A New Approach to Apply and Develop Biomechanical Techniques to Quantify Knee Rotational Stability and Laxity

LAM, Mak Ham

A Thesis Submitted in Partial Fulfilment
of the Requirements for the Degree of
Doctor of Philosophy
in
Orthopaedics and Traumatology

The Chinese University of Hong Kong
September 2011

Thesis/Assessment Committee

Professor Qin Ling (Chair)
Professor Chan Kai Ming (Thesis Supervisor)
Professor Fong Tik Pui (Thesis Co-supervisor)
Professor Yung Shu Hang (Committee Member)
Professor Chen Chih Hwa (External Examiner)

論文評審委員會

秦嶺教授（主席)
陳啓明教授（論文導師)
方迪培教授（論文導師)
容樹恆教授(委員)
陳志華教授（校外委員)

Abstract

Abstract of thesis entitled:

A new approach to apply and develop biomechanical techniques to quantify knee rotational stability and laxity

Submitted by LAM, Mak Ham

for the degree of doctor of philosophy in orthopaedics and traumatology

at The Chinese University of Hong Kong in July 2011

Sports related injury has become an inevitable consequence with the increase in number of sports participation. Among the injuries, knee ligamentous injury is one of the most common sports injuries and it results in different degrees of adverse effect to the athletes, such as knee rotational instability. Physical examination is often used to document knee rotational stability for injury diagnosis and evaluation of surgical treatment. Regarding the limitation of the physical examination, the outcome highly depends on examiners' skill and experience. Furthermore, the passive assessment cannot produce sufficient rotational stress that reflects the real physical demand. Therefore, this dissertation aims to apply advanced biomechanical technology and develop new biomechanical methodology to quantify knee rotational stability as an attempt to provide alternatives to the current clinical problems.

Firstly, this dissertation presents various biomechanical techniques to quantify knee rotational stability that have been currently used in the literatures. Secondly, different techniques are chosen to apply on the current clinical problems in the field of orthopaedics sports medicine in order to supplement the limitation of physical examination. Computer assisted navigation system is used to investigate the

immediate effect of different reconstruction techniques of posterolateral corner (PLC). The PLC reconstruction with double femoral tunnel technique shows better rotational stability and resistance to posterior translation than the single femoral tunnel technique without compromising varus stability. Next, a simple and objective biomechanical meter to document knee rotational laxity is proposed. High validity and reliability are obtained in cadaveric verification using computer assisted navigation system as a gold standard. Further, optical motion analysis system is used to evaluate dynamic knee rotational stability before and after anterior cruciate ligament (ACL) reconstruction. The result shows that anatomic double-bundle ACL reconstruction successfully restores functional knee rotational stability during a high-demand pivoting movement to a normal level. When comparing the single-bundle and double-bundle techniques, the result shows a trend that both reconstructions have similar effect on knee rotational stability with no superiority in anatomic double-bundle ACL reconstruction. Lastly, optical motion analysis system is used to further investigate the anticipation effect during stop-jumping tasks on knee rotational stability. By showing different knee kinematics between planned and unplanned tasks in healthy male participants, the landing manuever is shown to be affected by the anticipation effect. It is suggested that both planned and unplanned stop-jumping tasks should be considered as one of the functional assessment tasks to monitor the rehabilitation progress after knee ligamentous injury.

Future studies on the correlation between passive laxity test and dynamic functional stability assessment are suggested such that functional stability would be predicted by simple biomechanical test, which is practical in sports medicine clinical setting.

Chinese abstract

隨著運動參與人數的上升，運動創傷已經成爲不可避免的後果。當中最常見的運動創傷是膝關節韌帶受傷，令傷者帶來不同程度的傷害，例如膝關節旋轉不穩定。臨床身體檢查是現時最普遍用來診斷受傷及評估手術後康復進展的方法。但是這種檢查的準確性限制於測試員的技術和經驗。再者，被動式的檢查不能提供足夠的旋轉扭力來反映真實生活中的需求。所以本論文旨在應用先進的生物力學儀器及研發新的生物力學方法來量化膝關節旋轉穩定性，並嘗試爲當前的臨床問題提供解決答案。

首先，本論文綜合多年來文獻中所描述的生物力學方法，報告有關量化膝關節旋轉穩定性的技術，再選取了數個合適的技術應用在運動醫學的臨床問題上，藉此補充了臨床身體檢查的不足。第一，利用電腦輔助導航系統研究不同後外側結構重建手術的即時成效。結果顯示雙股骨隧道技術比較單股骨隧道技術更有效修復旋轉及後移穩定性。第二，本論文研發出一個簡單和客觀的生物力學計量儀，來評估被動式膝關節旋轉穩定性。透過電腦輔助導航系統作爲量度的黃金標準進行了屍體驗証，並獲得高準確性及可靠性的結果。爲進一步評估動態穩定性，是次研究應用了光學動作分析系統爲前十字韌帶受傷的病人在術前術後進行了一個高強度轉向動作的穩定性評估。結果表明前十字韌帶雙束解剖重建手術能在功能上修復膝關節旋轉穩定性，並達致正常水平。當比較單束重建技術時，由於兩種手術方法均對旋轉穩定性起了相同的效果，所以不能反映雙束解剖重建技術之優勝處。最後，光學動作分析系統再被應用在一個急停跳躍的動作上，分析預期反應對旋轉穩定性之影響。從健康的男受試者中發現預期及非預期動作在運動學上有明顯分別，証明了落地時的動作受到預期反應的影響。當評估膝關節韌帶受傷後的康復情況時，應考慮預期及非預期的急停跳躍動作爲功能測試之一。

未來方向包括研究被動式穩定性測試及動態功能穩定性測試的相關性，令臨床上能以簡單的生物力學測試來預測膝關節功能穩定性。

Acknowledgement

I would like to express my thanks to the following individuals and parties for their supervision, help and support.

- Prof. Kai-Ming CHAN, my chief supervisor, for his guidance, advice, support, supervision and encouragement throughout my study.
- Prof. Daniel Tik-Pui FONG, my co-supervisor, for his guidance, advice, support, supervision and encouragement throughout my study.
- Dr Patrick Shu-Hang YUNG for his advice, support and encouragement throughout my study.
- Prof. Wood-Yee CHAN for his advice and support in preparation of cadaveric experiment and manuscript writing.
- Dr Kwai-Yau FUNG, for sharing Gait Laboratory facility in Alice Ho Miu Ling Nethersole Hospital.
- Dr Eric Po-Yan HO for his advice in conducting research experiment and effort in managing surgical procedure.
- Miss Miko LAO, Miss Mandy Man-Ling CHUNG, Mr. Kam-Ming MOK and Mr. Aaron See-Long HUNG for their assistance in data collection and processing.
- Innovation technology commission of the Hong Kong Special Administrative Region for the financial support for the research in chapter 4 (Ref.: ITS/039/09).
- Faculty of Medicine, The Chinese University of Hong Kong for the financial support for the research in chapter 6 (Ref.: 2008.2.020).

Abbreviation

A&E	**Accident and emergency**
ACL	**Anterior cruciate ligament**
AM	**Anteromedial**
ANOVA	**Analysis of variance**
AP	**Anterior-posterior**
ASIS	**Anterior superior iliac spine**
CI	**Confidence interval**
DOF	**Degree of freedom**
EM	**Electromagnetic**
ICC	**Intraclass correlation**
LCL	**Lateral collateral ligament**
IKDC	**International knee documentation committee**
MCL	**Medial collateral ligament**
MRI	**Magnetic resonance imaging**
PCL	**Posterior cruciate ligament**
PFL	**Popliteofibular ligament**
PL	**Posterolateral**
PLC	**Posterolateral corner**
RSA	**Roentgen stereophotogrammetric analysis**
SD	**Standard deviation**

Table of content

Chapter 1 Introduction

Chapter summary

In the beginning of this dissertation, a brief background introduction that leads to the study aim and objective would be elaborated in this chapter. The increase in the number of sports participation comes after the awareness of the relationship between healthy lifestyle and mortality rate. Sports related injury has become an inevitable consequence. Among these injuries, knee ligamentous injury is one of the most common sports injuries and it results in different degrees of harm to the athletes, such as knee rotational instability. In view of the knee rotational stability assessment, physical examination is often used in the field of orthopaedics sports medicine for injury diagnosis and evaluation of surgical treatment and rehabilitation. Regarding the limitation of the physical examination, the outcome is affected by patients' muscle reflex and it also depends on the examiners' skill and experience. Furthermore, the passive assessment cannot produce sufficient rotational stress that reflects the real physical demand. Therefore, this dissertation aims to apply advanced biomechanical technology and develop new biomechanical methodology to quantify knee rotational stability as an attempt to provide solutions to the current clinical problems.

