tasks of daily life (BERCHUCK et al.1990; GARDINIER et al. 2012; GEORGOULIS et al. 2003; WEXLER et al. 1998).

Sagittal plane adaptations during the locomotion process were found on a kinematic as well as on a kinetic level. Furthermore, some adaptations were obvious even at six months after ACL reconstructions and some diminished with increasing time after the reconstruction.

In particular, the ACL group subjects showed in the analyzed kinematic parameters tendencies of functional adaptations, in terms of generally deeper flexed knee joint positions throughout the stance phase. These deeper flexed knee joint positions were found in the injured/reconstructed and non-injured legs and appeared in the early stance up to 50% of the stance phase and over the whole stance phase while performing the step turn strategy and the spin turn strategy. These deeper flexed knee joint positions not only appeared in the test sessions seven weeks after the tears and seven weeks after the reconstructions. These were also found at three and six months after reconstruction compared to the CG. Thus, the ACL group showed in turning locomotion, tendencies of similar kinematic adaptation strategies as detected in straight locomotion tasks, wherein also higher knee flexion were found, aiming to reduce stress to the reconstructed autograft and to provide and increase stability to the injured and reconstructed knee joint during straight (BERCHUCK et al. 1990; GARDINIER et al. 2012; KNOLL et al. 2004a; TORRY et al. 2000; WEXLER et al. 1998). Due to the findings of studies investigating straight locomotion tasks (BERCHUCK et al. 1990; GARDINIER et al. 2012; KNOLL et al. 2004a; TORRY et al. 2000; WEXLER et al. 1998), these adaptation strategies seemed beneficial in the short- and mid-term rehabilitation phase after the ACL reconstruction.

Inconsistently, in some turning conditions the kinematics recovered onto the level of the healthy CG or showed no tendencies of kinematic adaptations at all test sessions. These findings revealed that the ACL reconstructed subjects showed an ambiguous recovery of the kinematics in turning gait. However, if the detected functional kinematic adaptations, existing at six months after reconstruction, would persist longer, they could bear the risk to manifest. Manifestations of these functional adaptations could change the performance in the respective locomotion tasks in general, which could increase the risk of musculoskeletal disorders and diseases (ANDRIACCHI & MÜNDERMANN 2006).

These tendencies of kinematic adaptations were underlined by the analyses of the sagittal plane kinetics. Therein, tendencies of functional adaptations were detected in turning locomotion conditions, where accompanied tendencies of kinematic adaptations were detected or where no tendencies of functional kinematic adaptations occurred. However, as no general pattern could have been detected, it seemed that there rather existed task-specific and individual kinetic adaptations, according to the recovery process of the knee joint. Such a task-specific individual course of the rehabilitation was assumed due to described individually varying adherence to post-surgical rehabilitation, differing individual influence in the extent of potential concomitant injuries of other biological structures on the rehabilitative functional outcome (MYKLEBUST & BAHR 2005) and due to the fact that, generally, task-specific training effects occur in healthy subjects (AAGAARD et al. 1996; GIBOIN et al. 2015; KRAEMER et al. 2002). These findings led to the implication that task-specific adaptations and individual compliance to specific rehabilitation exercises exist in ACL teared and reconstructed subjects, which might highly influence the rehabilitative outcome.

As stated earlier, no general pattern of kinetic adaptations could be found according to the turning locomotion task and the turning locomotion strategy. Therefore, a variety of kinetic adaptations appeared, with rather increased knee flexion loads, decreased knee extension loads, and increased time of acting knee flexion moments in the 90° step turns at six months after reconstruction. These adaptation characteristics appeared as well in the injured/reconstructed legs, acting as leading legs in 180° step turns. Additionally, tendencies of functional kinetic adaptations in the spin turns were detected, which appeared to be very heterogeneous. However, the most remarkable finding in the spin turns was that exclusively knee extension moments appeared in the leading legs. These appeared to be increased up to 130% compared to the mean peak knee extension moments in the step turns. Due to the described negative influence of high knee extension moments, producing high stress to the implanted autograft (BERCHUCK et al. 1990; GARDINIER et al. 2012; KNOLL et al. 2004a; TORRY et al. 2000; WEXLER et al. 1998), this turning locomotion strategy was considered unbeneficial short- and mid-term after ACL reconstruction.

These summarized results showed that there was limited access in generalization of sagittal kinematics and kinetics in turning locomotion tasks. However, the results showed that individually distinct functional adaptations in the sagittal plane occurred on a kinematic and a kinetic level. Despite the methodological limitations of this study, the data revealed tendencies, which gave the implication that task-specific individual functional adaptations occurred on a kinematic and kinetic level even at six months after ACL reconstruction. Due to the fact that in the spin turns the leading legs had to withstand more than twice the load compared to the leading legs in the step turns, rehabilitation of normal turning locomotion should consider to generally avoid the spin turn strategy to reduce unbeneficial loads to knee joints of ACL reconstructed subjects.

In conclusion, due to the turning gait analyses in the ACL group and the CG, it seems essential in the post-reconstructive rehabilitation process to include exercises to recover normal movement locomotion behavior in sport-specific movements and, especially, as well in daily occurring movements. This purposes to help to recover normal locomotion behavior and, additionally, to reduce misbalanced kinematics and kinetics in the reconstructed knee joint. As ADLs occur with a great variety multiple times in daily life, manifestations of functional adaptations in these movements or movement components, on a kinematic or kinetic level, would highly increase misloading situations in the legs (ANDRIACCHI & MÜNDERMANN 2006; GEORGOULIS et al. 2003). Therefore, movement locomotion exercises to recover normal movement behaviors seem equally important as the recovery of muscular and neuromuscular capabilities by strength and conditioning exercises.

8.4 Reduced Injury Related Self-Concept

The before-discussed findings of the functional clinical tests, the dynamic and static FPTs, and the analyses of the ADL turn walking underlined that reconstructed leg deficiencies occurred on a multi-modal functional level along with locomotion adaptations up to six months after ACL reconstruction. As the post-reconstructive rehabilitation program mainly aimed to recover muscular and neuromuscular capacities of the knee joint and the injured leg (WHITING & ZERNICKE 2008), it has shown that, although the muscular functionality of the legs enhanced with increasing time after the reconstruction, deficiencies occurred pronounced in the individual side-to side differences of the legs and compared to the CG even at six months after reconstruction. This showed that the applied rehabilitation programs positively influenced functional recovery, however, it seemed that these recovery processes follow rather an individual task-specific than a uniform progression.

Of course, the recovery of strength capabilities, in general, is important for the recovery of the functionality after ACL tears and reconstructions to regain functionality and stability of the knee joint (KEAYS et al. 2003). Nonetheless, rehabilitation programs should not only focus on the recovery of strength capabilities, because there exists one important factor, which can strongly influence a negative or unsatisfying functional outcome after ACL reconstructions, although on a physiological level the individual seems fully recovered. These factor is of psychological nature and is characterized by reduced self-confidence in relation to the knee joint functionality, increased fear of re-injury and/or experiences of repetitive situations of insecurity and instability to the reconstructed knee joint (BREWER et al. 2007; CHMIELEWSKI et al. 2008; EVERHART et al. 2015; KVIST et al. 2005; TE WIERKE et al. 2013).

To reach these requirements, the KOOS was included into the comprehensive test battery of this thesis, to measure the subjects' self-administered evaluation of the knee joint functionality under the aspects of *pain*, other *symptoms and* joint *stiffness*, *function in daily living*, *function in sport and recreation*, and *knee related QoL* at each test session (KESSLER et al. 2003; ROOS et al. 1998).

If analyzing the KOOS results of this study, it appeared that highest scores were reached in the sub-categories *pain* (84.1 ± 14.1) and *ADL* (91.4 ± 10.9) at six months after ACL reconstruction. Although these scores were significantly different to the CG (*Pain*: 98.7 ± 3.7; *ADL*: 100 ± 0), nonetheless, the ACL group only reported little amount of situations of moderate to severe experiences of pain and only little limitations in ADL. Furthermore, these scores were on a similar level as the scores of ACL reconstructed subjects (*Pain*: 89.9 ± 8.1; *ADL*: 96.5 ± 3.6) investigated by ROOS et al. (1998) at six months after reconstruction.

Therefore, the results of the ACL group of this study implied that in relation to self-evaluated *pain* and *function in ADL*, the ACL reconstructed subjects approached the level of other ACL reconstructed individuals and nearly the level of healthy subjects at six months after ACL reconstruction, although differences in the sub-categories *pain* and *function in ADL* occurred. Therefore, in relation to *pain* and knee joint *function in ADL*, it can be stated that the results of the ACL group subjects, participated in this study, represented a normal progression after ACL reconstruction. Additionally, as pain is one major factor, which influences the general well-being of reconstructed subjects, these findings led to the implication that the ACL group subjects seemed to recover on good level. This was underlined by the fact that the ACL group subjects only suffered from little limitations and restrictions in the category *function in ADL*. Both results could build a good basement for the other sub-categories *symptoms and stiffness*, *function in sport and recreation* and *knee-related QoL*.

However, although the ACL group reached scores in *symptoms and stiffness* at six months after ACL reconstruction (74.3 ± 18.7), which were significantly lower to the CG (94.8 ± 8.1) and reduced to the scores in *symptoms and stiffness* of the subjects tested in ROOS et al. (1998), the ACL group showed a clear increase in the reduction of *symptoms and stiffness* in relation to the reconstructed knee joint up to six months after ACL reconstruction. This increase was additionally seen as positive development in terms of functional recovery.

All before mentioned sub-categories showed a certain increase in direction of an acceptable self-evaluated state of well-recovered knee joint functionality, on a level, which appeared to be decreased to healthy subjects by around one standard deviation (*COHEN'S d:* 1.1 to 1.4) up to six months after ACL reconstruction. However, the scores of the KOOS sub-categories *sports and recreation function* (69 ± 24.0) and *QoL* (59.6 ± 22.1) were reduced more pronounced at six months after ACL reconstruction compared to the CG (*Sports and recreation function*: 99.5 ± 1.5; *QoL*: 97.8 ± 2.6) by about two standard deviations (*COHEN'S d:* 1.8 to 2.3). The results of both latter sub-categories shatter the before-mentioned findings of the formerly sub-categories and, thus, the primary deduced enhancement of self-evaluated functionality of the knee joint cannot generally be stated. Especially, in the *knee-related QoL* sub-category, where the lowest of all scores appeared, a strong reduction occurred in the ACL group at six months after reconstruction compared to the CG.

As the results in the FPTs, which required demands similar to those in sports, were significantly reduced at six months after reconstruction, it was expectable that the ACL group subjects self-evaluated the *function in sports and recreational activities* on such a low level. Interestingly, there appeared also a lower score compared to the mean score of the subjects investigated by ROOS et al. (1998) at six months after reconstruction (70.8 ± 15.8). In line with the strongly reduced self-evaluated *QoL* of the ACL group (59.6 ± 22.1) at six months after reconstruction compared to the CG (97.8 ± 2.6) of this study, the ACL group subjects of ROOS et al. (1998) reached a same score (58.9 ± 10.1). As the questions of the *knee-related QoL* sub-category aiming to detect the general relationship of the reconstructed subjects to the ACL injury and the impaired knee joint, this sub-category is especially informative in relation to potential individual psychological constraints. The *knee-related QoL* sub-category showed strongly reduced scores in the ACL reconstructed subjects of this thesis and as well in further studies, applying the KOOS to ACL reconstructed subjects (ROOS et al. 1998). These findings strengthened that the ACL reconstructed subjects were in critical self-evaluative functional state to consider six months after ACL reconstruction as time-point full recovery and, especially, as time-point to return in pre-injury sports and pre-injury intensity level.

As psychological well-being and self-confidence is highly related to well-being in demanding activities (SCHEIER & CARVER 1987), functional self-evaluation should be more taken into account if considering a full recovery of ACL reconstructed subjects or a release in pre-injury sports and intensity level.

This seemed to be even more essential in recreational athletes than in competitive athletes. As competitive athletes with higher or more competitive level of pre-injury activity are more used to deal with injuries that prevent from sports participation, they should be emotionally more resilient (TRACEY 2003; BREWER et al. 2007). Emotional resilience was assumed to be advantageous for the recovery after ACL tear and the subsequent rehabilitation process, because they are fewer influenced by feelings of negative outcome and fear of re-injury (TRACEY 2003; BREWER et al. 2007). However, recreational athletes are not that used to injury situations than competitive athletes, including a strong reduction of the QoL. Therefore, frustrations or negatively steered emotional well-beings can occur more pronounced after the ACL tear, the reconstruction, and the rehabilitation process, because a recovery of the knee joint and therewith the general period of rehabilitation lasted longer than previously expected and experiences of similar situations were missing (TE WIERKE et al. 2013). Therefore, more realistic views with a higher level of objectivity of the functional level should be done in the decision-making by therapists (CASCIO et al. 2004), including the ACL reconstructed subjects functional self-evaluation. Furthermore, counseling interventions should find standardized inclusion in the rehabilitation cycle and should accompany physical rehabilitation in form of psychological rehabilitation (TE WIERKE et al. 2013).

8.5 Practical Implications and Recommendations

The purpose of this thesis was to provide data of the progression of functionality from pre- to six months post-reconstruction to the field of ACL rehabilitation by conducting a comprehensive test battery at multiple test sessions. Hence, the detected results and the deduced findings showed that, in general, the recovery of functionality after ACL reconstructions proceeded very individual and has a strong dependence on potential concomitant knee injuries, the state of functionality prior to the ACL tear and the adherence to the post-surgical rehabilitation program. However, the results of this thesis provided, as the first of its kind, longitudinal data of ACL teared and reconstructed subjects from pre- to six months post-reconstruction in the setting of functional testing and in comparison to a matched healthy CG. Nonetheless, these data enabled, firstly, to draw progressions and developments of functional capacities over the whole post-surgical rehabilitation cycle up to six months after the reconstruction and, secondly, to compare the respective results to the pre-reconstruction state and to a matched healthy CG.

The described results and findings, deduced from the conducted tests of this thesis, showed that the level of functionality of the ACL group, generally hardly achieved the level of the healthy CG up to six months after ACL reconstruction. Nonetheless, an enhancement of the functional level was found in the ACL group with increasing time after ACL reconstruction. This confirmed that the applied rehabilitation program led to increased knee joint functionality with increasing time after the reconstruction. However, with the applied rehabilitation program the general functional level of healthy control subjects could not get achieved. In contrast, the analyses showed that functional recovery processes remained very individual and specific, as some ACL reconstructed subjects reached the level of functionality of the healthy CG, but, in contrast, some showed strongly reduced level of functionality at the same time point. However, as, in average, the functional level of the CG was not reached, it was assumed that the ACL reconstructed subjects have not reached their pre-injury level of knee joint functionality up to six months after ACL reconstruction.