1.1 Sports participation and sports injury

Research has clearly shown the benefits of regular physical activity in prevention of chronic disease and lowering of mortality rates (US Department of Health and Human Services, 1996). With a new initiative of 'exercise is medicine', which jointly sponsored by the American College of Sports Medicine and the American Medical Association (Sallis, 2009), people all around the world are more engaging to sports activity and exercise. In Hong Kong, with the impact of hosting the Olympic Equestrian Sports in 2008 and East Asian Game in 2009, local people are becoming more active and participating sports with more varieties than before. According to the government survey, over half of the citizens participate in sports at least once per week (Consultancy Study on Sport for All, 2009). The increasing sports participation is also reflected by the number of participants in the annual local marathon race. According to a event report of Standard Chartered Hong Kong Marathon 2010 (Hong Kong Amateur Athletic Association, 2010), the number of participants has progressively increased year by year, from 1000 runners in 1997 to over 60000 runners last year. This local race has now become a remarkable sports event internationally.

Although sports participation brings people health, it sometimes causes injury. The injury rate in sports is comparable to other common types of injury reported in A&E department. A one-year prospective study in Sweden reported that 17% of the 3341 acute visits to a clinic due to accidents are from sports, while 26% and 19% go to home accident and work accident, respectively (de Loes and Goldie, 1988). For adolescent who actively participates in sports, half of reported injuries in A&E department are occurred during school sports (Abernethy and MacAuley, 2003). Locally, sports related injury is the fourth common injury recorded in A&E

department, which accounts for 12%. The first three categories are domestics, industrial and traffic, which accounted for 35.5%, 28% and 12.5%, respectively (Fong et al., 2008). When the sports participation rate becomes high, the exposure to potential injury would increase and thus the incidence of sports injury (Shephard, 2003).

1.2 Problems of sports injury

While researchers are aware of the benefits from exercises, sports related injury may negate the gain (Marshall and Guskiewicz, 2003). Sports injury would result in pain (Fahlstrom et al., 2006), loss of playing or working time (Orchard and Hoskins, 2007) as well as medical expenditure (Knowles et al., 2007). Severe injury may result in bone fractures (Wojcik et al., 2010), functional instability (Hurd and Snyder-Mackler, 2007), decreased muscle strength (Moisala et al., 2007), inferior proprioception (Friden et al., 2001), limited mobility (Logerstedt et al., 2010), disability, permanent cease of sports participation (Myklebust and Bahr, 2005), psychological problem (Mann et al., 2007), and even death (Quigley, 2000). Without adequate treatment and rehabilitation, sports injury may also cause significant susceptibility in developing osteoarthritis (Lohmander et al., 2007) and other kinds of permanent sequela (Marchi et al., 1999).

The economic expenditure due to sports injury would significantly increase the society's burden. In late 20th century, the overall mean cost per acute sports injury in a prospective study conducted in Germany was US$335 (de Loes, 1990), while the mean direct cost per youth sports injury in Canada was CAN$775 reported in 2010 (Leadbeater et al., 2010). Although it is hardly comparable with studies varying with different sports, durations and medical systems, it is no doubt that the medical expenditure as well as economic loss would increase with the sports participation. In Hong Kong, the total medical expenditure caused by injury was HK$890 million in 2008, without accounting the social and economic loss resulted from the sick leave after injury (Hong Kong Department of Health, 2010). Among these injuries, 14.1% is from sports accident. The figure may be even higher if the absence of players is from world class and commercial sports team.

1.3 Knee ligamentous injury and knee instability

The knee is the most commonly injured body site in sports, which account for 10-40% (Hinton et al., 2005; Louw et al., 2008; Majewski et al., 2006). Among all sport-related knee injuries, around 45% is related to ligamentous injury (Ingram et al., 2008; Majewski et al., 2006). The major knee ligaments include cruciate ligament, collateral ligament and posterior lateral ligament (Daniel et al., 1990). Although extensive research have reported that MCL would heal after an isolated injury without any intervention (Woo et al., 1997), some of the ligamentous injuries are complex such as PLC injury (LaPrade et al., 2006) and more importantly most of the ligaments do not heal when torn. Therefore, ligament reconstruction has become the standard treatment in the field of orthopaedics sports medicine (Beynnon et al., 2005). Untreated knee ligamentous injury would affect gait pattern (Shelburne et al., 2005), increase the risk of re-injury (Arnason et al., 2004) and eventually contribute to long-term joint degeneration (Tashman et al., 2004).

Athletes who suffer from ligament disruption would experience knee instability (Veltri et al., 1995). The term 'instability' has been used to describe (1) an abnormal motion or motion limit that exists to the joint due to a ligament injury; and (2) symptomatic giving-way of the knee joint that occurs during activity (Noyes, 2010).

In the following of this dissertation, knee instability is defined as the former one. In view of the knee ligament function, disruption of ligaments alone, or in combination, would alter the limits of knee motion in a predictable way. In 1980, Butler and coworkers introduced a concept of primary and secondary restraints to motion in a specific direction (Butler et al., 1980). The structure that provides the greatest limitation for a specific direction is considered the primary restraint while the remaining structures that limit the motion after disruption of primary restraint are termed secondary restraint. For example, ACL functions as the primary restraint and secondary restraint to limit AP translation and tibial rotation, respectively (Petersen and Zantop, 2007), and PLC prevents varus rotation and external rotation of the tibia as a primary restraint.

1.4 Knee rotational stability

The knee rotational stability is recently being emphasized because of the controversial issue that anatomic double-bundle ACL reconstruction has been suggested to restore rotational stability better than single-bundle ACL reconstruction (Fu and Zelle, 2007). Moreover, in view of the anatomical and biomechanical understanding of the PLC, the current gold standard of reconstruction has not been well established (Arciero, 2005; Cooper et al., 2006; Schechinger et al., 2009).

The PLC (Gollehon et al., 1987) and the ACL (Fu and Zelle, 2007) of the knee are two of the primary and secondary structures for stabilizing knee axial rotation. The anatomy of the PLC is complex, and it is composed of both static and dynamic stabilizers. Previous studies (Nielsen and Helmig, 1986; Nielsen et al., 1984; Seebacher et al., 1982; Shahane et al., 1999) reported that there are three primary stabilizers of the PLC including LCL, popliteus muscle tendon unit and PFL, which served as the primary restraints of knee external rotation at 30° of knee flexion. Residual laxity has been reported after PLC reconstruction suggesting that single-femoral tunnel could not address the different insertion sites of the popliteus and LCL (Arciero, 2005).

Traditional surgical treatment of ACL injury used a single-bundle ACL reconstruction, which provides good resistance to anterior tibial loads but not to rotational loads (Woo et al., 2002). It has been further reported that the rotational instability was found during a pivoting movement after single-bundle ACL reconstruction (Ristanis et al., 2005). Recently, anatomic double-bundle ACL reconstruction (Hara et al., 2000; Yagi et al., 2007) has been used to better mimic and restore the anatomy and biomechanics of the intact ACL in the reconstructed knee. Although the double-bundle technique has been suggested to improve rotational stability in cadaveric models (Woo et al., 2006; Yagi et al., 2002), the superiority over single-bundle technique has not been proven in human subject (Meredick et al., 2008).

1.5 Physical examination and its limitation

In the literatures, various methodologies have been reported to evaluate knee rotational stability. It includes clinical examination (Ostrowski, 2006), self-reported questionnaire (Harreld et al., 2006), image scanning (Tashiro et al., 2009), biomechanical instrument (Ristanis et al., 2005) and computational modeling (Andriacchi et al., 2006). In view of the practicability in clinical setting, physical examination would be the most common way for physicians to examine knee instability. It has also suggested that a comprehensive physical examination would enhance a practitioner's ability to achieve an accurate clinical diagnosis (Lubowitz et al., 2008). For example, a positive result of pivot shift test is the best among others for ruling in an ACL rupture (Ostrowski, 2006).

Although recent clinical studies (Jarvela, 2007; Kondo et al., 2008; Tsuda et al., 2009) still rely on physical examination as a primary outcome, it should be reminded that the examination has three main limitations, which include patients' inability to relax because of anxiety (Lubowitz et al., 2008), high dependence on examiners' skill and experience (Musahl et al., 2007) and inability to test the movement and force that reflect real physical demands (Noyes et al., 1980). In view of these limitations, separate attempt should be made to tackle the problem specifically. In chapter 2, a systematic review of biomechanical techniques for quantification of tibial rotation is presented. In chapter 3 to 6, different biomechanical techniques are chosen to apply in various clinical related situations for supplement of clinical examination's limitations. Figure 1.1 illustrates how this dissertation tackles the limitations by using different biomechanical techniques. A cadaveric model is used in chapter 3 to eliminate any muscle contraction involved and the tool for evaluation is intra-operative navigation system. In chapter 4, an objective biomechanical meter is devised using motion and torque sensors to make the evaluation process less dependence on skill and experience. Lastly, in chapter 5 and 6, knee rotational stability is quantified using optical motion analysis system during high-demand pivoting task and unanticipated stop-jumping task. This dynamic functional assessment would provide an evaluation platform to mimic real physical demands, which could not be done in passive laxity test.

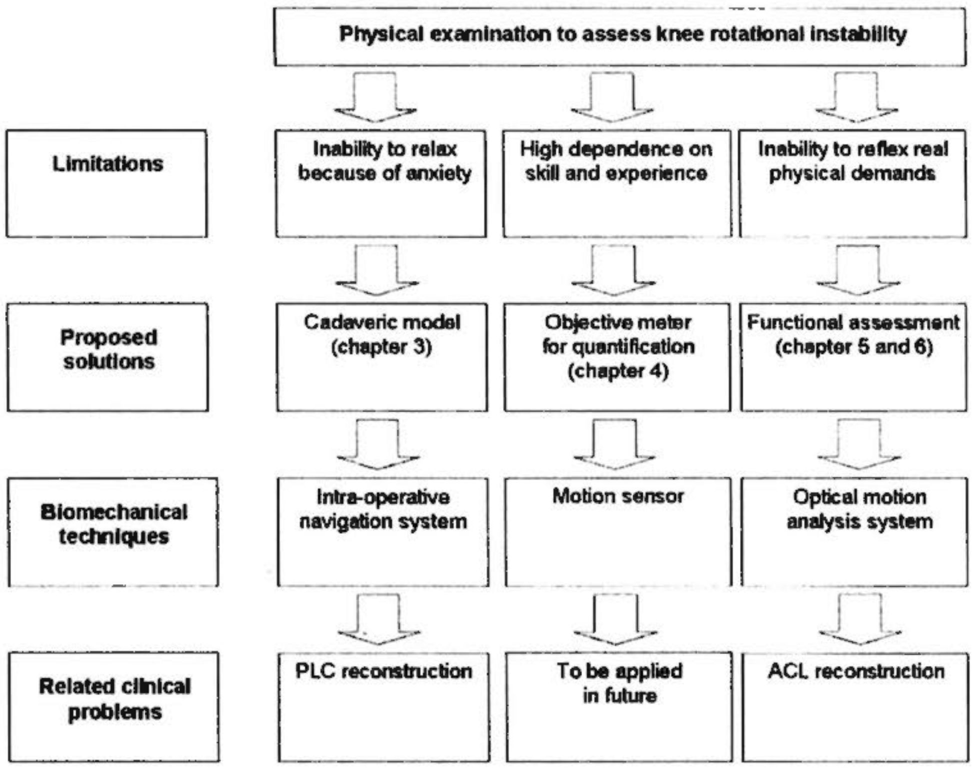


Figure 1.1 Illustration of how this dissertation tackles the limitations of clinical examination by using different biomechanical techniques.

1.6 Study aim and objective

This dissertation aims to apply advanced biomechanical technique and develop new biomechanical methodology to quantify knee rotational stability. The objectives of this dissertation include the followings:

1. To apply computer assisted navigation system to evaluate two PLC reconstruction techniques using a cadaveric model;
2. To develop an accurate and reliable biomechanical meter to evaluate knee rotational laxity such that the evaluation process would be less dependence with skill and experience;
3. To apply optical motion analysis system to investigate dynamic knee rotational stability before and after ACL reconstruction; and provide a real game simulated platform to evaluate functional knee rotational stability.

Chapter 2 Biomechanical techniques for evaluation of tibial rotation – a systematic review

Chapter summary

This chapter systematically reviews the biomechanical techniques to evaluate tibial rotation, for the better understanding of choosing suitable protocol with specific clinical application. A systematic search was conducted and finally 104 articles were included in this review. The articles under review were classified according to three conditions in which the knee was examined: external load application, physical examination and dynamic task. The results showed that over 80% of the studies with external load application used cadaveric model. The techniques included magnetic sensing, optical tracking system and radiographic measurement. Intraoperative navigation system was used to document knee rotational kinematics when the knee was examined by the physical examination. To further evaluate knee rotational stability in terms of tibial rotation during dynamic tasks, optical motion analysis system with skin reflective marker and radiographic measurement were suggested. Similar biomechanical techniques were summarized for discussion. This chapter provides information of choosing suitable biomechanical techniques for the following chapters that aim to solve specific clinical problem in relation to knee rotational stability.

Publication: This chapter is submitted to Knee Surgery, Sports Traumatology, Arthroscopy.

Lam MH, Fong DTP, Yung PSH, Chan KM (2nd revision). A systematic review on the biomechanical techniques to evaluate tibial rotation. Knee Surgery, Sports Traumatology, Arthroscopy

2.1 Introduction

The knee is the most commonly injured body sites during sports, accounting for about 40% of all sports injuries (Majewski et al., 2006). Traumatic knee injury such as ligament tear would lead to knee instability, prohibiting athletes from returning to sports, and resulting in early retirement (Myklebust and Bahr, 2005) or even premature end to sport career (Kvist, 2004). Functional knee stability is one of the key return to sports criteria (Kvist, 2004) as high demanding movements that stress on knee are always involved in real game situation. In clinical practice, knee laxity evaluation is based on the physical examination performed by trained physician. Force or torque is manually applied to the knee joint to check if there is any abnormal motion when compared with the intact side. However, physical examination has a few limitation (Lubowitz et al., 2008), including inability to produce sufficient magnitude of force to simulate physical activity and subjective grading from physician's experience.

In the literature, there are various studies to assess knee laxity and stability. Besides physical examination, self-reported outcome questionnaire is often used in clinical research. Knee stability items that reflect patients' functional limitation and instability are included in these questionnaires such as IKDC subjective knee evaluation scores (Irrgang et al., 2001). Another passive knee laxity assessment includes stressed magnetic resonance imaging (Scarvell et al., 2005) and objective clinical device (Tsai et al., 2008). These assessments involve a controlled stress to the knee joint in a specific direction followed by an objective biomechanical rating for the corresponding laxity. In the contrary, dynamic movement is directly performed so that knee stability would be monitored during specific motion. For example, previous studies have suggested that abnormal joint kinematics during dynamic movements after ACL reconstruction would contribute to long-term joint degeneration (Ristanis et al., 2005; Tashman et al., 2007).

In view of the way to assess knee laxity and stability, biomechanics plays an important role. With the advanced biomechanical techniques, assessments have become objective, practical and accurate that suits the increasing demand on measuring knee rotational laxity and stability such as the knee anatomical structure, injury diagnosis and effect of ligament reconstruction. Therefore, there is a need to understand and familiar with the biomechanical techniques for its quantification and evaluation. Because the research that lead to a better understanding of knee laxity and stability would not be ethical to employ on living human, for example validation of measurement tool, techniques that have been used in cadaveric studies were also included.

In the current review, tibial rotation is defined as the relative movement of femur and tibia in the transverse plane. The biomechanical techniques would be classified when the knee is examined with different conditions: (1) under a certain external load (Woo et al., 2002), (2) physical examination by physician (Kubo et al., 2007), or (3) a specific dynamic task performed by the participants (Waite et al., 2005). Since there is a wide spectrum of measuring tools, there is a need for orthopaedic specialists and sport biomechanists to understand the overview and to choose the most suitable technique for specific application.