Therefore, due to the findings of this thesis and of recently conducted studies in the field of ACL rehabilitation, the general practical implication was deduced that with emerging evidence the rehabilitation outcome can be strongly enhanced and the incidence of secondary ACL injury can be dramatically reduced by training programs targeting specific movements and neuromuscular control strategies (HEWETT et al. 2005 in WHITING & ZERNICKE 2008). Accordingly, these training programs should not only target asymmetries and deficiencies in sport-specific high-intense movements but also include the rehabilitation of emerging asymmetries in ADLs, as gait asymmetries (GARDINIER et al. 2012). Therefore, as MANDELBAUM et al. (2005) proposed, a rehabilitation program after ACL reconstruction should be most comprehensive, dependent on detected individual functional deficiencies by functional testing throughout the rehabilitation process.

Therefore, out of the findings and conclusions of this thesis, the following practical implications were deduced:

- Repetitive comprehensive functional testing enables an adequate detection of potential functional deficiencies.
- According to detected functional deficiencies, individual adaptation of the rehabilitation program.
- Purpose of most comprehensive rehabilitation program to recover locomotion in a wide range of setting.
- According to functional deficiencies in daily living tasks, exercises to recover normal locomotion pattern components and to increase postural stability components.
- According to functional deficiencies in sport-specific tasks, exercises to enhance the physical capacities in strength, agility, and endurance.
- According to injury related psychological constraints, assistant care and counseling to enhance self-confidence and self-esteem.

8.6 Conclusions

Full recovery and rehabilitation of the knee joint is fundamental for a return to normal locomotion in ADLs and the complete return to pre-injury sports and activities on pre-injury intensity level. Therefore, examination of ACL rehabilitation after tears and reconstructions represents a substantial field of research, including a vast field of recently and formerly conducted studies. However, to the best of my knowledge, no studies exist, which conducted a close longitudinal comprehensive functional testing approach after a ACL tear up to six months after ACL reconstruction.

Hence, the contribution of knowledge about decisive factors and developments throughout the rehabilitation process, which lead to full recovery or incomplete rehabilitation are major concerns of ACL rehabilitation programs after ACL tears and subsequent reconstructions.

Therefore, findings of studies, examining functional adaptations in the rehabilitation after ACL reconstruction represent an essential contribution for clinicians and therapists to enhance and adapt rehabilitation programs more individualized in regard to potential individual knee joint deficiencies. Furthermore, the detection of more individualized points in time after the reconstruction to determine full knee joint recovery is enabled to release ACL reconstructed subjects back to pre-injury sports and intensity level.

To contribute valuable knowledge to this field of orthopedics, this thesis purposed to add more sophisticated data by the conduction of a multi-disciplinary comprehensive longitudinal test battery. The comprehensive test battery comprised subject’s self-administered evaluation of the knee joint function, functional clinical tests, functional performance tests, and the analyses of functionality of the ACL subjects in turning locomotion, over the half-year rehabilitation process after reconstruction. Furthermore, by applying these test battery at four test sessions from pre- to six months post-ACL reconstruction, a close monitoring of the progression and development of knee joint functionality from various perspectives could be determined. Summarized, the studies, integrated in this thesis, revealed the following findings and conclusions:

(1) Reproducibility of daily occurring turns showed that there exist individually fixed locomotion strategies in these turns. Therefore, it was assumed that recovery of normal locomotion strategies in activities of daily living is essential to achieve full knee joint functionality after ACL tears and reconstructions.

(2) Reconstructed leg deficiencies in knee joint ROM and muscular atrophy of the reconstructed legs at six months after the reconstruction were assumed as pre-determining factors for subsequent deficiencies in locomotion tasks of daily living and in recreational and competitive sports.

(3) Significantly reduced functionality in jumping and reduced isometric strength capacities indicated strong functional deficiencies and incomplete recovery of the reconstructed legs at six months after ACL reconstruction compared to the healthy control group, although, the level of functionality increased in these tests with increasing time after ACL reconstructions. Significant side-to-side imbalances indicated that ACL reconstructed subjects should not get released in pre-injury sports-intensity level without any dynamic functional testing.

(4) Tendencies of functional kinematic and kinetic adaptations in daily occurring turns were detected short-term, but as well three and six months after the reconstruction. These tendencies of adaptations in the reconstructed and non-injured legs can increase and intensify locomotion imbalances. Recovery of full functionality and normal locomotion pattern in daily life activities and in sport-specific locomotion tasks is essential to achieve full knee joint recovery.

Summarizing the findings of this thesis, it can be stated that valuable knowledge was contributed to the field of functional recovery over the six months rehabilitation cycle after the ACL reconstruction. As this study represented the first of its kind with such a closed-monitored comprehensive test design, it adds important results and findings to the state, progression and development of functional knee joint rehabilitation from various important viewpoints at multiple test sessions up to six months after ACL reconstruction. Furthermore, it motivates a more standardized inclusion of comprehensive testing into the post-surgical ACL rehabilitation paradigm to receive more precise data about the state of knee joint functionality.

Nonetheless, the general positive effects of the applied rehabilitation programs were confirmed by the increasing knee joint functionality and increasing performance outcome in the ACL reconstructed subjects with increasing time after the ACL reconstruction. However, the great variety of results imply that strong individual processes remain, which immensely influence the outcome of functional knee joint rehabilitation.

Due to the highly individual-dependent rehabilitation process, we motivate to generally add more standardized functional testing to the field of post-surgical ACL rehabilitation to detect functional deficiencies more specifically and more individually. Out of these findings a more individually adaption of the rehabilitation programs is enabled, precisely according to the assessed potential individual deficiencies. Therefore, in conclusion of the results of this thesis, a general return of individuals to pre-injury sports and intensity level seems not to be indicated without any functional testing at six months after ACL reconstruction. This assumption was drawn, as in nearly none of the applied tests, the performance outcome or the level of functionality of the CG was reached. Furthermore, large individual variations appeared in the level of knee joint functionality at specific time points. These findings implied that the development of knee joint functionality in low-intense and high-intense locomotion tasks proceeded very individual over the testing period from pre- to six months post-ACL reconstruction, as hardly any crucial criteria, proposed in literature for releasing ACL reconstructed individuals back in pre-injury sports, was reached.

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10 Appendix

10.1 General Questionnaires of the Study

Subjects Information

Patienteninformation

Studie „Kinetische und Kinematische Analysen von Belastungen der Beinen bei ausgewählten Bewegungen bis 1 Jahr nach vorderer Kreuzbandverletzung“

BioMotion Center, Institut für Sport und Sportwissenschaft (IfSS),
Karlsruher Institut für Technologie (KIT)

Sehr geehrte Studienteilnehmerin, sehr geehrter Studienteilnehmer,

die folgenden Informationen sollen Ihnen die Entscheidung erleichtern, ob Sie an dieser Studie teilnehmen möchten. Lesen Sie das Dokument sorgfältig bevor Sie eine Entscheidung treffen. Der Testleiter, der Sie am 1. Testtag betreut, wird dieses Dokument mit Ihnen besprechen. Es ist wichtig, dass Sie nachfragen, wenn etwas unklar ist.

Einleitung

Vordere Kreuzbandverletzungen (62 %) stellen die größte Gruppe an Verletzungen innerhalb der Knieverletzungen (60.000/Jahr) dar. Auffallend ist in diesem Zusammenhang, dass die Häufigkeit vorderer Kreuzbandverletzungen seit dem Jahr 2000 um 30 % gestiegen ist. (Quelle: statistisches Bundesamt)

Auffallend ist in diesem Zusammenhang die deutliche Zunahme von Kreuzbandverletzungen bei Breiten- und Freizeitsportlern (z.B. Carving-Ski). Für alle Patienten, ob Leistungs- oder Freizeitsportler, bedeutet diese Verletzung einen langen Weg der Rehabilitation verbunden mit erheblichen Einschränkungen in der Bewegungsfreiheit. Diese Beeinträchtigungen folgern nicht nur in Problemen bei einer Rückkehr auf das Sportniveau vor der Verletzung, sondern bringen auch erhebliche Probleme bei Bewegungen des alltäglichen Lebens, in Haushalt und Beruf, mit sich.

Auf Grund der, aus der Verletzung folgenden, Beeinträchtigungen für das alltägliche und sportliche Leben, ist die Verbesserung der Therapie nach einer Kreuzbandverletzung von großer Bedeutung. Nur mit einer weiteren Verbesserung der Therapie, vor allem auch für den Breiten- und Freizeitsportbereich, kann gewährleistet werden, dass die Patienten wieder eine Leistungs- und Funktionsfähigkeit ihres Kniegelenks erreichen, mit der sie das alltägliche Leben und in der Folge auch Sport auf

Vorverletzungsniveau, beschwerdefrei durchführen können. Den Therapieprozess zu verbessern, ist von erheblichem wissenschaftlichem und therapeutischem Interesse. Dazu soll diese Studie einen wichtigen Beitrag leisten.

Ziel dieser Studie ist es durch Analyse von typischen Alltagsbewegungen und funktionellen Bewegungsaufgaben der Sportleistungsdiagnostik kurz vor, sowie an verschiedenen Testzeitpunkten nach der Operation (bis 1 Jahr nach der Operation) Rückschlüsse auf die Qualität des Reha-Prozesses ziehen und bessere Aussagen über eine Rückkehr in den Sport treffen zu können. Zudem sollen mittels dieser Untersuchung auch, die aus dieser Verletzung entstehenden degenerativen Prozesse am Kniegelenk (Arthrose), besser kontrolliert und verstanden werden können.

In dieser Studie liegt daher das Hauptaugenmerk darauf, in wieweit sich über den Therapieprozess Seitigkeitsphänomene, hinsichtlich einer Belastungsverschiebung in den Beinen, einstellen und u.U. manifestieren und so das Belastungsgefüge in den Beinen nachhaltig verändern. Diese Veränderungen könnten zu Bewegungseinschränkungen führen und die Entwicklung von Folgeschädigungen unterstützen.

Um dieses Forschungsthema aufzuarbeiten ist geplant im biomechanischen Labor, dem BioMotion Center des Instituts für Sport und Sportwissenschaft, mit 25 Patienten, die eine Verletzung des vorderen Kreuzbandes erlitten haben, Bewegungsanalysen von Alltagsbewegungen (z.B. Gehen) durchzuführen und aus den Ergebnissen Zusammenhänge zu Bewegungs- und Belastungsanalysen funktioneller Sportleistungstest zu ziehen.

Ablauf der Untersuchungen

Bei dieser Studie wird es zwei Versuchsgruppen geben. Eine Versuchsgruppe wird durch Patienten mit verletztem vorderem Kreuzband repräsentiert. Die zweite Versuchsgruppe dient als Kontrollgruppe. Die Probanden dieser Versuchsgruppe werden den Probanden der Patientengruppe hinsichtlich anthropometrischer Daten und Aktivität des täglichen Lebens angepasst.

Wir möchten mit Ihnen, als Proband der Patientengruppe, an fünf Testzeitpunkten innerhalb eines Jahres Bewegungstests durchführen und dabei dokumentieren wie sich Ihre funktionelle Leistungsfähigkeit und Ihre Belastungssituation in den Beinen bei alltäglichen Bewegungen (Gehen, Laufen, Treppensteigen) und bei funktionellen Tests aus der Sportleistungsdiagnostik über die Zeit ausprägt bzw. verändert. Hierbei ist für uns von besonderem Interesse, wie sich bei Ihnen das Belastungsverhältnis zwischen den Beinen darstellt und wie sich dieses über den Untersuchungszeitraum verändert.

Um diesen Sachverhalt umfassend wissenschaftlich aufarbeiten zu können, möchten wir mit Ihnen über ein Jahr an fünf Testtagen, die weiter unten beschriebenen, Tests durchführen.

Vor den durchzuführenden Tests bitten wir Sie, Angaben zu ihrer Person, eine Einwilligungserklärung zur Teilnahme an der Studie und zur Einordnung ihres körperlichen Status, eine Unbedenklichkeitserklärung ausfüllen.

Zu Beginn eines jeden Testtages bitten wir Sie Sie zwei evaluierte und standardisierte Fragebögen zu beantworten, in denen Sie Angaben über ihre körperliche Leistungsfähigkeit, Aktivitätsniveau und etwaige alltägliche Einschränkungen auf Grund Ihrer Knieverletzung, machen sollen (Tegner Activity Score (TAK), „KOOS“-Kniefragebogen). Im Anschluss an die Beantwortung dieser Fragebögen, finden die Bewegungsanalysen und funktionellen Tests statt. Von Testzeitpunkt zu Testzeitpunkt bitten wir Sie zudem in einem Formular, das Sie ausgehändigt bekommen, ihre körperlich-sportliche oder rehabilitative Aktivität zu dokumentieren.

Das Testprocedere werden Sie einmal vor der Operation und viermal in einem Jahr nach der Operation des vorderen Kreuzbandes durchlaufen. Testtag I wird 1 bis 3 Wochen vor Ihrer Operation sein, Testtag II 6 Wochen nach der Operation; Testtag III, IV und V 3, 6 bzw. 12 Monate nach der Operation.

Während dieser Zeit dokumentieren Sie bitte die erhaltenden Rehaleistungen und ausgeführten körperlich, sportlichen Aktivitäten auf beiliegendem Formular. (Aktivitätserfassungsbogen)

Die praktischen bewegungsanalytischen Tests werden mit dem 3D-Bewegungsanalyse-System Vicon® durchgeführt. Bei diesen Aufnahmen werden reflektierende Marker auf die Haut über den Gelenken ihres Körpers geklebt. Um eine möglichst hohe Qualität der Daten zu erreichen sollten Männer nicht mehr als eine eng anliegende Hose und Frauen eine eng anliegende Hose und einen BH tragen. Da weit anliegende Kleidung die Markerplatzierung erschwert und durch die Bewegung der Kleidung Markerbewegungen stattfinden, würde die Datenqualität damit stark beeinträchtigt werden.

Bei der Ganganalyse mit Störeinflüssen laufen Sie zunächst über einen ebenen Laufsteg, in den eine Kraftmessplatte integriert ist. Beim Kontakt mit der Kraftmessplatte wird diese leicht auslenken (die Richtung ist Ihnen nicht bekannt). Aber die Auslenkung wird nicht so stark sein bzw. Sie in einer solchen Weise beeinträchtigen, dass Sie stürzen könnten. Wichtig für diesen Test ist zu erfahren, wie Sie derartige Störeinflüsse des Untergrundes mit Ihrem Bewegungsapparat kompensieren.

Während der Untersuchung werden lediglich der Projektleiter und eine studentische Hilfskraft, die extra für diese Testdurchführung geschult ist, mit Ihnen im Testlabor sein. Das Labor und damit die Untersuchung sind für Dritte von außen nicht einsehbar. Außerdem ermöglicht die Betreuung der Patienten durch einen Orthopäden (Prof. Dr. Stefan Sell) einen reibungsfreien Ablauf der Untersuchungen ohne Komplikationen. Aus wissenschaftlicher und vor allem aus medizinischer Sicht schaffen die Ergebnisse der Untersuchung Grundlage und Erkenntnis für zukünftige Therapiemaßnahmen nach Kreuzbandverletzung, die nicht nur die akute Rehabilitation und den Outcome der Patienten aus der Therapie verbessern sollen, sondern den Therapieprozess auch so zu verbessern, dass zusätzlich zukünftige degenerative Folgeerkrankungen am betroffenen Gelenk schon in der Frühphase der Therapie nach einer Operation entgegengewirkt werden wird.