2.2 Method

A systematic literature search of MEDLINE (from 1966) was conducted during the last week of December in 2010. The search keyword was (knee OR tibial OR tibia)

AND (rotation OR rotational OR rotatory OR pivot OR pivoting) AND (biomechanics OR biomechanical OR kinematics OR displacement) AND (stability OR laxity), which appeared in the title, abstract or keyword fields. After duplicates were removed, the initial total number of articles in the database was 532. The title and abstract of each entry was identified. Non-English articles, review and surgical technique, animal studies and non-related articles were excluded. After this subsequent trimming, the count was reduced to 190. Online and library searches for the full text of these articles were conducted. Articles not available in the library of The Chinese University of Hong Kong were requested from libraries in other local universities. Only full text of two articles could not be retrieved, and the final number of articles with full text was 180.

The full text of each retrieved articles was read to determine the inclusion and exclusion criteria in the systematic review. The inclusion criteria were: (1) the study must employ human, either cadaver specimen or living participant, (2) the study must present tibial rotation, measuring the relative movement of femur and tibia in the transverse plane, as a dependent parameter, (3) the study must not involve total knee arthroplasty or the prescription of knee prosthesis, since the knee anatomy is greatly altered in these studies. Current concepts, reviews, case reports, computerized model such as finite element model and the studies without detailed description of the measuring technique were excluded. After the screening process, the final number of articles included in the analysis was 104.

The 104 selected articles were categorized by the conditions of how the knee was examined: (1) external load application – when the knee was under a certain rotational load in a controlled manner; (2) physical examination – when the knee was clinically examined by an orthopaedic specialist, a physiotherapist or a biomechanist; (3) dynamic task -- when the participant was performing a specific dynamic movement. Demographic data of all studies, including year of the study, testing subject, biomechanical techniques and the study application were summarized.

2.3 Result

For all included studies, 69 articles (66%) used human specimen in the experiment and the rest 35 studies (34%) used living human. The earliest study in the search was conducted by Shoemaker and his coworkers (Shoemaker and Markolf, 1982) in 1982. Increasingly, the studies between 1980 and 1989, 1990 and 1999, 2000 and 2010 were 12, 16 and 76, respectively. The application of these studies included investigation of knee structures such as ACL, PLC and meniscus, and evaluation of taping and bracing effect. The most common interest for researchers was ACL followed by PLC. The biomechanical technique that was used in the included studies was shown in the following.

2.3.1 External load application

Of the 104 included articles, 74 articles (71%) were classified in this session. Sixty one studies (82%) applied on human cadaver for the testing subjects and the rest (13 studies) applied to living human.

2.3.1.1 Direct displacement measurement

The most direct way to measure rotational displacement was by using a goniometer (Andersen and Dyhre-Poulsen, 1997; Gupte et al., 2003; Krudwig et al., 2002; Scopp et al., 2004; Ullrich et al., 2002; Wojtys et al., 1987; Wojtys et al., 1990) or electrogoniometer (Baxter, 1988; Lundberg and Messner, 1994; Morin et al., 2008;

Shapiro et al., 1991; Wascher et al., 1993). Goniometer, also termed as protractor (Robinson et al., 2006), potentiometer (Anderson et al., 1992; Engebretsen et al., 1990; Johannsen et al., 1989; Markolf et al., 2010; Shoemaker and Markolf, 1985; Shoemaker and Markolf, 1982; Stoller et al., 1983), transducer (Draganich et al., 1990; Draganich et al., 1989; Gollehon et al., 1987; Lane et al., 1994; Shahane et al., 1999; Veltri et al., 1996), was a general term and all techniques shared the same principle. While both sides of the knee were fixed, the goniometer was placed on the plane, which was perpendicular to the axis of tibia rotation. The rotational displacement was presented in a two dimensional plane on which the tibia rotation was controlled during load application. In addition, one study (Hofmann et al., 1984) used bony pin to define rotational displacement such that the movement was restricted in transverse plane and the relative movement between pins was then documented.

2.3.1.2 Magnetic sensing

Sixteen studies were reported using magnetic sensing technique since 1996. The technique was both applied to cadaver (Anderson et al., 2010; Apsingi et al., 2009; Apsingi et al., 2008; Apsingi et al., 2008; Bull et al., 1999; Coobs et al., 2010; Griffith et al., 2009; Lie et al., 2007; McCarthy et al., 2010; Nau et al., 2005; Nau et al., 2005; Samuelson et al., 1996; Tsai et al., 2010) and living human (Shultz and Schmitz, 2009; Shultz et al., 2007; Tsai et al., 2008). In cadaveric studies, magnetic sensors were directly attached to the femur and tibia, and the relative movement between both sides was monitored externally. Sensors were rigidly fixed to both sides using nylon posts (Bull et al., 1999) or fiberglass cylinders (Samuelson et al., 1996), while it was attached on skin in the application to living human. The lateral aspect of the subject's thigh and the tibial shaft were recommended as a reference site according to Shultz et al.'s study (Shultz et al., 2007). Different from direct displacement measurement, signal generated from an external receiver were extracted with the help of a computer assisted program, which provided three dimensional position and orientation of the sensors (Musahl et al., 2007). Self-complied program was also needed for calculation of knee kinematics (Anderson et al., 2010; Tsai et al., 2010).

2.3.1.3 Optical tracking system

Optical instrument is one of the recent techniques for measurement of tibial rotation. Eight studies (Ferrari et al., 2003; Kondo et al., 2010; Laprade et al., 2008; LaPrade et al., 2004; Mannel et al., 2004; Matsumoto, 1990; Mueller et al., 2005; Park et al., 2008), with the earliest one published in 1990 (Matsumoto, 1990), used this technique and all applied to cadavers except one study (Park et al., 2008) investigating the gender difference in passive knee laxity test. The principle was similar to magnetic instrument. Clusters consisting of three to four infrared emitting spherical markers (Ferrari et al., 2003; LaPrade et al., 2004) were rigidly fixed to femur and tibia with metaphyseal bone screws (Mannel et al., 2004). Instead of an external magnetic receiver, infrared camera, was used to locate three dimensional coordinates of markers that needed to be further digitized to establish an anatomical based coordinate system (Grood and Suntay, 1983; Wu and Cavanagh, 1995). The rotational displacement was finally presented after mathematical calculation by the system software or self-complied program.

2.3.1.4 Radiographic measurement

Radiographic method was regarded as the most accurate technique over the other measurements (Granberry et al., 1990) since it provided direct bone-to-bone information. RSA was firstly developed in 1989 among a group of researchers from Sweden (Jonsson and Karrholm, 1990; Karrholm et al., 1989), applying to living human to measure knee rotational kinematics. Three to six tantalum markers with 0.8 mm diameter were inserted to the femur and tibia by means of arthroscopy or under local anesthesia. Bi-planar roentgenographic exposure films with 2-4 Hz was collected 1-2 months later when the testing knee was under controlled rotational torque. The two dimensional coordinates of the markers were plotted on roentgen films and three dimensional coordinates were computed in relation to the laboratory coordinate system. The displacement was then calculated by customized program. Since invasive procedure was involved when inserting markers into the femur and tibia, this technique was only used in cadaveric studies (Gaasbeek et al., 2005; Kaneda et al., 1997).

2.3.2 Physical examination

Physical examination is commonly used in clinics to evaluate knee laxity after ligamentous injury. Pivot shift test is one of the common tests in clinical setting for evaluation of knee rotational laxity while some clinicians apply external and internal rotational torque manually. However, the outcome of these tests is limited to subjective grading and no objective kinematics data can be obtained. Therefore, it is of researchers' interest to collect knee rotational kinematics by means of biomechanical techniques. In this category, fifteen studies were included. All studies were conducted after 2002. The three major techniques for measursment of tibial rotation when examiner performed clinical tests were goniometer (Sekiya et al., 2008; Whiddon et al., 2008; Zehms et al., 2008), EM sensing (Hagemeister et al., 2002; Hagemeister et al., 2003; Yagi et al., 2007) and computer assisted navigation system (Brophy et al., 2008; Colombet et al., 2007; Hofbauer et al., 2010; Ishibashi et al., 2008; Ishibashi et al., 2005; Ishibashi et al., 2009; Miura et al., 2010; Song et al., 2009; Zaffagnini et al., 2008). These techniques were applicable on both cadaver and living human.

2.3.2.1 Computer assisted navigation system

Computer assisted navigation system is a newly developed technique which especially designed for helping surgeons during operation. In the early stage of navigation development, it was used to assist orthopaedic surgeon to improve accuracy of reconstruction and replacement surgery (Picard et al., 2001). New software recently has allowed for six DOF knee kinematics measurement (Hofbauer et al., 2010). Therefore, it would provide an immediate evaluation of the surgical outcome (Colombet et al., 2007). For example, the effect of AM and PL bundles during anatomic double-bundle ACL reconstruction could be evaluated during operation in terms of knee kinematics (Ishibashi et al., 2005).

The navigation system was firstly applied to living human in 2005. The system consisted of two transmitters with four markers attached, one calibration pointer and a high speed camera connected to computer for exporting the data. There were a few procedures before knee kinematics measurement (Ishibashi et al., 2005). Radiographic film was assessed pre-operatively for creating virtual bone model in the computer system. Two sets of external reflective markers on each transmitter were firmly fixed on the femur and tibia. To locate the relative movement, several intra-articular and extra-articular landmarks were manually digitized and were registered by the system using a straight pointer. After the six DOF directions between the femur and tibia were defined, continuous real-time knee kinematics could be obtained in the computer while performing the clinical tests.

2.3.3 Dynamic task

In this category, fifteen studies were included and all were published after 2000 except two from 1980s. In all studies, knee rotational kinematics was recorded while the testing participants were performing specific dynamic tasks. In the early years, electrogoniometer was used for measuring knee rotational displacement during treadmill running (Czerniecki et al., 1988; Knutzen et al., 1987). Before RSA was applied on living human in 2001 (Brandsson et al., 2001), there were about 10 years of vacuity where no journal paper was found in the search. The main techniques were summarized below.

2.3.3.1 Optical motion analysis system with reflective skin markers

Motion analysis is a study of locomotion using continuous photographic technique. Advanced technique using motion analysis system with reflective skin markers to measure knee rotational stability was reported in 2003 (Georgoulis et al., 2003). Skin markers were placed on typical bony landmarks and the participants were asked to perform specific motions, which probably would give a rotational stress to the knee, while the three dimensional coordinates of the markers were captured by optical instruments. The markers' global coordinates were collected by high speed optical cameras and then transformed to the femoral and tibial reference frames. Relative displacements between both frames were calculated by computer programs based on the previous description of knee kinematics (Grood and Suntay, 1983; Wu and Cavanagh, 1995). The marker set, therefore, was critical in which the bony location and number of markers varied. One of the frequently used models developed by Vaughan (Vaughan et al., 1992) consisted of 15 markers on lower extremities. Kinematics of the hip, knee and ankle joints including tibial rotation could be derived from the markers' global coordinates and the anthropometric measurements of the participant.

2.3.3.2 Radiographic measurement

In 2001, Brandsson and coworkers (Brandsson et al., 2001; Brandsson et al., 2002) used RSA to measure knee rotation of the patients after ACL tear. Before the experiment, 4-5 tantalum markers were inserted into the distal femur and proximal tibia through arthroscopy surgery. Two radiographic tubes were used to obtain simultaneous exposures at 2-4 Hz. The radiographs were processed manually to digitized images using a scanner for subsequent digital analysis. In recent years, the radiographic measurement of tibial rotation in several studies (Defrate et al., 2006; Li et al., 2008; Papannagari et al., 2006; Van de Velde et al., 2008) has reduced its invasiveness during the procedure. The subjects' knees were magnetic resonance scanned before their motions were captured by fluoroscopic testing system. The system combined the pre-scanned knee model and adjusted in six DOF until its projections matched with the outlines of the bones in the fluoroscopic images. The six DOF knee position was reproduced using this knee model.

2.4 Discussion

2.4.1 External load application

In the cadaveric studies, the femur and tibia were mounted in fixation systems, which provided three to six DOF including primary motion (flexion-extension) and secondary motion (AP translation, internal-external rotation and abduction-adduction) (Dyrby and Andriacchi, 2004) for free movement under certain testing conditions. Among these fixation systems, a robotic/universal force moment sensor testing system has been developed since 1996 (Rudy et al., 1996) and frequently applied to tissue biomechanical research (Allen et al., 2000; Darcy et al., 2006; Zantop et al., 2007) and simulated clinical testing research (Hsu et al., 2006; Kanamori et al., 2002; Yamamoto et al., 2006; Yamamoto et al., 2004). In addition, there were a few studies recruiting living human as subjects (Baxter, 1988; Johannsen et al., 1989; Louie and Mote, 1987; Lundberg and Messner, 1994; Shoemaker and Markolf, 1982; Shultz et al., 2007; Stoller et al., 1983; Yagi et al., 2007). These studies used a self-customized fixation system, in which rotational stress was applied to the participants until their limit of comfort (Leven, 1978).

The external load applied on the testing specimens or participants included isolated external and internal rotation torque (Andersen and Dyhre-Poulsen, 1997), valgus and varus torque (Lundberg and Messner, 1994), anterior tibial load (Hoher et al., 1998), muscle load (Li et al., 2002) as well as increased graft tension (Brady et al., 2007). These specific loads provided a controlled situation that was widely applicable to research based studies. Due to its experimental nature, it is not ethical to apply too much load to living human and it explains why 80% of the studies used a cadaveric model. However, there were a few studies (Leven, 1978; Park et al., 2008) recruiting living human as subjects that load was applied until the subjects' limit of comfort. The amount of load should be specifically designed and carefully estimated before applying to the living human. In view of the amount of torque applied, over 50% of the cadaveric studies used 5 Nm while other studies varied from 1.5 Nm to 20 Nm. The torque was much lower when applied to the living subjects, ranging from 1.5 Nm to 10 Nm with four out of 12 studies using 5 Nm as the testing torque.

Among the four techniques, magnetic sensing has been reported to have highest accuracy with 0.15° (Nau et al., 2005) followed by radiographic measurement with

0.2° and reproducibility with 1.4° (Karrholm et al., 1989). Since most of the included studies used cadavers, measurement tools such as magnetic sensor or pin marker could be directly attached or implanted to the bone, which inevitably results in a high accuracy measurement. On the other hand, there is always a concern that skin motion artifact exists when measuring knee rotation on the living human and there would be an ethical problem of direct bony pin implantation. Regardless the ethical problem, RSA with bony marker implantation would be considered the most accurate technique for measurement of tibial rotation on living human.

2.4.2 Physical examination

Physical examination is one of the most feasible and practical way to evaluate knee rotational stability in orthopaedic clinics. The main defect, its subjective and discontinuous rating, has limited its application to research study. Different from experimental laboratory setting, operation theatre is not an ideal place to provide controlled load of application due to the instrument size and hygiene concern. With no doubt, intraoperative navigation system would be the most suitable measurement tool in the operation theatre. Because the torque to the knee should be applied manually by the tester, it is suggested that all physical examinations should be performed by one tester and reliability test should be conducted to ensure good consistency across trials.

Intraoperative navigation system provides immediate evaluation of surgical treatment. This technique has been suggested to spend an extra 10 minutes time on average in addition to original procedures (Martelli et al., 2007). The extra time is acceptable as it provides a more reliable clinical result (Plaweski et al., 2006) and an objective way to quantify knee kinematics. Moreover, this technique offers a good repeatability

(Martelli et al., 2007) and a comparable result with mechanical testing devices such as KT-1000 and goniometer (Kendoff et al., 2007). Implementing the high precision navigation technique for comparison of different reconstruction methods (Steckel et al., 2007) and extension to other knee surgeries (Martelli et al., 2006) would be one of the key research areas in the future.

Despite the fact that there are a number of advantages as discussed above, more attention should be paid to address the drawbacks. One should be reminded that the procedure involves invasiveness that may cause extra wounds in the thigh and shank of the patients. To accurately locate the relative movement, transmitters with markers were screwed into the femur and tibia. The invasive procedure would result in additional bone loss and surgical scar to the patients. To minimize the invasive effect, magnetic sensors was attached on the skin by plastic braces (Yagi et al., 2007). However, validation of such technique should be established before its application to the living human.

2.4.3 Dynamic task

Compared with the cadaveric study which is of limited clinical utility (Fu and Zelle, 2007), dynamic task provides valuable information of knee stability of different conditions such as intact knee (Thambyah et al., 2004), injured knee (Houck and Yack, 2001) as well as reconstructed knee (Brandsson et al., 2002). In early years, techniques involving external fixation structure attached to participants' limb would highly affect the gait pattern (Czerniecki et al., 1988). Optical motion analysis system and radiographic measurement have therefore become the most frequently adopted techniques to measure dynamic knee rotational stability.