Testprocedere

- Angaben zur Person, Einwilligungserklärung, Unbedenklichkeitserklärung
- Fragebögen: Tegner-Activity-Score (TAS) und (Knee inury and Osteoarthritic Outcome Score = KOOS)
- Test zur Bestimmung des Bewegungsausmaßes des Kniegelenks und der Kniegelenksschwellung
- Aktivitätserfassungsbogen von Testzeitpunkt zu Testzeitpunkt
- Ganganalyse geradeaus, geradeaus mit variablem Untergrund und beim Kurve gehen
- Ganganalyse Treppe auf- und absteigen
- Einbeinsprungtests
- Isometrische Krafttests der Beine

Risiken

Die durchzuführenden Tests umfassen Bewegungen, die die Probanden vor einer Kreuzbandoperation bzw. frühestens 6 Wochen nach der Operation problemlos durchführen können. Die Bewegungen umfassen zum einen Ganganalysen bei ebenem Gehen, bei Kurvengehen und beim Treppensteigen. Diese Bewegungen sollten ohne Beschwerden/ Probleme durchführbar sein. Die Ganganalyse bei unebenem Untergrund wird mit einer speziell für diesen Test konzipierten und gebauten Kraftmessplatte ausgeführt. Diese Kraftmessplatte ist beweglich, wodurch Störeinflüsse beim Gehen simuliert werden können. Diese beeinflussen die Probanden aber lediglich in einer Art und Weise, die dieser gut tolerieren kann. Durch diese Störeinflüsse sind keine Gefährdungen durch Gleichgewichtsstörungen oder sogar Stürze zu erwarten, die die Patienten in eine unangenehme oder etwa gefährdende Situation bringen würden. Zumal sind die Probanden während der Ganganalysen durch einen Tragegurt (ähnlich eines Kletterharnisches) gesichert, so dass keine Gefahren für die Gesundheit der Patienten bestehen.

Die funktionellen Leistungstests aus der Sportleistungsdiagnostik (Sprungtest, Maximalkrafttest im Kraftmessstuhl) sollen zwar mit der Patienten möglichen höchsten Intensität ausgeführt werden, allerdings nur in jenem Maße, dass die Patienten die Tests absolut beschwerdefrei ausführen können. Bei diesen Tests ist es wichtig, die zum jeweiligen Testzeitpunkt bestmöglichen Leistungen zu messen; jedoch ist stets von oberster Priorität, zu messen, inwiefern durch das gesunde Bein die Leistungen des verletzten Beines in der jeweiligen Testaufgabe kompensiert werden.

Probleme, Einschränkungen oder gar Schmerzen und andere Beschwerden jedweder Art, mitgeteilt durch den Patienten während des Tests, gelten stets sofort als Abbruchkriterium für den jeweiligen Test.

Zudem wird für die Durchführung der Untersuchung ausschließlich geschultes Personal eingesetzt, das eine sichere Durchführung der Tests gewährleistet und im Notfall auch sofort erste Hilfe Maßnahmen einleiten kann. Außerdem ermöglicht die Betreuung der Patienten durch einen Orthopäden (Prof. Dr. med. Stefan Sell) einen reibungsfreien Ablauf der Untersuchungen ohne unerwartete Komplikationen.

Nutzen

Insgesamt wird für jeden Patienten ein Probandengeld von 75 € erstattet. Die Bezahlung wird in drei Schritte á 25 €, über das Studienjahr, gestaffelt sein.

Aus wissenschaftlicher und vor allem aus medizinisch-therapeutischer Sicht trägt diese Studie dazu bei, den Therapieprozess qualitativ und quantitativ zu überprüfen. Daher sollen die Ergebnisse und Schlussfolgerungen dieser Studie dann gewinnbringend für zukünftige Therapiemaßnahmen genutzt werden können und so der Therapieprozess und der Outcome nach der Therapie stetig verbessert werden. Zusätzlich können die Ergebnisse u.U. helfen degenerativen Folgeerkrankungen an den Gelenken der Beine schon im Therapieprozess entgegen zu wirken.

Freiwilligkeit der Teilnahme

Ihre Teilnahme an der Studie ist ausschließlich freiwillig. Sie absolvieren die Tests auf eigene Gefahr. Die Studienleitung übernimmt keine Haftung für Verletzungen, Krankheiten oder sonstige gesundheitliche Beschwerden, die durch die Studie verursacht oder ausgelöst werden; es sei denn, sie sind durch schuldhaftes Verhalten (z.B. Nichteinhaltung der Sicherheitsmaßnahmen oder fehlerhaftes Bedienen von Geräten) durch die jeweiligen Testleiter verursacht.

Sie können jederzeit und ohne Angabe von Gründen Ihre Einverständniserklärung zurückziehen und damit jeden Test zu jedem Zeitpunkt sofort abbrechen. Es entstehen von Seiten der Studienleitung dadurch keine Schadenersatzansprüche. Die Studienleitung hat das Recht, Sie aus Sicherheitsgründen oder sonstigen Gründen aus der Studie herauszunehmen.

Datenschutzrechtliche Bestimmungen

Durch Ihre Unterschrift auf der Einwilligungserklärung erklären Sie sich damit einverstanden, dass personenbezogene Daten zum Zweck der Studie erhoben und verarbeitet werden dürfen. Die personenbezogenen Daten werden für den Zweck der Verwaltung und Durchführung der Studie sowie für Zwecke der Forschung und statistischen Auswertung verwendet. Die Daten werden in verschlüsselter Form verarbeitet und gespeichert. Hierzu werden die Daten mit einer Codenummer versehen (Pseudonymisierung der Daten). Auf den Codeschlüssel, der es erlaubt die Daten mit den Namen der Patienten in Verbindung zu bringen, haben ausschließlich der verantwortliche Projektleiter sowie seine, für die Auswertung der Daten zuständigen Mitarbeiter, Zugriff.

Sie haben das Recht auf Auskunft über alle vorhandenen personenbezogenen Daten über Sie. Sie haben auch das Recht auf Benachrichtigung unrichtiger personenbezogener Daten. Im Falle des Widerrufs der Studienteilnahme und des Widerspruchs gegen die Verarbeitung Ihrer Daten, werden diese gelöscht. Bitte beachten Sie, dass die Ergebnisse der Studie in der Fachliteratur veröffentlicht werden, wobei Ihre Identität allerdings stets anonym gehalten wird.

Study Participation Criteria

Teilnahmekriterien

Studie „Kinetische und Kinematische Analysen von Belastungen der Beine bei ausgewählten Bewegungen bis 1 Jahr nach Verletzungen des vorderen Kreuzbandes“

BioMotion Center, Institut für Sport und Sportwissenschaft (IfSS), Karlsruher Institut für Technologie (KIT)

Liebe Studienteilnehmerin, lieber Studienteilnehmer,

vielen Dank, dass Sie an der Studie „Kinetische und Kinematische Analysen von Belastungen bei Alltagsbewegungen und funktionellen Leistungstests nach Verletzungen des vorderen Kreuzbandes“ teilnehmen möchten. Bevor Sie mit den ersten Tests anfangen können, füllen Sie bitte diesen Fragebogen aus. Er dient der Abklärung von Kriterien, die eine Teilnahme an der Studie ausschließen würden.

Bitte beantworten Sie alle Fragen wahrheitsgemäß und sorgfältig!

Wenn Sie alle Fragen mit **„Nein“** beantworten können, bestehen keine gesundheitlichen Bedenken bezüglich einer Teilnahme an den Therapiesitzungen im Rahmen der Studie.
Sollten Sie eine oder mehrere Fragen mit **„Ja“** beantworten, können möglicherweise Beschwerden bei der Durchführung der Therapie auftreten. Wir können Sie daher unter Umständen nicht für die Teilnahme an der Studie nicht berücksichtigen.

Gez. Frieder C. Krafft (Projektleiter, IfSS), Dr. Thorsten Stein (Leiter BioMotion Center, KIT), Prof. Dr. Alexander Woll (Institutsleiter, IfSS).

Fragen

	Ja	Nein
1. Nehmen Sie im Therapiezeitraum (14 Tage) Schmerzmittel?	☐	☐
2. Haben Sie maligne Erkrankungen im verletzten Kniegelenk?	☐	☐
3. Haben Sie weitere, akute Erkrankungen im verletzten Kniegelenk?	☐	☐
4. Haben Sie weitere, chronische Erkrankungen im verletzten Kniegelenk?	☐	☐
5. Hatten Sie früher schon einmal eine Verletzung am jetzt verletzten Kniegelenk?	☐	☐
6. Haben Sie Herzrhythmusstörungen?	☐	☐
7. Haben Sie einen Herzschrittmacher?	☐	☐

☐ **Ich kann alle der oben gestellten Fragen mit „Nein“ beantworten und möchte weiterhin an der Studie teilnehmen.**

☐ **Ich kann eine oder mehrere der oben gestellten Fragen mit „Ja“ beantworten und kann daher an der Studie nicht teilnehmen.**

Ich habe den Sinn und Zweck des Fragebogens verstanden und alle Fragen zu meiner Gesundheit wahrheitsgemäß beantwortet.

Datum, Unterschrift Studienteilnehmer/-in

____

Patienten ID (wird vom Testleiter eingetragen): _______________

Declaration of Consent

Einwilligungserklärung

Studie „Kinetische und Kinematische Analyse von Belastungen von ausgewählten Bewegungen bis 1 Jahr nach Verletzungen des vorderen Kreuzbandes“

BioMotion Center, Institut für Sport und Sportwissenschaft (IfSS), Karlsruher Institut für Technologie (KIT)

Hiermit erkläre ich,

Vorname ___________________________

Nachname ___________________________

Geburtsdatum ___________________________

Adresse ___________________________

____

____

Telefonnummer ___________________________

E-Mail ___________________________

Patienten-ID ___________________________ (wird vom Testleiter eingetragen)

dass ich durch Herrn/Frau ____

(Name des Testleiters)

mündlich und schriftlich über das Wesen, die Bedeutung, die Tragweite und mögliche Risiken der einzelnen Untersuchungen im Rahmen der o.g. wissenschaftlichen Studie informiert wurde und ausreichend Gelegenheit hatte, meine Fragen hierzu in einem Gespräch mit dem/der Testleiter/Testleiterin zu klären.

Ich habe insbesondere die mir vorgelegte Patienteninformation verstanden und eine Ausfertigung derselben und dieser Einwilligungserklärung erhalten.

Mir ist bekannt, dass ich meine Einwilligung jederzeit ohne Angabe von Gründen und ohne nachteilige Folgen für mich zurückziehen und einer Weiterverarbeitung meiner erhobenen Daten jederzeit widersprechen und ihre Löschung verlangen kann. Ich bin bereit, an allen Untersuchungen im Rahmen der o.g. wissenschaftlichen Studie teilzunehmen.

Ich erkläre mich damit einverstanden, dass sämtliche, im Rahmen dieser Studie erhobenen Daten/Angaben über mich verschlüsselt (pseudonymisiert) und auf elektronischen Datenträgern aufgezeichnet und verarbeitet werden.
Einer Veröffentlichung der anonymisierten Studienergebnisse stimme ich zu.

______________________________ ______________________

Unterschrift des Patienten Datum

____

Name des Patienten in Druckbuchstaben

Testleiter/Testleiterin, welche(r) die Einwilligung einholt

Hiermit erkläre ich, den/die o.g. Patienten/Patientin am ________________ über Wesen, Bedeutung, Tragweite und Risiken der o.g. Studie mündlich und schriftlich aufgeklärt und Ihm/ Ihr eine Ausfertigung der Patienteninformation sowie dieser Einwilligungserklärung übergeben zu haben.

1. Technische Geräte in einwandfreiem Zustand?	☐
2. Patienten über Risiken und Gefahren aufgeklärt?	☐
3. Fragen über Risikofaktoren überprüft?	☐
4. Ist die Notfallkette inklusive Notrufnummer bekannt?	☐
5. Ist ein funktionsfähiges Telefon vorhanden?	☐

___________________________________ _________________________

Unterschrift Datum

____

Name in Druckbuchstaben

Subjects Personal Specifications

Angaben zur Person

Studie „Kinetische und Kinematische Analysen von Belastungen der Beine bei ausgewählten Bewegungen bis 1 Jahr nach Verletzungen des vorderen Kreuzbandes“

BioMotion Center, Institut für Sport und Sportwissenschaft (IfSS), Karlsruher Institut für Technik (KIT)

Liebe Studienteilnehmerinnen, lieber Studienteilnehmer,

zur Bearbeitung der erhobenen Daten benötigen wir noch einige personenbezogene Angaben von Ihnen.
Bitte lesen Sie alle Fragen vor der Beantwortung genau durch. Bitte beantworten Sie alle Fragen, da nur vollständig ausgefüllte Fragebögen berücksichtigt werden können.
Alle Unterlagen sowie Angaben, die sie zu Ihrer Person machen, dienen ausschließlich wissenschaftlichen Zwecken und werden streng vertraulich behandelt. Die Auswertung erfolgt am Institut für Sport und Sportwissenschaft des KIT.
Die Erfassung von Name, Telefonnummer und E-Mail Adresse ist für die Kommunikation zwischen Projektleitung und Studienteilnehmer/in notwendig.

Bitte ausfüllen:

Patienten-ID (wird vom Testleiter eingetragen): ______________________________

Name, Vorname: ____

Telefonnummer: ____

E-Mail: ____

Persönliche Angaben

1. **Sie sind**
   ☐ weiblich

   ☐ männlich

2. **Wie alt sind Sie?** _________ Geburtsmonat/ Geburtsjahr
3. **Ihre Körpergröße?** _________ cm
4. **Ihr Körpergewicht?** _________ kg
5. **Mit welchem Fuß schießen Sie einen Ball?**

   ☐ rechts

   ☐ links

6. **Mit welchem Bein springen Sie ab?**

   ☐ rechts

   ☐ links

7. **Auf welchem Bein können Sie besser im Einbeinstand stehen?**
   ☐ rechts

   ☐ links

Angaben zur Kreuzbandruptur

1. **Welche Sportarten haben Sie vor Ihrem Kreuzbandriss betrieben?**

   ____

   ____

2. **Haben Sie akute Erkrankungen/ Verletzungen, außer der Kreuzbandverletzung, oder schon früher Verletzungen am selben Kniegelenk gehabt?**

   ☐ ja

   ☐ nein

   Wenn ja, welche?