When comparing the drawbacks of the two techniques, radiographic measurement obviously involves invasive procedures and radiation exposure. Although the amount of exposure has been reported to be similar to a single computerized tomography scan (Tashman et al., 2007), the controversial issue of implantation of bony markers through arthroscopic surgery has become another difficulty for participant recruitment. On the other hand, error due to skin movement when applying optical motion analysis system with reflective skin markers has been claimed (Taylor et al., 2005). A point cluster method has been developed in 1998 (Andriacchi et al., 1998) to minimize the skin movement by using an overabundance of markers on each segment. Yet, the computational complexity (Andriacchi and Alexander, 2000) has become the major technical challenge to orthopaedic specialists while biomechanists are advised to understand the principle behind in order to achieve high accuracy result.

Motion analysis system with skin markers technique is non-invasive, practical and applicable not only in research laboratory settings but also in orthopaedic clinics. The system consists of two or more high speed cameras and a few spherical markers. Commercialized software system also includes auto-digitizing and kinematics calculation. Nevertheless, results of knee internal and external rotation from different marker set protocols were poorly correlated (Ferrari et al., 2008). For example, Thambyah et al. (Thambyah et al., 2004) used 17 skin markers while Georgoulis et al. (Georgoulis et al., 2003) adopted the model with 15 skin markers. Self-compiled program for calculating knee kinematics was not standardized and comparison between studies with different marker set protocols would be highly difficult if not impossible.

In recent years, Tashman and coworkers (Tashman et al., 2004; Tashman et al., 2007) used RSA technique to evaluate knee kinematics of human ACL reconstructed knee during treadmill running after the application to canine ACL deficient knee in 2003. Similar to the protocol of biplane radiograph generation with a transverse plane computer tomography scan to determine transformations between marker based and anatomical coordinate systems, the exposure frequency of the RSA technique has been highly increased to 250 Hz, which enhances a sufficient smooth continuous kinematics data during most of the human dynamic movements.

The biomechanics technique for measurement of tibial rotation is well developed in cadaveric model. Accuracy of most of the techniques is high because bone to bone information could be obtained directly. There is still room of improvement on the techniques applied on living human, especially in the development of a practical and accurate technique for dynamic tasks. The future studies should focus on validity between magnetic measurement and radiographic measurement because the non-invasive magnetic sensor would be useful in orthopaedic clinics if it could produce reliable and valid measurement. Moreover, regarding the optical motion analysis system with reflective skin markers, consensus should be obtained for standardized market set protocol for measurement of tibial rotation during dynamic task.

2.5 Chapter conclusion

The biomechanical techniques to measure tibial rotation were summarized, providing an overview of knee rotational stability measurement techniques. We systematically reviewed, from fundamental cadaveric studies to newly developed intraoperative experiments, the measurement techniques according to the condition in which the knee was examined: external load application, physical examination and dynamic task. To choose a suitable measurement technique for specific clinical application, study purpose should be first identified, and more attention should be paid on whether cadaveric model would be used, and also the way of stress applied to the knee.

Chapter 3 The application of computer assisted navigation system for comparison of different techniques to reconstruct PLC of the knee

Chapter summary

This chapter aims to apply computer assisted navigation system to evaluate the immediate effect of two PLC reconstruction techniques. By adopting a cadaveric model, muscle contraction would be eliminated. Five intact formalin preserved cadaveric knees were used. Navigation system was used to measure knee kinematics (posterior translation, varus angulation and external rotation) after applying constant force and torque to the tibia. Four different conditions of the knee including intact knee, PLC sectioned knee and PLC reconstructed knees by the double-femoral tunnel technique and single-femoral tunnel technique were evaluated during the biomechanical test. Sectioning the PLC structures resulted in significant increase in external rotation at 30° of flexion, posterior translation at 30° of flexion, and varus angulation at 0° of flexion. Both reconstruction techniques significantly restored the varus stability. The external rotation and posterior translation at 30° of flexion after reconstruction with double-femoral tunnel technique were significantly better than that of single-femoral tunnel technique. In conclusion, by using computer assisted navigation system, the results suggested that PLC reconstruction by a double-femoral tunnel technique achieves a better rotational control and resistance to posterior translation than single-femoral tunnel technique.

Publication: This chapter is published in Arthroscopy (Appendix A).

Ho EPY, Lam MH, Chung MML, Fong DTP, Law BKY, Yung PSH, Chan WY, Chan KM (2011). Comparison of two surgical techniques for reconstructing posterolateral corner of the knee - a cadaveric study evaluated by navigation system. Arthroscopy, 27(1):89-96

3.1 Introduction

The PL instability is reported to be a significant disabling condition (Clancy et al., 2003; LaPrade and Wentorf, 2002). Failure to recognize the PLC injury will lead to failure in reconstructing ACL and PCL (Covey, 2001; Gollehon et al., 1987; LaPrade et al., 2002; LaPrade et al., 2002; Seebacher et al., 1982). Our understanding of anatomy and biomechanics of the PLC has improved in the past two decades, but the best technique to reconstruct the PLC has not been well established (Arciero, 2005; Covey, 2001; LaPrade et al., 2002; Schechinger et al., 2009; Veltri and Warren, 1994).

3.11 Primary and secondary restraints of PLC

The anatomy of the PLC is complex, and it is composed of both static and dynamic stabilizers. Previous studies reported that there were three primary stabilizers of the PLC, including the LCL, popliteus muscle-tendon unit and PFL, which served as the primary restraints of tibial external rotation at 30° of flexion (Gollehon et al., 1987; Grood et al., 1988; Nielsen and Helmig, 1986; Nielsen et al., 1985; Nielsen et al., 1984; Seebacher et al., 1982; Shahane et al., 1999). The LCL was suggested to act as a primary restraint to varus angulation, whereas the PFL and the popliteus were suggested to act as secondary stabilizers to varus angulation. Because most reconstructive methods in the literature aimed to reconstruct the three primary stabilizers (LCL, PFL and popilteus muscle-tendon unit) (LaPrade et al., 2004; Larson et al., 1996; Nau et al., 2005), other structures of the PLC were removed to avoid their effect.

3.12 Reconstruction techniques of PLC

Larson and coworkers (Larson et al., 1996) described a technique for reconstruction in 1996 that involved the utilization of a free semitendinosis graft as a figure of eight through a transfibular tunnel and the fixation at an isometric point of the LCL and PFL using a screw and washer in the lateral femoral condyle. In previous decades various modifications of reconstruction technique and development on anatomic reconstruction of PLC have been reported (Arciero, 2005; Fanelli et al., 1996; Kumar et al., 1999; Stannard et al., 2005). Kumar and coworkers (Kumar et al., 1999) described a technique in 1999 in which a tunnel was drilled in the fibular head and the lateral femoral epicondyle. The PLC structure was reconstructed by use of autogenous tendon graft passing through the tunnels and secured with an interference screw in the lateral epicondyle tunnel. However, residual laxity was reported after PLC reconstruction with this technique (Arciero, 2005). It was suggested that the single isometric femoral tunnel did not address the different insertion sites of the popliteus tendon and LCL. In 2005, Arciero (Arciero, 2005) suggested another technique that aimed to provide a more anatomic reconstruction of the PLC by re-creating the insertion sites of the LCL and the popliteus on the femur using a dual-femoral sockets technique.

The purpose of this chapter was to compare the immediate effect of double-femoral tunnel technique and single-femoral tunnel technique for PLC reconstruction on knee kinematics, using an isolated cadaveric injury model. It was hypothesized that the knee kinematics was better restored by double-femoral tunnel technique.

3.2 Method

3.2.1 Specimen Preparation

Six intact human cadaveric formalin preserved knees were used. The specimens were checked by inspection, palpation and physical examination including the Lachman test and varus valgus stress test to detect any obvious bony deformity, previous fracture and ligamentous laxity. One knee was found to have severe degeneration after dissection that was not suitable for the experiment. Five cadaveric knees were finally used in the experimental test.

For all cadaveric specimens, the femur was sawed at 15 cm above the joint line and the ankle was disarticulated, keeping the distal tibiofibular joint being kept intact. The skin and muscle 10 cm above and below the joint line were removed, with the interosseous membrane being kept intact. The soft tissue was carefully dissected by a single surgeon while keeping the following structures intact: MCL, posteromedial complex, ACL, PCL, popliteus muscle-tendon unit, LCL, PFL and menisci. Apart from these structures, all other soft tissues were removed including the capsule, patellar tendon, iliotibial band, biceps tendon and hamstring tendons. The described procedures aimed to minimize the effects of the muscle tone, as well as restraint caused by the capsule so that the two reconstruction techniques were compared in a well-controlled condition.

The dissected knees were put on a custom-made testing apparatus in which the distal femur was rigidly held and that allowed free movement of the tibia and fibula for conducting biomechanical testing. A custom-made 8 mm diameter intrameduallary nail with an adapter over the distal end was inserted from distal tibia to the shaft of the tibia. Two 4.5 mm shanz screws were inserted to the tibia through two locking holes of the intramedually nail for anchoring the trackers of the navigation system (Figure 3.1). A torque sensor (Futek Advanced Sensor Technology, USA) with accuracy less than 0.02 Nm was attached to the distal end of intrameduallary nail for application of external rotation torque during the test. Another two parallel 4.5 mm shanz screws were inserted over distal shaft of femur for anchoring of the trackers of the navigation system.

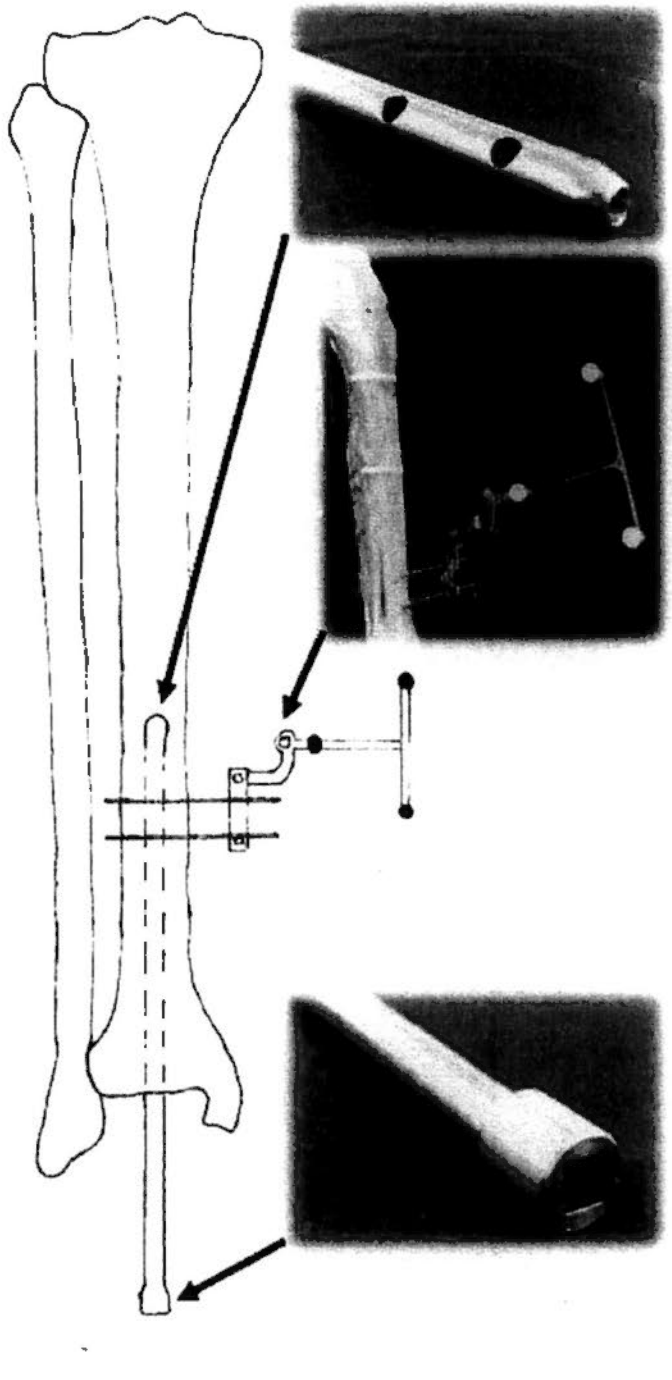


Figure 3.1 Anterior view of line diagram showing that the intramedullary nail was fixed inside the distal tibia by two shanz screws connected with navigation trackers. The distal end of the intramedullary nail was connected to the torque sensor for application of constant torque.

3.2.2 Testing protocol

Intraoperative navigation system (BrainLab, Feldkirchen, Germany) was used for measurement of the testing parameters. The BrainLab ACL Reconstruction System version 2.0 was used to measure the degrees of external rotation and posterior translation while the BrainLab Total Knee Replacement System version 2.1 was used to measure the varus angulation. For the biomechanical test, constant force and torque were first applied to the tibia of the intact knee. Testing included anterior and posterior pulling forces of 133 N (Gabriel et al., 2004) for measuring AP laxity at 30°/90° of flexion and rotational torques of 5 Nm (Gabriel et al., 2004) for measuring internal/external rotational laxity and varus/valgus laxity at 30°/90° and 0°/30° of flexion, respectively. The range of motion was guided by the navigation system, which was measured according to the guide pins and trackers inserted.

The popliteus, PFL and LCL structures of the knee were then sectioned through their midsubstance. The same testing procedures were repeated to document the laxity of the sectioned knee. Two different techniques of PLC reconstruction were performed. In both techniques a formalin fixed tibialis anterior tendon allograft was harvested from the same leg, and both ends of the tendon were whip-stitched with Ethibon No.5 suture (Ethicon, Somerville, NJ) for 1.5 cm. The diameter of the five tibialis anterior tendon allograft measured 7 mm, thus none of the graft can pass through the 6 mm graft sizer. During the technique B reconstruction, the two whip-stitched ends of the graft measured 9 mm in diameter, which was larger in the middle part of the graft. During the graft preparation, only 9 mm graft sizer would accommodate the passage of both ends together in all specimens. The details of both reconstruction techniques were described in the following section. The same testing procedures were used after each reconstruction.

3.2.3 Surgical technique

Technique A (Figure 3.2) - This technique aimed to reconstruct the LCL and PFL in a more anatomic way by creating two femoral tunnels according to the footprint of the LCL and the popliteus tendon as decribed by Arciero (Arciero, 2005). A 2.4 mm guide pin was inserted anterior and inferior to the fibula insertion of the LCL. It then posteromedially exited to the posterior aspect of the fibula head at level of the proximal tibio-fibular joint. A 7 mm diameter transfibular tunnel was created by the cannulated reamer. A 2.4 mm guide pin was inserted into the centre of the footprint of the LCL over the lateral epicondyle of the femur toward the medial cortex. A 7 mm femur tunnel was created by use of a cannulated reamer for the reconstruction of the LCL. A popliteofibular tunnel was created after establishment the tunnel for the LCL by insertion a 2.4 mm guide pin into the centre of the footprint of the popliteus tendon. A 7 mm popliteofibular tunnel was created by the cannulated reamer. The tendon graft was passed through the transfibular tunnel. The posterior limb was passed along the posterior aspect of the proximal tibiofibular joint, through the popliteus hiatus and then through the popliteal fibula tunnel toward the medial cortex. The anterior limb was passed over the posterior limb and then through the LCL tunnel towards the medial cortex. The graft was tensioned at 30° of flexion, internal rotation and slight valgus. It was then fixed by sutures tied around a post created by a 4.5 mm cortical screw with washer.

Technique B (Figure 3.3) - This was the modified Larson technique (Larson et al., 1996) described by Kumar (Kumar et al., 1999), which involved the use of single-femoral tunnel for the fixation of both anterior and posterior limbs of the graft. The transfibular tunnel created in technique A was reused. The femoral tunnel over the femoral insertion of the LCL created in technique A was used with the tunnel enlarged to 9 mm diameter. Graft was passed through the transfibular tunnel, and both anterior and posterior limbs were passed through the femoral tunnel with a whipping suture. The graft was tensioned at a position of 30° of flexion, internal rotation and slight valgus. The grafts were fixed by sutures tied around a post created by a 4.5 mm cortical screw.