   ____

   ____

3. Wie wurde Ihr Kreuzband operiert? Mit welcher Technik? Welche Art des Transplantats haben Sie?

4. Haben Sie sonstige, chronische Erkrankungen?

☐ ja

☐ nein

Wenn ja, welche?

5. Tragen Sie eine Orthese (Kniegelenksbandage)? Haben Sie eine Orthese getragen?

☐ ja, immer

☐ ja, bei folgenden Tätigkeiten/ Bewegungen:

☐ nein

6. Nehmen Sie derzeit Schmerzmittel ein?

☐ ja, welche:

☐ nein

7. Sonstige Anmerkungen

Bitte beachten Sie!

Ich habe den Fragebogen freiwillig bearbeitet. Mir ist bekannt, dass meine Daten ausschließlich zum Zwecke wissenschaftlicher Erkenntnisgewinnung verwendet und nicht an Dritte weitergegeben werden.

Vielen Dank für die Beantwortung der Fragen!

10.2 Study Related Questionnaires and Scores

Knee Injury and Osteoarthritis Outcome Score

Knee injury and Osteoarthritis Outcome Score (KOOS)

Datum:________________________ ID: ___________________________

Testtag-Nr.:____________________

ANLEITUNG:

Dieser Ankreuzbogen befragt Sie, welchen Eindruck Sie von Ihrem Knie haben.

Die dadurch gewonnene Information wird uns helfen zu überwachen, wie es Ihnen mit Ihrem Knie geht und wie gut Sie in der Lage sind, Ihre üblichen Aktivitäten zu verrichten.

Beantworten Sie bitte jede Frage durch ankreuzen des zugehörigen Kästchens.

Bitte nur ein Kästchen pro Frage ankreuzen.

Wenn Sie sich unsicher sind, wie Sie die Frage beantworten sollen, wählen Sie die Antwort aus, die Ihnen am zutreffendsten erscheint.

Symptome

Diese Fragen beziehen sich auf Beschwerden von Seiten Ihres Kniegelenkes in der **vergangenen Woche**.

S1. Haben Sie Schwellungen an Ihrem Knie?

niemals	selten	manchmal	oft	immer
☐	☐	☐	☐	☐

S2. Fühlen Sie manchmal ein Mahlen, hören Sie manchmal ein Klicken oder irgendein Geräusch, wenn Sie Ihr Knie bewegen?

niemals	selten	manchmal	oft	immer
☐	☐	☐	☐	☐

S3. Bleibt Ihr Knie manchmal hängen, oder blockiert es, wenn Sie es bewegen?

niemals	selten	manchmal	oft	immer
☐	☐	☐	☐	☐

S4. Können Sie Ihr Knie ganz ausstrecken?

immer	oft	manchmal	selten	nie
☐	☐	☐	☐	☐

S5. Können Sie Ihr Knie ganz beugen?

immer	oft	manchmal	selten	nie
☐	☐	☐	☐	☐

Steifigkeit

Die nachfolgenden Fragen betreffen die Steifigkeit Ihres Kniegelenkes während der **letzten Woche**. Unter Steifigkeit versteht man ein Gefühl der Einschränkung oder Verlangsamung der Fähigkeit Ihr Kniegelenk zu bewegen.

Für jede der nachfolgenden Aktivitäten sollen Sie das Ausmaß der Schwierigkeiten angeben, welche Sie durch Ihr Kniegelenk innerhalb der letzten Woche erfahren haben.

S6. Wie stark ist Ihre Kniesteifigkeit morgens direkt nach dem Aufstehen?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

S7. Wie stark ist Ihre Kniesteifigkeit nach dem Sie saßen, lagen, oder sich ausruhten im **Verlauf des Tages**?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

Schmerzen

P1. Wie oft tut Ihnen Ihr Knie weh?

niemals	monatlich	wöchentlich	täglich	immer
☐	☐	☐	☐	☐

Wie ausgeprägt waren Ihre Schmerzen in der **vergangenen Woche** als Sie z.B…:

P2. sich im Knie drehten?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

P3. Ihr Knie ganz ausstreckten?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

P4. Ihr Knie ganz beugten?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

P5. auf ebenem Boden gingen?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

P6. Treppen herauf oder heruntergingen?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

P7. nachts im Bett lagen?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

P8. saßen oder lagen, z.B. auf der Couch?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

P9. aufrecht standen?

keine	schwach	mäßig	stark	sehr stark
☐	☐	☐	☐	☐

Aktivitäten des täglichen Lebens

Die nachfolgenden Fragen beziehen sich auf Ihre körperliche Leistungsfähigkeit.
Hierunter verstehen wir Ihre Fähigkeit sich selbständig zu bewegen bzw. sich selbst zu versorgen.
Für jede der nachfolgenden Aktivitäten sollen Sie das Ausmaß der Schwierigkeiten angeben, welche Sie durch Ihr Kniegelenk innerhalb der **letzten Woche** erfahren haben.

Welche Schwierigkeiten hatten Sie **letzte Woche** als Sie z.B….:

A1. Treppen herunterstiegen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A2. Treppen heraufstiegen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A3. vom Sitzen aufstanden?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

Welche Schwierigkeiten hatten Sie **letzte Woche** als Sie z.B….:

A4. standen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A5. sich bückten um z.B. etwas vom Boden aufzuheben?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A6. auf ebenen Boden gingen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A7. ins Auto ein- oder ausstiegen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A8. einkaufen gingen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A9. Strümpfe/Socken anzogen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A10. vom Bett aufstanden?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A11. Strümpfe/Socken auszogen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A12. im Bett lagen und sich drehten, ohne das Knie dabei zu beugen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A13. in oder aus der Badewanne kamen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A14. saßen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A15. sich auf die Toilette setzten oder aufstanden?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A16. schwere Hausarbeit verrichteten (schrubben, Garten umgraben, ...)?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

A17. leichte Hausarbeit verrichteten (Staub wischen, kochen, ...)?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

Sport und Freizeit

Die nachfolgenden Fragen beziehen sich auf Ihre körperliche Belastbarkeit im Rahmen eher sportlicher Aktivitäten.
Für jede der nachfolgenden Aktivitäten sollen Sie das Ausmaß der Schwierigkeiten angeben, welche Sie durch Ihr Kniegelenk innerhalb der **letzten Woche** erfahren haben.

Hatten Sie Schwierigkeiten **letzte Woche** als Sie z.B….:

SP1. in die Hocke gingen?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

SP2. rannten?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

SP3. hüpften?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

SP4. sich auf Ihrem kranken Knie umdrehten?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

SP5. sich hinknieten?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

Beeinflussung der Lebensqualität durch das betroffene Knie

Q1. Wie oft spüren Sie Ihr erkranktes Knie?

nie	monatlich	wöchentlich	täglich	immer
☐	☐	☐	☐	☐

Q2. Haben Sie Ihre Lebensweise verändert um eventuell Ihrem Knie schadende Tätigkeiten zu vermeiden?

nicht	wenig	etwas	stark	vollständig
☐	☐	☐	☐	☐

Q3. Wie sehr macht es Ihnen zu schaffen, dass Ihr Knie nicht stabil ist?

gar nicht	wenig	einiges	schlimm	sehr schlimm
☐	☐	☐	☐	☐

Q4. Wie würden Sie insgesamt die Schwierigkeiten bewerten die Sie durch das Knie haben?

keine	wenig	einige	große	sehr große
☐	☐	☐	☐	☐

Tegner Activity Score

Tegner Aktivitäts-Score (TAS)

Datum:________________________ ID: ___________________________

Testtag-Nr.:____________________

Standardisierter und evaluierter Fragebogen zur Bestimmung der körperlich, sportlichen Aktivität. Je nach Aktivitätsniveau werden 0 bis 10 Punkte vergeben. (Tegner & Lysholm, 1985)[6]

	Derzeitiges Aktivitäts-niveau	**Aktivitätsgrad**	**Punkte**
		Leistungssport Fußball – nationale und internationale Elite	**10**
		Leistungssport Fußball (untere Ligen), Eishockey, Ringen, Turnen	**9**
		Leistungssport Bandy, Squash oder Badminton, Leichtathletik (Sprünge etc.), Ski Alpin	**8**
		Leistungssport Tennis, Leichtathletik (Rennen, Laufen), Moto-Cross (Speedway), Handball, Basketball **Freizeitsport** Fußabll, Bandy und Eishockey, Squash, Leichtathletik (Sprünge), Geländelauf (Leistungs- und Freizeitsport)	**7**
		Freizeitsport Tennis und Badminton, Handball, Basketball, Ski Alpin, Joggen (min. 5 mal pro Woche)	**6**
		Wettkampfsport Radfahren, Skilanglauf **Freizeitsport** Joggen auf unebenem Untergrund (min. 2 mal pro Woche) **Arbeit**	**5**

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[6] Tegner, Y. & Lysholm, J. (1985). Ratings Systems in the Evaluation of Knee Ligament Injuries. *Clinical Orthopaedics and Related Research*, *23* (198), 43-49.

		Schwere Arbeit (z.B. Bauarbeiter, Waldarbeiter)	
		Freizeitsport Radfahren, Skilanglauf, Joggen auf ebenem Untergrund (min. 2 mal pro Woche) **Arbeit** Mittelschwere Arbeit (z.B. Fernfahrer, schwere häusliche Arbeit)	**4**
		Leistungs- und Freizeitsport Schwimmen **Arbeit** Leichte Arbeit (z.B. Krankenpflege) **Gehen** Gehen im Wald ist möglich	**3**
		Arbeit Leichte Arbeit **Gehen** Auf unebenem Grund möglich; aber Gehen im Wald unmöglich.	**2**
		Arbeit Sitzende Arbeit **Gehen** Auf ebenem Untergrund möglich	**1**
		Im Krankenstand oder Erwerbsunfähigkeitsrente wegen Knieproblemen	**0**

10.3 Landmarks for Assessment of the Subjects' Anthropometrics

Table 8. Landmarks of the anthropometric measurements.

Name	Definition	Measuring Instruction
Weight	Body Weight	Measured by the force platforms.
HLeg	Functional Leg Length	Vertical distance of pubic bone to the ground. Use of a spirit level between the legs in parallel orientation to the ground.
HWaist	Height of the Waist	Narrowest part of the waist above the iliac crest; vertical distance from ground to the most medial point of the thorax's frontal profile between the iliac crest and the lower costal arch.
HXiphoid	Height of the Sternum's Xiphoid	Vertical distance in the median plane of the Sternum's Xiphoid to the ground.
HAtlas	Height of the Atlas Vertebra	Vertical distance of the onset of the cranial bone (small depression in the neck) to the ground.
LFoot	Foot Length	Horizontal distance of the most prominent point of the heels to the longest of the toes (1st or 2nd toe).
CCalf	Largest Circumference Calf	Stand up straight, Muscles loose, at the point of largest circumference of the calf.
CThigh	Largest Circumference Thigh	Stand up straight, Muscles loose, at the point of largest circumference of the thigh (note the transition of the Mm. glutei).
CLowerLegS	Smallest Circumference Calf	Stand up straight, Muscles loose, close to the upper ankle joint.
Whip	Largest Hip Width	Largest horizontal distance between the most lateral landmarks of the hip.
WWaist	Width of the Waist	Horizontal distance of the two most medial points of the thorax's frontal profile between the iliac crest and the lower costal arch.
CHip	Largest Circumference Hip	Horizontal circumference in height of the most prominent bulks of the Mm. glutei.
CWaist	Waist Circumference	Horizontal circumference in height of the most medial points of the thorax's frontal profile between the iliac crest and the lower costal arch
WBreast	Thorax Frontal Width	In level of the lower sternum; horizontal distance of the most lateral costal points in the frontal plane.
DBreast	Thorax Sagittal Width	Linear sagittal distance from the lower edge of the Xiphoid to the most dorsal point at the spine.
LHand	Hand Length	Hand rests extended on a table; horizontal distance from the centre of the wrist to the most distal point of middle finger.
CUpperArmL	Largest Circumference Upper Arm	Elbow flexed 90° with no M. biceps contraction. Horizontal circumference at the most prominent muscular bulks.

CForeArmL	Largest Circumference Forearm	Arm in extended position. Point of most prominent muscular bulks, close to the elbow joint.
CForeArmS	Smallest Circumference Forearm	Arm in extended position. Close to the wrist.
CCervical	Neck Size	Perpendicular to the vertical axis of the neck. Horizontal circumference, directly below the larynx.
LPate	Head Height	Distance from the most prominent point of the lower jaw in median plane to the most prominent point of the parietal bone in median plane.

Ovierview of the anthropometric measurements. In the first column the names of the measuring points are listed. The second column contains the anatomic definition. In the third column the measuring instructions are presented.

10.4 Dynamicus Marker Set

Table 9. Applied markers (abbreviations) attached to the respective anatomical landmarks. *According to the ALASKA, Dynamicus Marker-Set (HÄRTEL & HERMSDORF 2006).*

HEAD			
LFHD	Left front head	**RFHD**	Right front head
LBHD	Left back head	**LBHD**	Right back head
TRUNK			
C7	7th cervical vertebrae	**CLAV**	Clavicle
T10	10th thoracic vertebrae	**STRN**	Sternum
UPPER LIMB			
LACR	Left acromion	**RACR**	Right acromion
LHUM	Left humerus	**RHUM**	Right humerus
LELB_med	Left elbow medial epicondyle	**RELB_med**	Right elbow medial epicondyle
LELB_lat	Left elbow lateral epicondyle	**RELB_lat**	Right elbow lateral epicondyle
LWRI_med	Left wrist medial	**RWRI_med**	Right wrist medial
LWRI_lat	Left wrist lateral	**RWRI_lat**	Right wrist lateral
LFIN	2nd phalanx left hand	**RFIN**	2nd phalanx right hand
PELVIS			
LASI	Left anterior iliac spine	**RASI**	Right anterior iliac spine
LPSI	Left posterior iliac spine	**RPSI**	Right posterior iliac spine

LOWER LIMB			
LKNE_med	Left knee medial joint space	**RKNE_med**	Right knee medial joint space
LKNE_lat	Left knee lateral joint space	**RKNE_lat**	Right knee lateral joint space
LMAL_med	Left medial malleolus	**RMAL_med**	Right medial malleolus
LMAL_lat	Left lateral malleolus	RMAL_lat	Right lateral malleolus
LHEEL	Left heel	**RHEEL**	Right heel
LFOOT_med	Head of the proximal phalanx of the first toe left	**RFOOT_med**	Head of the proximal phalanx of the first toe left
LFOOT_lat	Head of the proximal phalanx of the little toe left	**RFOOT_lat**	Head of the proximal phalanx of the little toe left
LTOE	Left big toe	**RTOE**	Right big toe

10.5 Summarized Rehabilitation Program of the ACL Reconstructed Subjects

Table 10. Summarized Rehabilitation Program of the ACL Reconstructed Subjects.

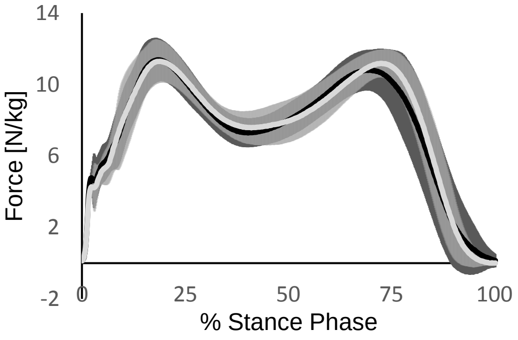
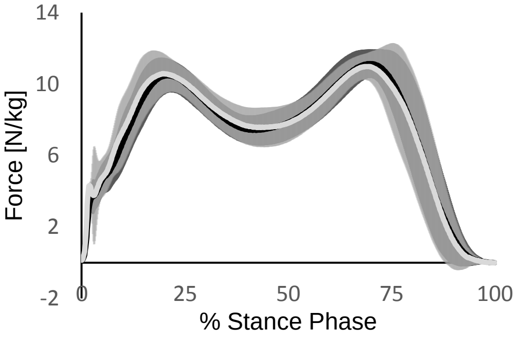
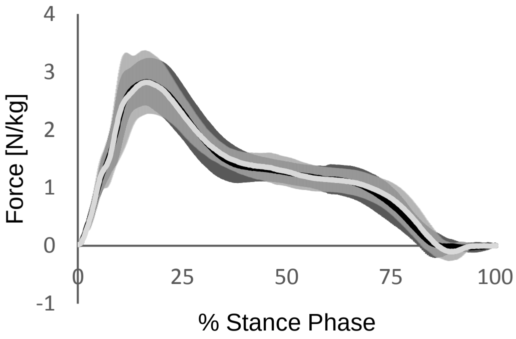
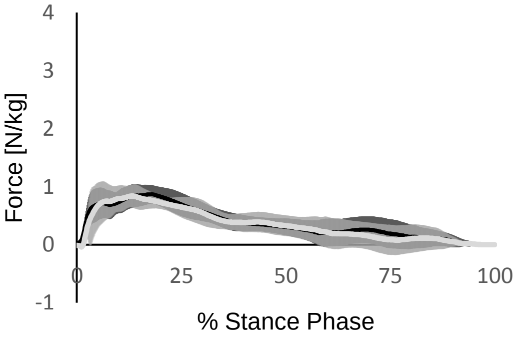
	Time post-reconstruction	**Rehabilitation exercises**
1st stage	1st week	PT: Lymphatic drainage, physical therapy (passive ROM exercises, massage).
		ADL: Walking with crutches.
	2nd week	PT: Lymphatic drainage, physical therapy (passive ROM exercises, massage, closed-kinetic chain exercises).
		ADL: Walking with crutches.
	3rd week	PT: Lymphatic drainage, physical therapy (passive ROM exercises, massage, closed-kinetic chain exercises).
		ADL: Walking with crutches.
	4th week	PT: Lymphatic drainage, physical therapy (passive ROM exercises, massage, closed-kinetic chain exercises, stability exercises).
		ADL: Walking without or with one crutch.
	5th week	PT: Proprioceptive training (One-legged stance, step-up forward/ backward, stability exercises), ROM exercises, closed-kinetic chain exercises.
		ADL: Walking without or with one crutch, stair climbing.
	6th week	PT: Proprioceptive training (One-legged stance, step-up forward/ backward, stability exercises), ROM exercises, closed-kinetic chain exercises.
		ADL: Walking without crutches, stair climbing ergometer cycling, Aqua jogging.
	7th week	PT: Proprioceptive training (One-legged stance, step-up forward/ backward, stability exercises), ROM exercises, closed-kinetic chain exercises.
		ADL: Walking without crutches, ergometer cycling, Aqua jogging.
2nd stage	8th week	PT: core strength training, proprioceptive training unstable surface, gymnastics/stretching.
		ADL: Walking, (ergometer) cycling, Aqua jogging.
	9th week	PT: core strength training, proprioceptive training unstable surface, gymnastics/stretching.
		ADL: Walking, (ergometer) cycling.
	10th week	PT: core strength training, low-intensity lunges, leg press, proprioceptive training unstable surface, gymnastics/stretching.
		ADL: Walking, (ergometer) cycling.

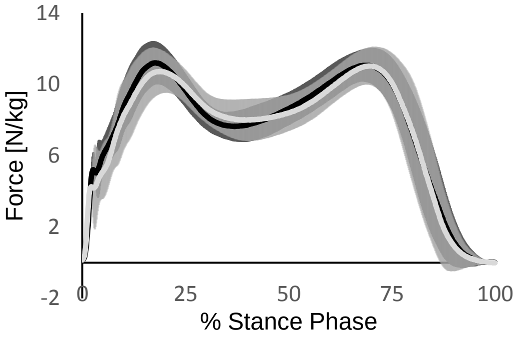
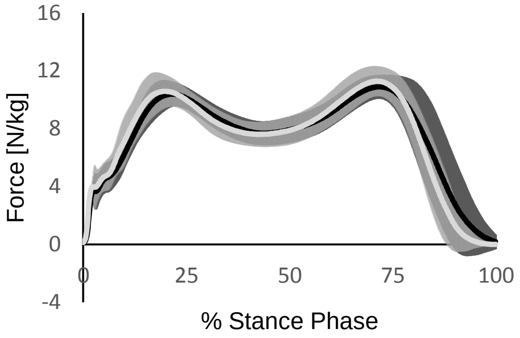
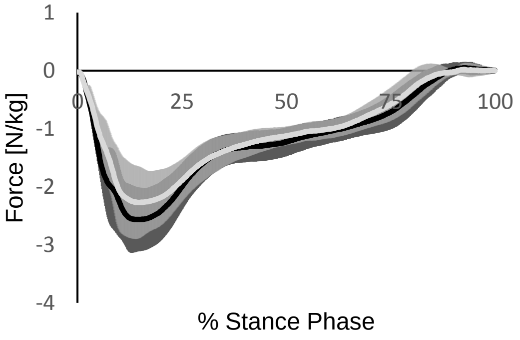
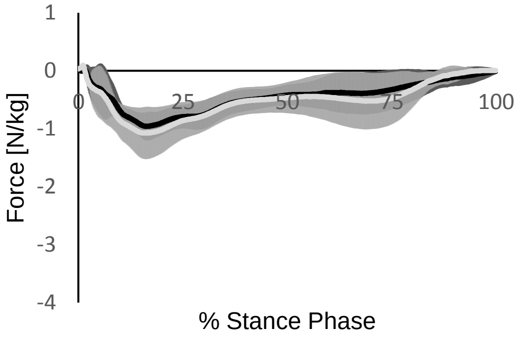
	11th week	PT: core strength training, medium-intensity lunges, leg press, proprioceptive training unstable surface.
		ADL: (Ergometer) cycling, Cross-Trainer, Walking on treadmill.
	12th week	PT: core strength training, medium-intensity lunges, leg press, proprioceptive training unstable surface.
		ADL: (Ergometer) cycling, Cross-Trainer, Walking on treadmill.
	13th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface, one-legged lunges.
		ADL: Cross-Trainer, Walking on treadmill, cycling.
	14th week	ADL: Cross-Trainer, Walking on treadmill, cycling.
3rd stage	15th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface.
		SP: Swimming, cycling.
	16th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: Swimming, cycling.
	17th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: Swimming, cycling, moderate jogging.
	18th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: Swimming, cycling, moderate jogging.
	19th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: Swimming, cycling, moderate jogging.
	20th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: Swimming, cycling, moderate jogging.
	21st week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: Swimming, cycling, moderate jogging.
	22nd week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: One-legged jumps for distance and vertical, swimming, cycling.
	23rd week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: unilateral and bilateral lateral jumps, jogging.

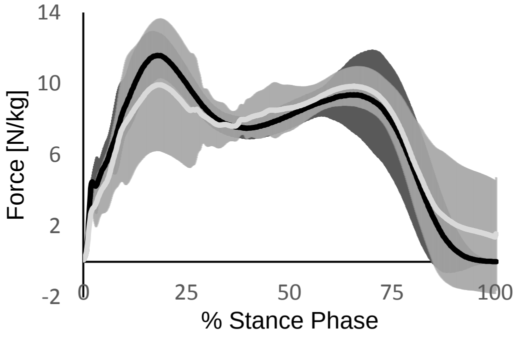
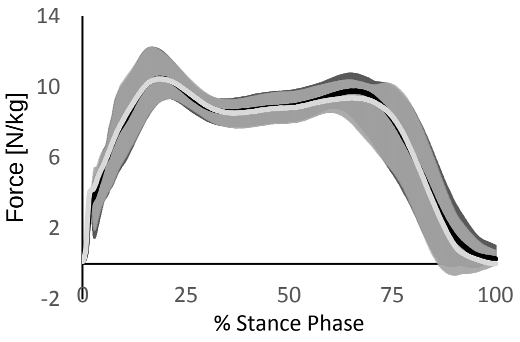
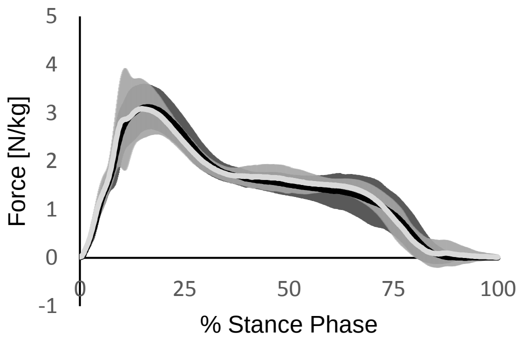
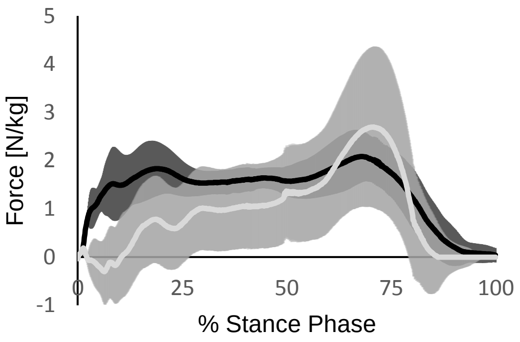
	24th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: jogging, pre-injury sports.
	25th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: jogging, pre-injury sports
	26th week	PT: Core strength training (leg press, Abduction, knee flexion), proprioceptive training unstable surface
		SP: jogging, pre-injury sports

Summarized rehabilitation program of the ACL reconstructed subjects. *Summarized rehabilitation programs and performed recreational and/or sports activities of the ACL reconstructed subjects up to 6 months post-ACL reconstruction. Distinguished in physiotherapeutic exercises (PT), activities of daily living (ADL), and recreational or sports activities (SP).*

10.6 Means of Force-Over-Time of all Tested Turning Conditions

	90 left	
	Leading Leg	**Trailing Leg**
F_z		
F_y		

	90 right	
	Leading Leg	**Trailing Leg**
F_z		
F_y		

	180 left	
	Leading Leg	**Trailing Leg**
F_z		
F_y		

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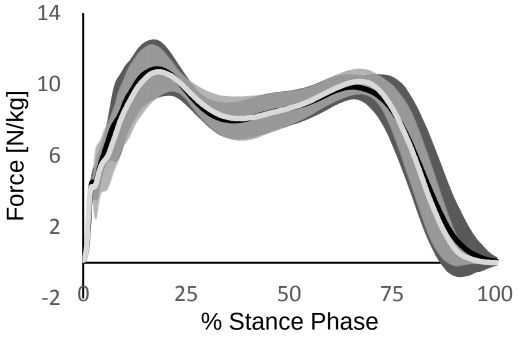

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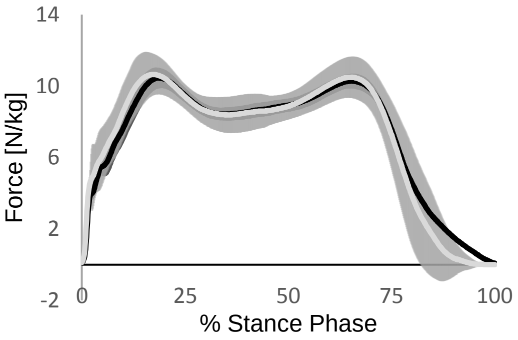

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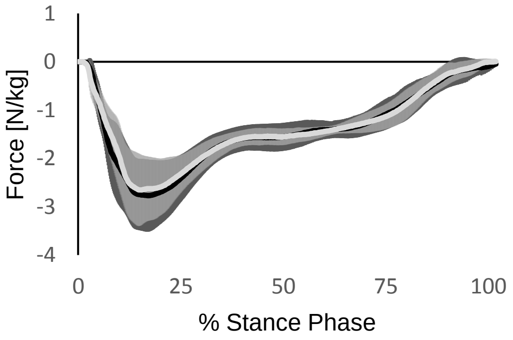

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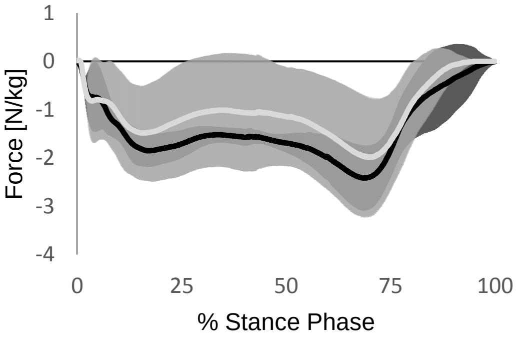

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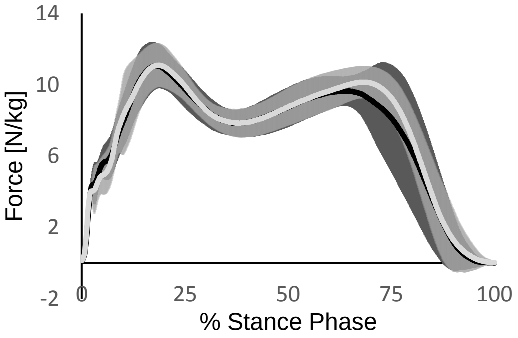
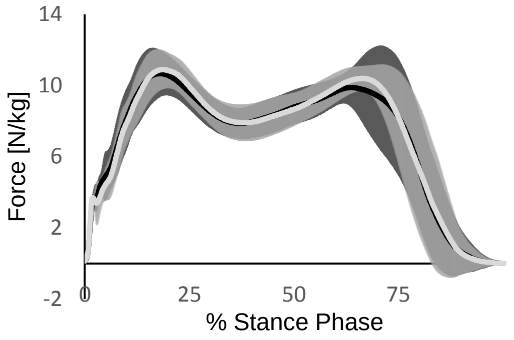
<tr><td>F_z</td><td>
</td><td>
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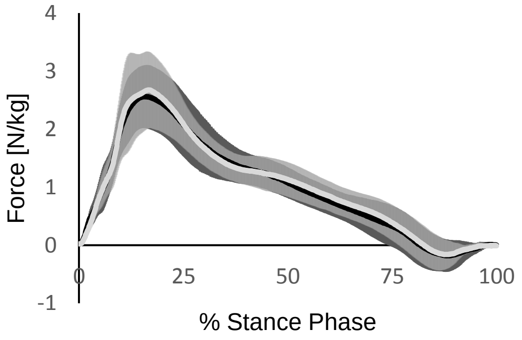
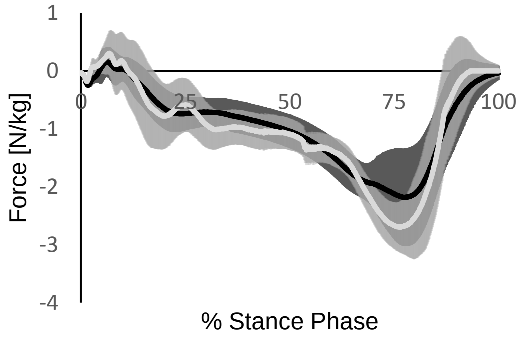
<tr><td>F_y</td><td>
</td><td>
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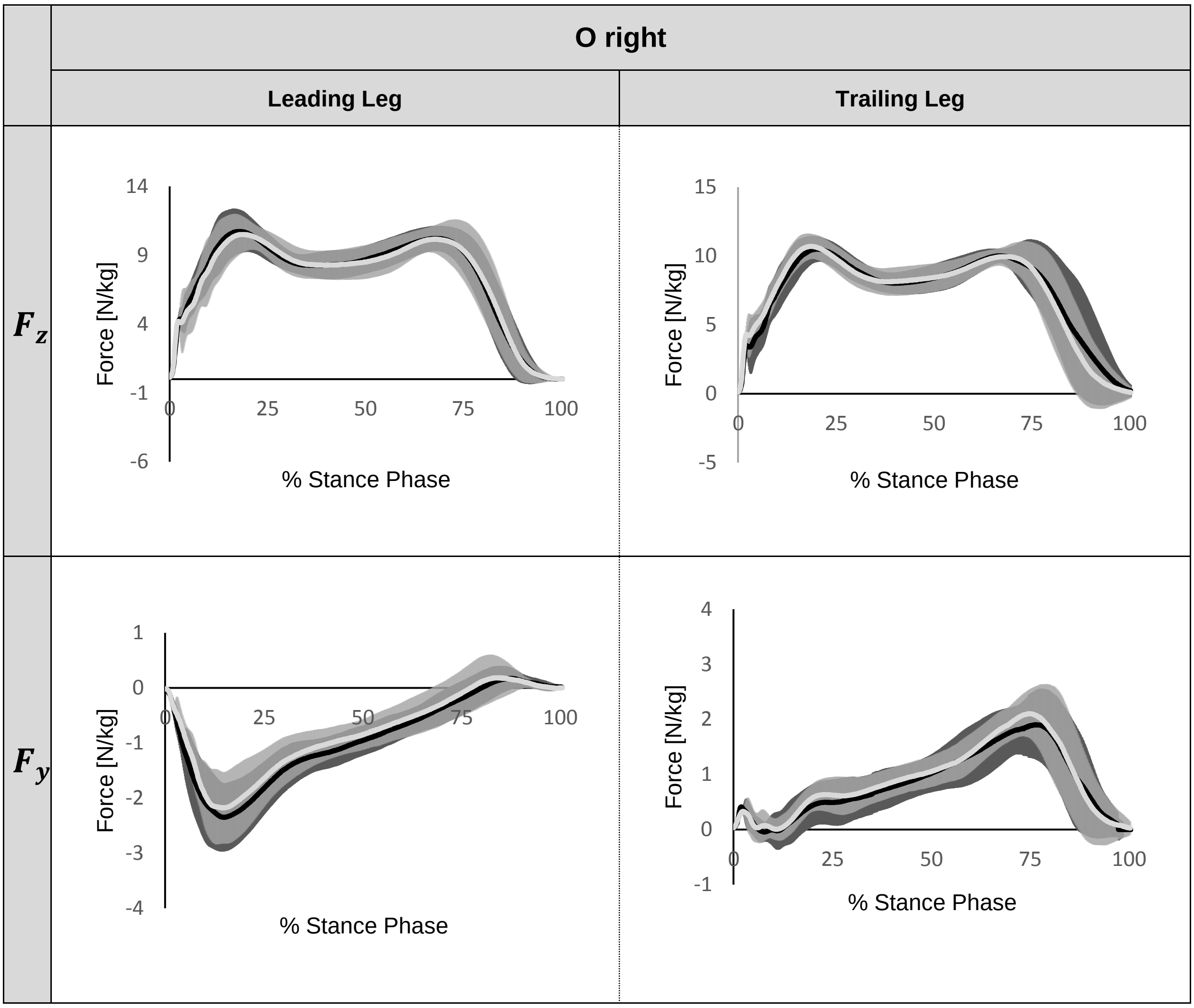


Figure 36. Means of force-over-time over the three turning conditions '90' (90° turn), '180' (180° turn), and 'O' (turn as avoiding an obstacle) with their two orientations, clockwise (right) and counter-clockwise (left). *The X-axes are normalized in % stance phase. The Y-axes show the force values in Newton per bodyweight [N/kg]. The black lines represent the means from the test session (SD in dark grey) and the light grey lines (SD light grey) represent the retest session.*

10.7 Results of the Isometric Force Tests

Table 11. Mean LSIs and standard deviations (±) of the analyzed parameters of the isometric force tests.

Parameter	Test condition	T1	T2	T3	T4	Control group	Significant differences
F_{max} **[N/kg]**	Flexion 90°	0.74 ± 0.22	0.27 ± 0.10	0.43 ± 0.09	0.58 ± 0.08	1.05 ± 0.13	T_1/T_2: $T(17) = 5.00,\ P < 0.01, d = 0.91$ T_2/T_3: $T(16) = 3.22,\ P = 0.01, d = 0.82$ T_3/T_4: $T(17) = 3.28,\ P < 0.01, d = 0.77$ T_4/CG: $T(38) = 6.05,\ P < 0.01, d = 1.91$
	Flexion 110°	0.64 ± 0.18	0.34 ± 0.20	0.46 ± 0.13	0.49 ± 0.09	1.02 ± 0.12	T_1/T_2: $T(12) = 2.89,\ P = 0.01, d = 1.10$ T_2/T_3: $T(11) = 4.62,\ P < 0.01, d = 0.54$ T_3/T_4: $T(15) = 2.47,\ P = 0.03, d = 0.38$ T_4/CG: $T(38) = 7.00,\ P < 0.01, d = 2.21$
	Extension 90°	0.76 ± 0.13	0.47 ± 0.13	0.62 ± 0.15	0.73 ± 0.12	1.03 ± 0.15	T_1/T_2: $T(17) = 4.66,\ P < 0.01, d = 0.88$ T_2/T_3: $T(16) = 3.45,\ P = 0.01, d = 0.54$ T_4/CG: $T(38) = 3.06,\ P < 0.01;\ d = 0.97$
	Extension 110°	0.83 ± 0.14	0.46 ± 0.18	0.63 ± 0.10	0.75 ± 0.09	1.08 ± 0.09	T_1/T_2: $T(14) = 4.98,\ P < 0.01, d = 1.14$ T_2/T_3: $T(13) = 3.54,\ P < 0.01, d = 0.61$ T_3/T_4: $T(16) = 4.57, P < 0.01, d = 0.80$ T_4/CG: $T(38) = 5.02, P < 0.01;\ d = 1.59$

Parameter	Test condition	T1	T2	T3	T4	Control group	Significant differences
RFD_{max} **[N/kg*s]**	Flexion 90°	0.60 ± 0.16	0.34 ± 0.13	0.53 ± 0.11	0.67 ± 0.20	1.06 ± 0.19	T_1/T_2: $T(19) = 2.97,\ P < 0.01, d = 0.75$ T_4/CG: $T(38) = 2.85,\ P < 0.01, d = 0.90$
	Flexion 110°	0.59 ± 0.18	0.52 ± 0.26	0.40 ± 0.14	0.56 ± 0.11	1.04 ± 0.17	T_1/T_2: $T(16) = 2.58,\ P = 0.02, d = 0.54$ T_3/T_4: $T(19) = 3.79,\ P < 0.01, d = 0.69$ T_4/CG: $T(38) = 4.66,\ P < 0.01, d = 1.47$
	Extension 90°	0.94 ± 0.22	0.61 ± 0.20	0.67 ± 0.18	0.82 ± 0.18	1.21 ± 0.19	T_1/T_2: $T(19) = 2.60,\ P = 0.02, d = 0.62$ T_3/T_4: $T(19) = 3.15,\ P < 0.01, d = 1.06$
	Extension 110°	0.89 ± 0.26	0.55 ± 0.23	0.56 ± 0.19	0.69 ± 0.14	1.12 ± 0.15	T_1/T_2: $T(17) = 2.69,\ P = 0.02, d = 0.72$ T_3/T_4: $T(19) = 2.49,\ P = 0.02, d = 0.58$ T_4/CG: $T(38) = 4.22,\ P < 0.01;\ d = 1.33$
RFD_{200max} **[N/kg*s]**	Flexion 90°	0.65 ± 0.23	0.36 ± 0.16	0.61 ± 0.30	0.60 ± 0.12	1.18 ± 0.37	T_4/CG: $T(38) = 2.93,\ P < 0.01, d = 0.93$
	Flexion 110°	0.61 ± 0.18	0.44 ± 0.23	0.44 ± 0.14	0.61 ± 0.22	1.12 ± 0.40	T_1/T_2: $T(16) = 2.35,\ P = 0.03, d = 0.54$ T_4/CG: $T(38) = 2.21,\ P < 0.03, d = 0.70$
	Extension 90°	0.92 ± 0.32	0.54 ± 0.22	0.94 ± 0.34	0.81 ± 0.19	1.04 ± 0.16	
	Extension 110°	0.93 ± 0.30	0.42 ± 0.20	0.54 ± 0.20	0.66 ± 0.18	1.22 ± 0.28	T_1/T_2: $T(17) = 3.01,\ P < 0.01, d = 0.90$ T_4/CG: $T(38) = 3.23,\ P < 0.01, d = 1.03$

Mean Leg symmetry indices with 95% confidence intervals of the parameters analyzed in the isometric force tests: Maximum force (F_{max}), maximum rate of force development (RFD_{max}) and maximum rate of force development in the first 200ms after contraction initiation (RFD_{200max}) standardized by body weight (kg). In the last column all significant differences with COHEN's d of the post-hoc analysis are illustrated ($P < 0.05$).

10.8 Knee Flexion Graphs of Turning Gait Analyses with Tendencies of Functional Adaptations in the Injured Leg at all four Test Sessions Compared to the Control Group

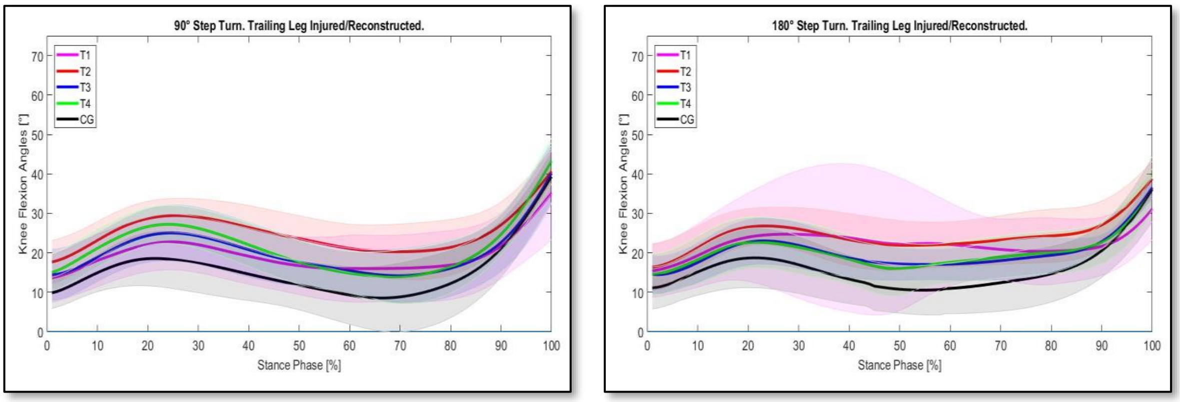


Figure 37. Knee flexion angles of the injured/reconstructed leg during the stance phase in the 90° (left) and 180° (right) step turns. *Mean graphs of the knee flexion angles of the injured/reconstructed legs of the ACL group acting as trailing legs in both turns at the four test sessions (T1 to T4) and the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.*

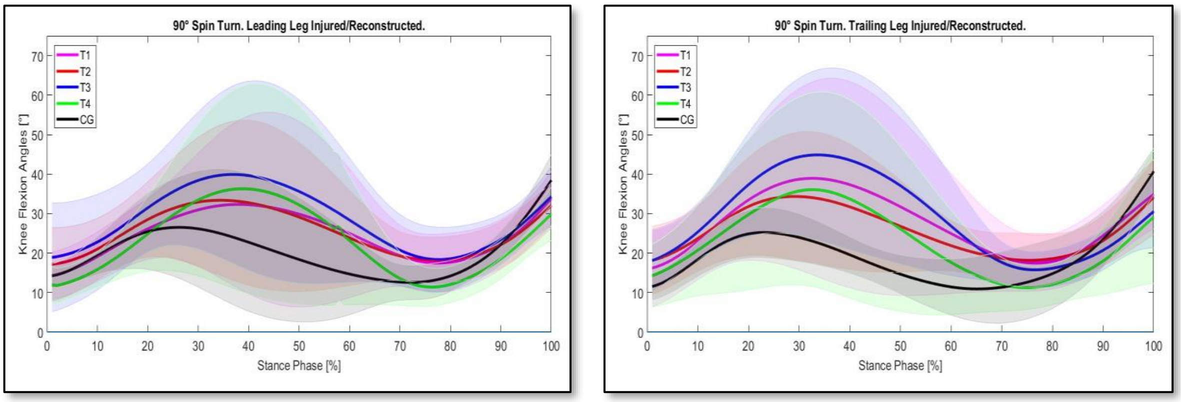
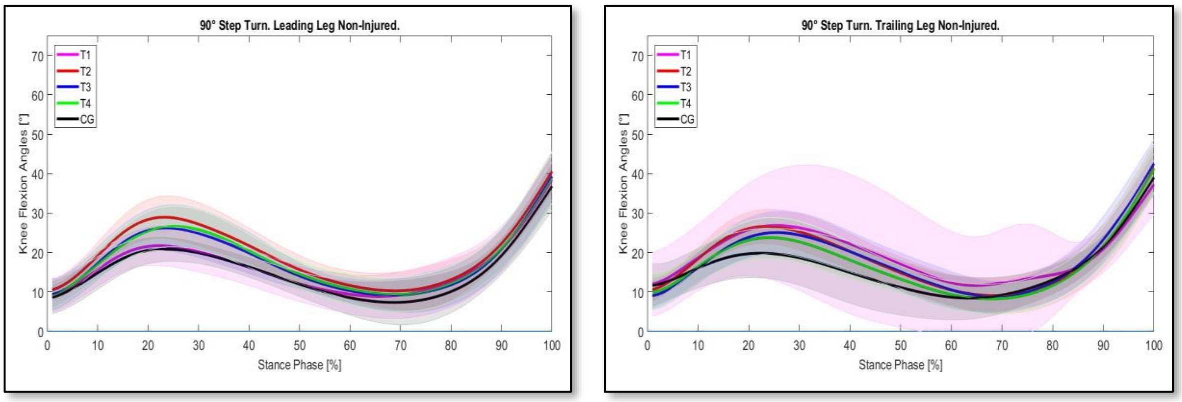


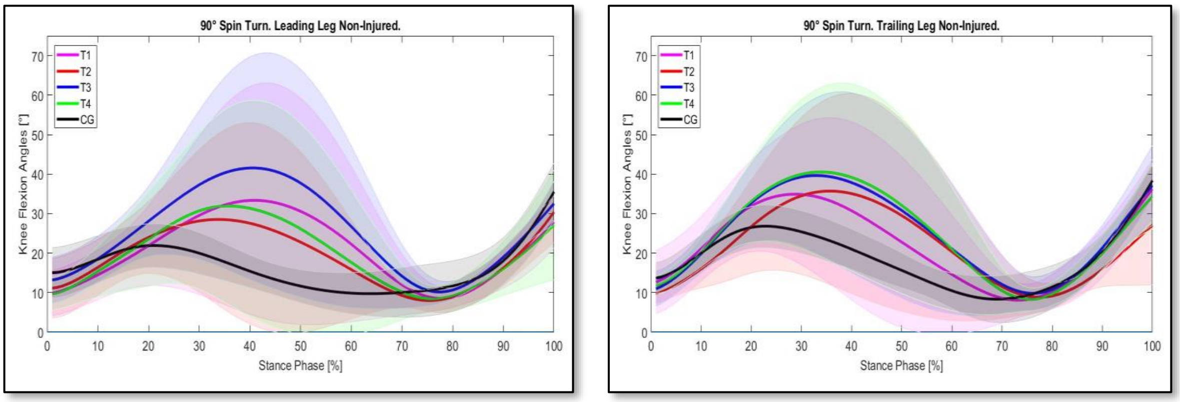
Figure 38. Knee flexion angles of the injured/reconstructed leg during the stance phase in the 90° spin turns. *Mean graphs of the knee flexion angles of the injured/reconstructed legs of the ACL group acting as leading legs (left) and as trailing legs (right) in the 90° spin turns (T1 to T4). The knee flexion angles of the injured/reconstructed legs were compared to the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.*



90° Step Turn. Leading Leg Non-Injured.

90° Step Turn. Trailing Leg Non-Injured.

__Figure 39. Knee flexion angles of the non-injured leg during the stance phase in the 90° step turns.__ Mean graphs of the knee flexion angles of the non-injured legs of the ACL group acting as leading legs (left) and as trailing legs (right) in the 90° step turns (T1 to T4). The knee flexion angles the non-injured legs were compared to the dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.

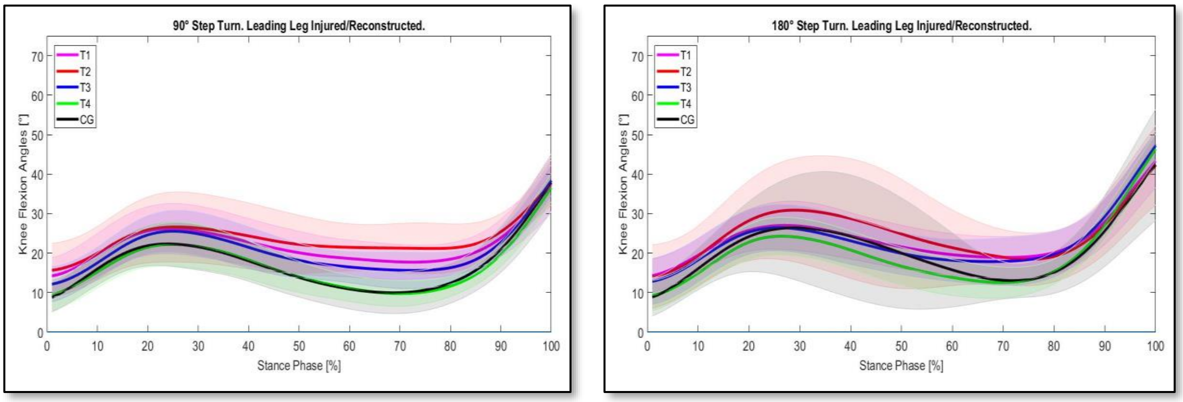


90° Spin Turn. Leading Leg Non-Injured.

90° Spin Turn. Trailing Leg Non-Injured.

__Figure 40. Knee flexion angles of the non-injured leg during the stance phase in the 90° spin turns.__ Mean graphs of the knee flexion angles of the non-injured legs of the ACL group acting as leading legs (left) and as trailing legs (right) in the 90° spin turns (T1 to T4). The knee flexion angles of the non-injured legs were compared to the dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.

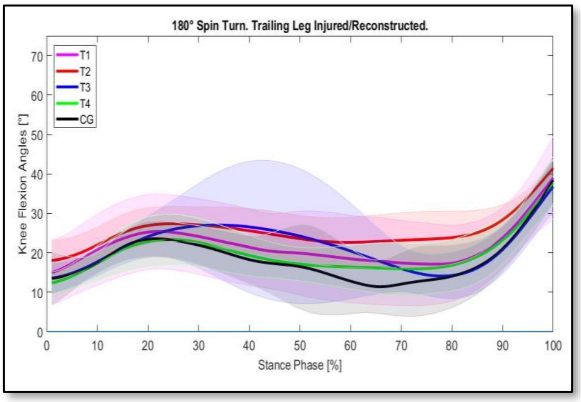
10.9 Knee Flexion Graphs of the Turning Locomotion Conditions with Increased Knee Flexion T1 to T3 and Balanced Knee Flexion at T4 Compared to the CG



90° Step Turn. Leading Leg Injured/Reconstructed.

180° Step Turn. Leading Leg Injured/Reconstructed.

Figure 41. Knee flexion angles of the injured/reconstructed leg during the stance phase in the 90° step turns (left) and the 180° step turns (right). *Mean graphs of the knee flexion angles of the injured/reconstructed legs of the ACL group acting as leading legs in the 90° step turns (left) and 180° step turns (right). The knee flexion angles of the injured/reconstructed legs were compared to the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.*



180° Spin Turn. Trailing Leg Injured/Reconstructed.

Figure 42. Knee flexion angles of the injured/reconstructed legs during the stance phase in the 180° spin turns. *Mean graphs of the knee flexion angles of the injured/reconstructed legs of the ACL group acting as trailing legs in the 180° spin turns. The knee flexion angles of the injured/reconstructed legs were compared to the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.*

10.10 Knee Flexion Graphs of the Turning Gait Analyses with Uniform Courses

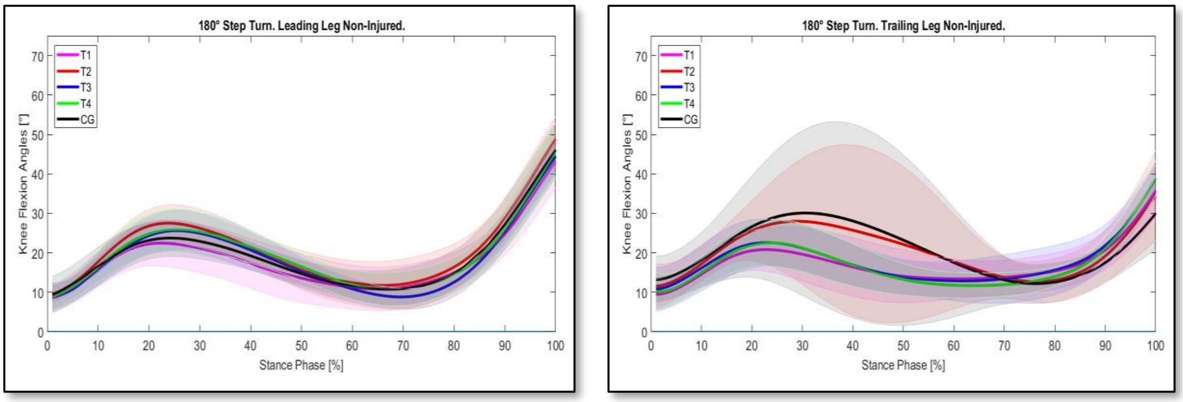


Figure 43. Knee flexion angles of the non-injured legs in the 180° step turns. *Mean graphs of the knee flexion angles of the non-injured legs of the ACL group acting as leading legs (left) and trailing legs (right) in 180° step turns. The knee flexion angles of the non-injured legs were compared to the dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.*

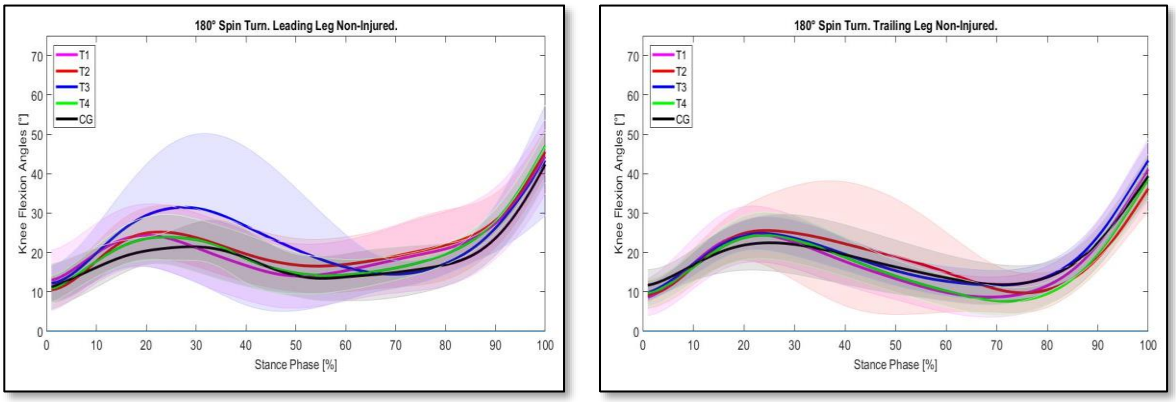


Figure 44. Knee flexion angles of the non-injured legs in the 180° spin turns. *Mean graphs of the knee flexion angles of the non-injured legs of the ACL group acting as leading legs (left) and trailing legs (right) in the 180° spin turns. The knee flexion angles of the non-injured legs were compared to the dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.*

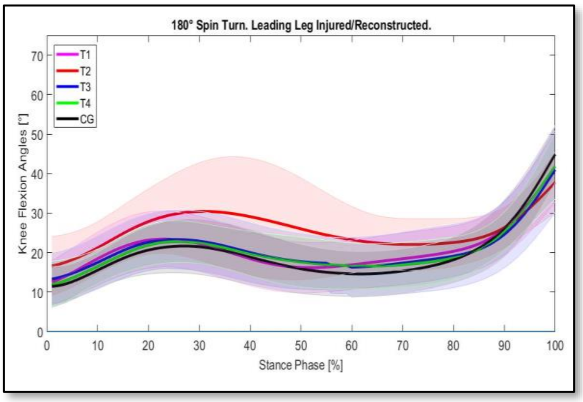


Figure 45. Knee flexion angles of the injured/reconstructed legs during the stance phase in the 180° spin turns. *Mean graphs of the knee flexion angles of the injured/reconstructed legs of the ACL group acting as leading legs in the 180° spin turns. The knee flexion angles of the non-injured legs were compared to the dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored line, T3 by the blue-colored line, and T4 by the green-colored line. The black-colored line illustrates the knee flexion course of the CG. Shaded areas represent the standard deviations. Positive values indicate knee flexion angles, negative values indicate knee extension angles.*

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10.11 Knee Moment Graphs of Turning Locomotion Conditions Showing Tendencies of Kinetic and Kinematic Adaptations

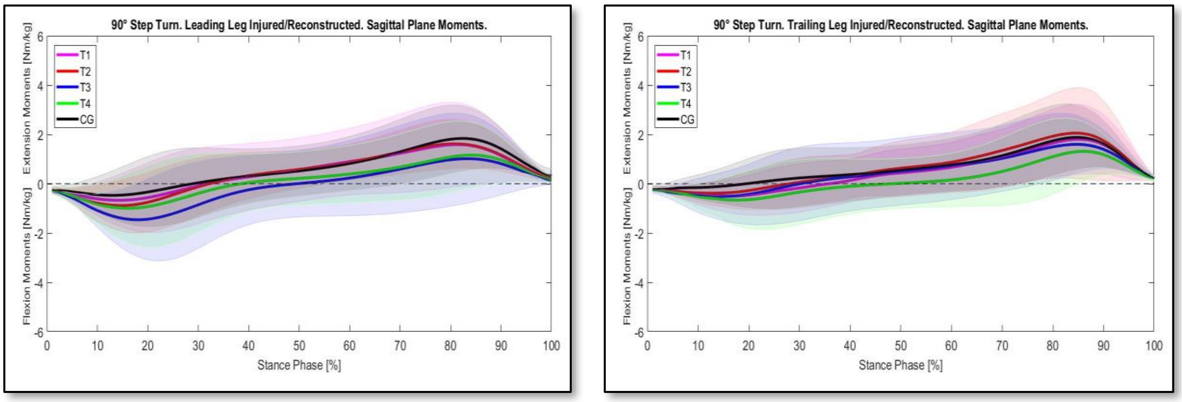

Figure 46. Knee Moments of the Injured/Reconstructed in the 90° Step Turns. *Graphs of the mean sagittal plane knee moments of the injured/reconstructed legs in the ACL group, acting as leading legs (left) and acting as trailing legs (right) in the 90° step turns. Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed legs in the ACL group were compared to the non-dominant of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

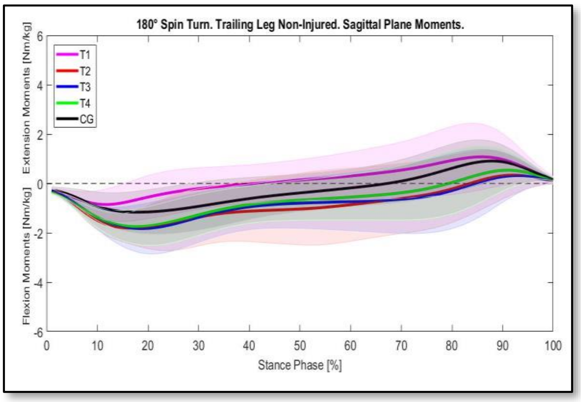

Figure 47. Knee Moments of the Injured/Reconstructed in the 180° Step Turns. *Graphs of the mean sagittal plane knee moments of the injured/reconstructed legs in the ACL group, acting as leading legs in the 180° step turns. Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed legs in the ACL group were compared to the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

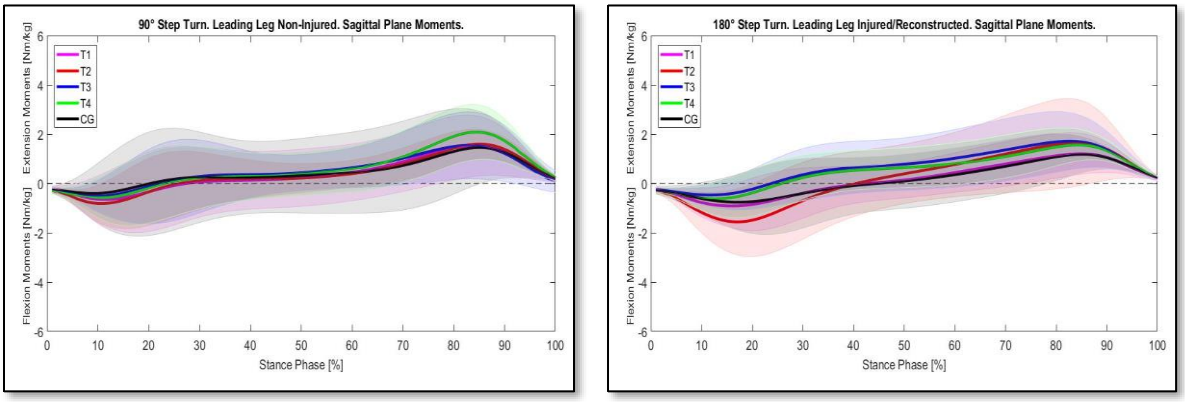

Figure 48. Knee Moments of the Leading Legs in the 90° and 180° Step Turns. *Graphs of the mean sagittal plane knee moments of non-injured legs in the ACL group, acting as leading legs in the 90° step turns (left) and the injured/reconstructed legs, acting as leading legs in the 180° step turns (right). Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed and the non-injured legs in the ACL group were compared to the non-dominant and dominant legs of the control group (CG), respectively. T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

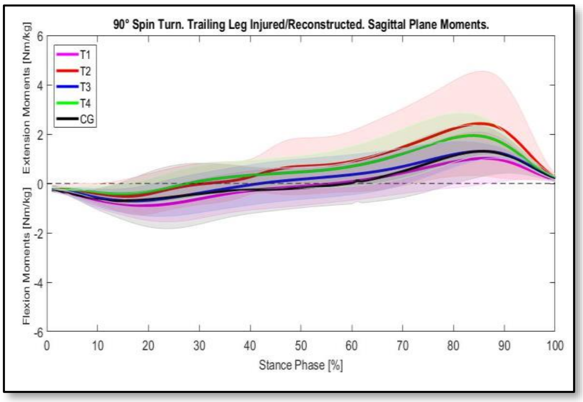

Figure 49. Knee Moments of the Injured/Reconstructed legs as Trailing Legs in the 90° Spin Turns. *Graphs of the mean sagittal plane knee moments of the injured/reconstructed legs in the ACL group, acting as trailing legs in the 90° spin turns. Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed legs in the ACL group were compared to the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

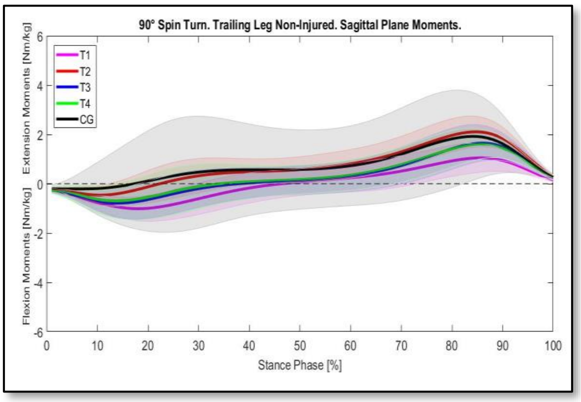

Figure 50. Knee Moments of the Non-injured Legs as Trailing Legs in the 90° Spin Turns. *Graphs of the mean sagittal plane knee moments of the non-injured legs in the ACL group, acting as trailing legs in the 90° spin turns. Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed legs in the ACL group were compared to the non-dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

10.12 Knee Moment Graphs of Turning Locomotion Conditions Showing No Tendencies of Kinetic Adaptations, But Showing Kinematic Adaptations

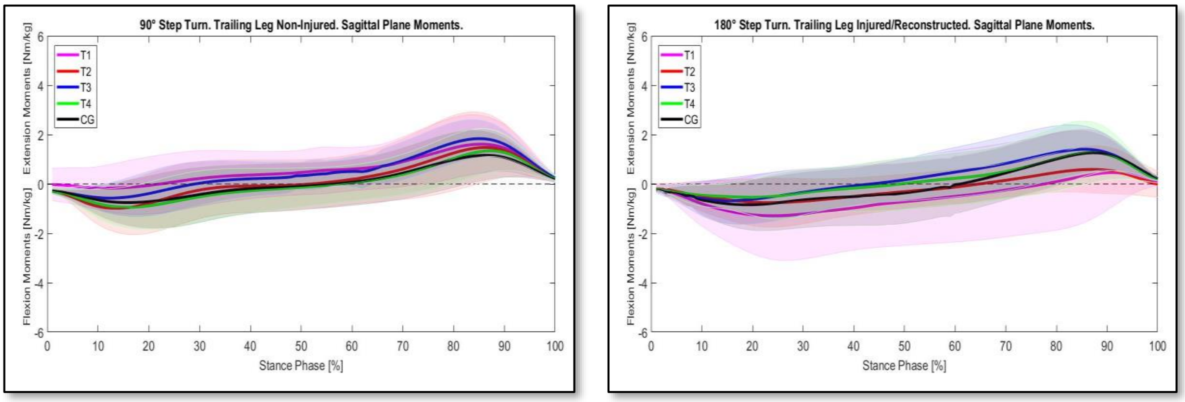

Figure 51. Knee Moments of the Trailing Legs in the 90° and 180° Step Turns. *Graphs of the mean sagittal plane knee moments of the non-injured legs in the ACL group, acting as trailing legs in the 90° step turns (left) and the injured/reconstructed legs, acting as trailing legs in the 180° step turns (right). Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed and the non-injured legs in the ACL group were compared to the non-dominant and dominant legs of the control group (CG), respectively. T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

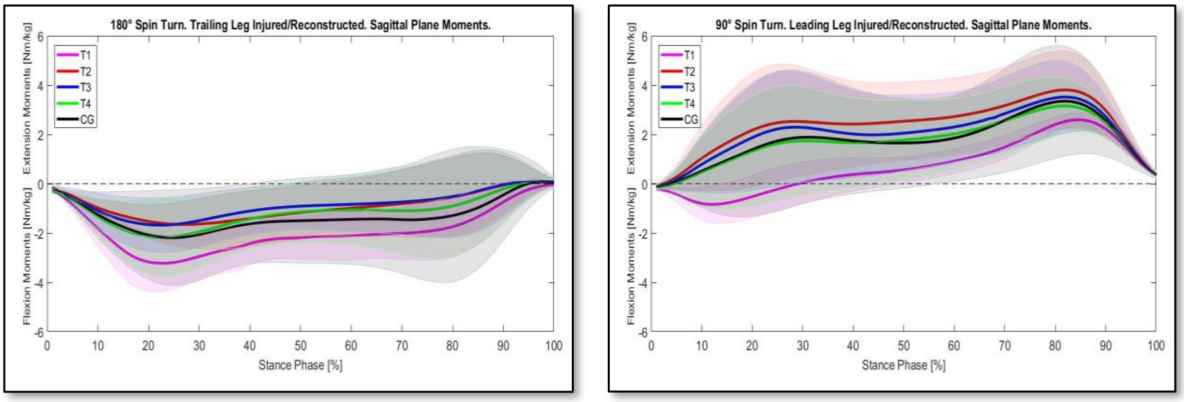

Figure 52. Knee Moments of the Trailing Legs in the 180° Spin Turns and the Leading Legs in the 90° Spin Turns. *Graphs of the mean sagittal plane knee moments of the of the injured/reconstructed legs in the ACL group, acting as trailing legs in the 180° spin turns (left) and the injured/reconstructed legs, acting as leading legs in the 90° spin turns (right). Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed legs in the ACL group were compared to the non-dominant of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

10.13 Knee Moment Graphs of Turning Locomotion Conditions Showing Tendencies of Kinetic Adaptations, But No Kinematic Adaptations

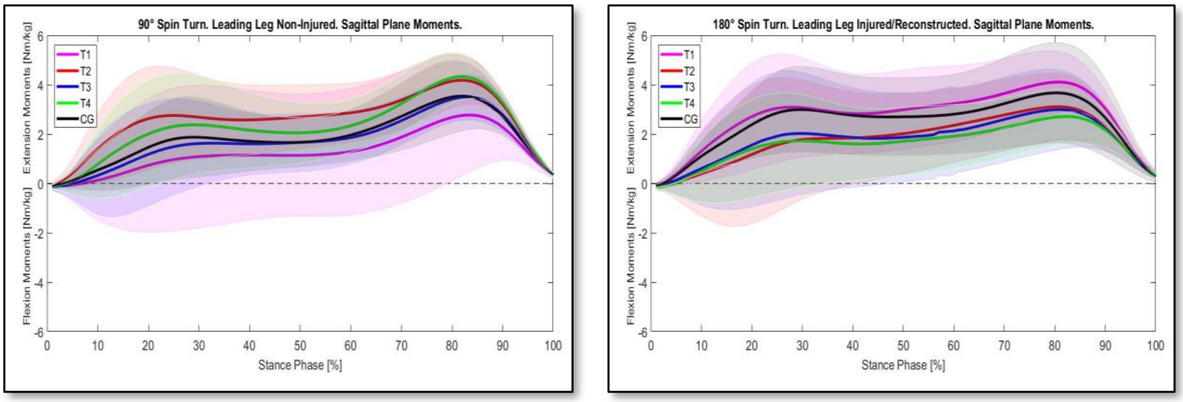

Figure 53. ***Knee Moments of the Leading Legs in the 90° and the 180° Spin Turns.*** *Graphs of the mean sagittal plane knee moments of the non-injured legs in the ACL group, acting as leading legs in the 90° spin turns (left) and the injured/reconstructed legs, acting as leading legs in the 180° spin turns (right). Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the injured/reconstructed and the non-injured legs in the ACL group were compared to the non-dominant and dominant legs of the control group (CG), respectively. T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

10.14 Knee Moment Graphs of Turning Locomotion Conditions Showing No Tendencies of Kinetic Adaptations and No Kinematic Adaptations

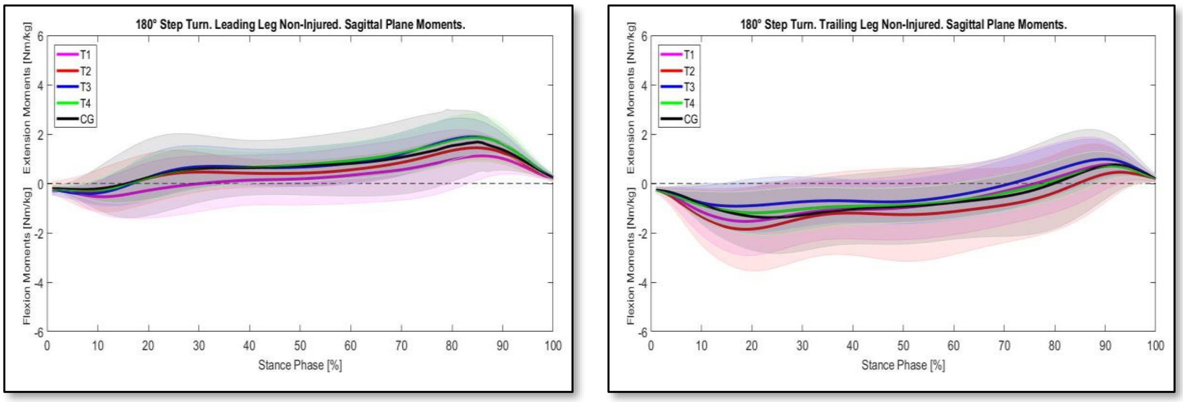

Figure 54. ***Knee Moments of the Leading and Trailing Legs in the 180° Step Turns.*** *Graphs of the mean sagittal plane knee moments of the non-injured legs in the ACL group, acting as leading legs in the 180° step turns (left) and acting as trailing legs in the 180° step turns (right). Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the non-injured legs in the ACL group were compared to the dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

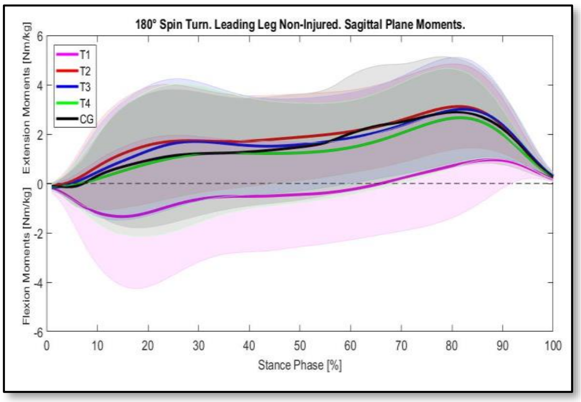

Figure 55. Knee Moments of the Non-injured Legs as Leading Legs in the180° Spin Turns. *Graphs of the mean sagittal plane knee moments of the non-injured legs in the ACL group, acting as leading legs in the 180° spin turns. Negative values indicate internal knee flexion moments, positive values indicate internal knee extension moments. The knee moments of the non-injured legs in the ACL group were compared to the dominant legs of the control group (CG). T1 is illustrated by the magenta-colored line, T2 by the red-colored lines, T3 by the blue-colored lines, and T4 by the green-colored lines. The black-colored lines illustrate the knee moment courses of the CG. Shaded areas represent the standard deviations.*

Statutory Declaration

Hiermit erkläre ich, dass die vorliegende Dissertation mit dem Titel

> „Comprehensive Assessment and Investigation of Knee Joint Functionality in ACL Reconstructed Subjects – Course of Performance Capacities from Pre- to Six Months Post-ACL Reconstruction."

Selbständig angefertigt wurde und keine anderen als die angegebenen Hilfsmittel benutzt sowie die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht und die Satzung des Karlsruhe Institut für Technologie (KIT) zur Sicherung guter wissenschaftlicher Praxis beachtet habe. Diese Arbeit wurde nicht bereits anderweitig als Prüfungsarbeit verwendet.

Karlsruhe, den 15. August 2018

(Frieder Cornelius Krafft)