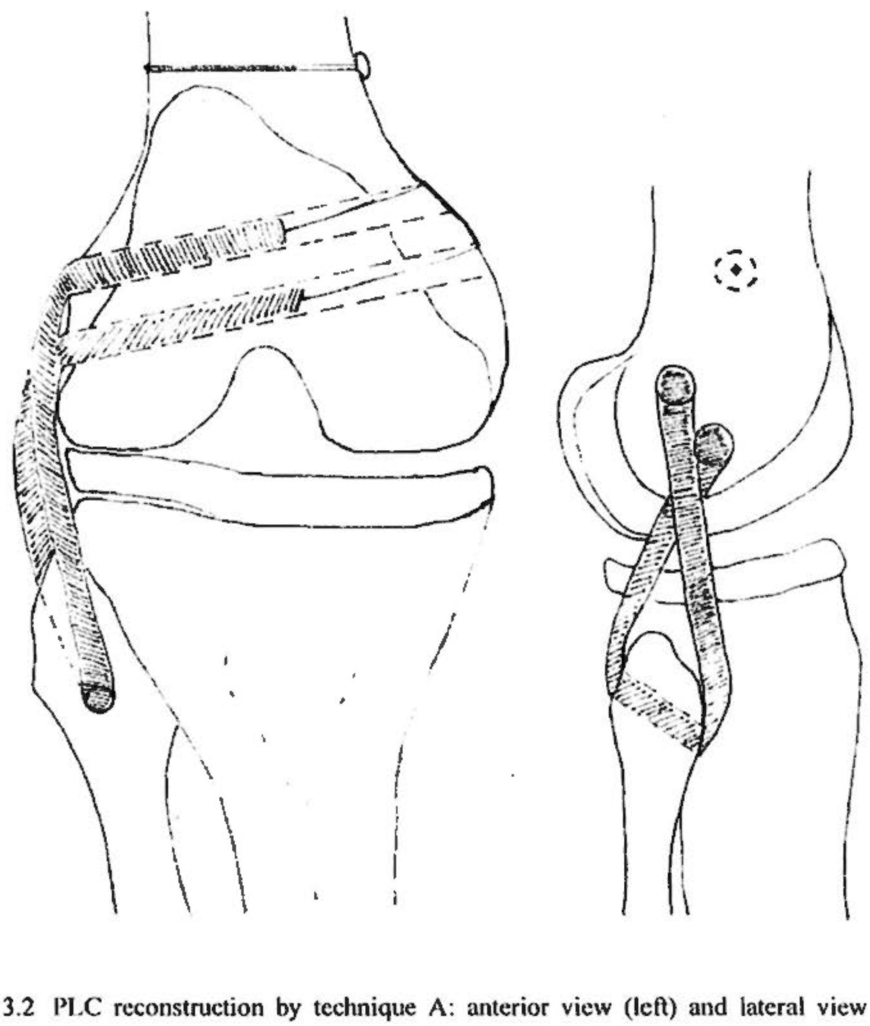


Figure 3.2 PLC reconstruction by technique A: anterior view (left) and lateral view (right). Two femoral tunnels measuring 7 mm in diameter were created according to the footprint of the LCL and popliteus tendon. The tendon graft was passed through the 7 mm transfibular tunnel, the posterior limb was passed to the poplteal fibula tunnel, and the anterior limb was passed over the posterior limb then through the LCL tunnel toward the medial cortex. It was then fixed by sutures tied around a post created by a 4.5 mm cortical screw with a washer.

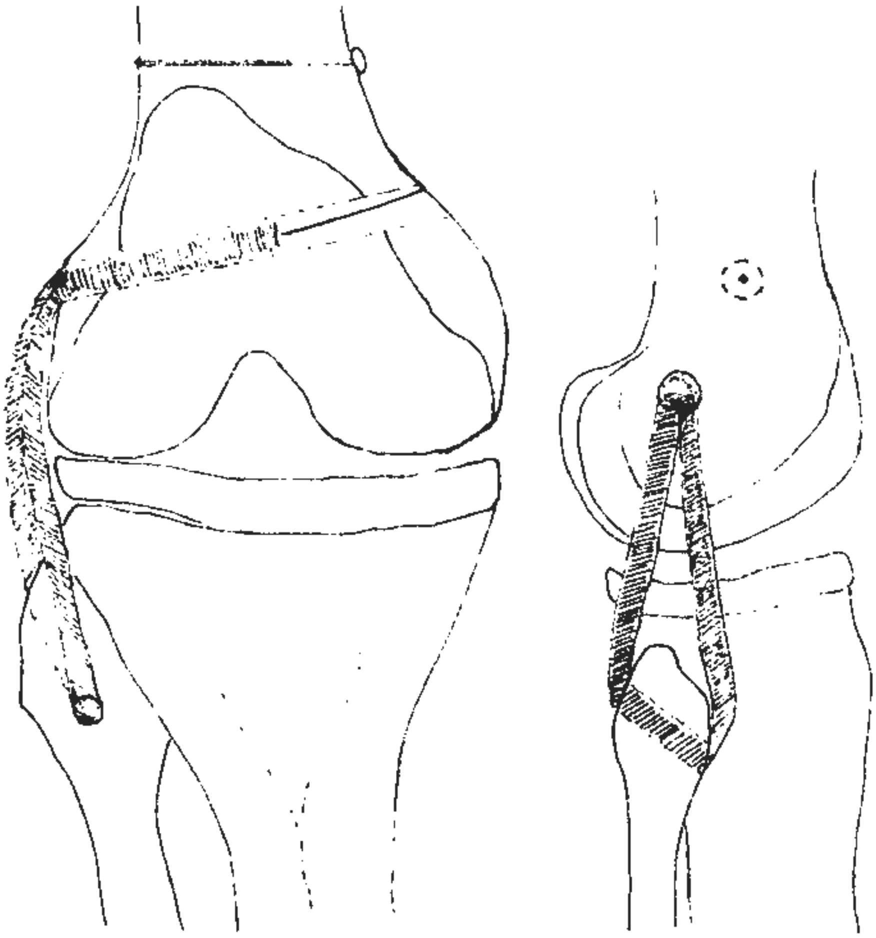


Figure 3.3 PLC reconstruction by technique B: anterior view (left) and lateral view (right). A single-femoral tunnel measuring 9 mm in diameter was created over the lateral epicondyle for the passage of both anterior and posterior limbs of the graft. The graft was fixed by sutures tie around a post.

3.2.4 Statistical Analysis

One-way multivariate ANOVA with repeated measures was used to examine the difference in all dependent variables. One-way ANOVA with repeated measures was used on each parameter to examine any significant differences between all testing conditions, which included intact knee, sectioned knee and reconstructed knees. Least-square difference post hoc pairwise comparisons were used between the different conditions. All statistical tests were calculated by statistical analysis software (SPSS software, version 16.0, USA). The level of significance was set at p=0.05. Results were presented as mean (SD).

3.3 Results

Multivariate ANOVA showed that knee kinematics was significantly affected by the four different conditions of the knee ($P<0.05$). ANOVA also showed that all dependent variables except posterior translation at 90° of flexion were significantly affected by the four conditions of the knee ($P<0.05$). The results of the post hoc pairwise comparsions in different conditions of posterior translation, external rotation and varus angulation were summarized in Table 3.1.

3.3.1 Posterior Translation

After sectioning the structures of the PLC, there was a significant increase in posterior translation at 30° of flexion from 3.4 mm (1.5) to 7.4 mm (3.8 mm) after application of posterior pulling force (Figure 3.4). After reconstruction of the PLC by technique A, there was an improvement at 30° of flexion to 3.4 mm (2.7 mm), which showed a significance difference compared with the sectioned knee ($p<0.05$). There was no significant difference compared with the intact knee ($p>0.05$). Reconstruction of the PLC by technique B decreased posterior translation from 7.4 mm (3.8 mm) to 5.0 mm (2.3 mm) compared with the sectioned knee, which was not significant ($p>0.05$). Moreover, reconstruction by technique B showed an inferior result in resisting posterior translation when compared with technique A ($p<0.05$).

Table 3.1 Statistical results of different parameters comparing four testing conditions (Intact, Sectioned, Technique A and Technique B)

Knee specimen	I	S	A	B	Statistical test (ANOVA[a]/Post hoc[b])
External rotation (°) at 30° of flexion					
1	7.0	17.0	12.0	15.0	
2	12.0	19.0	11.0	12.0	
3	12.0	29.0	10.0	15.0	
4	14.0	27.0	9.0	14.0	
5	11.0	31.0	9.0	16.0	
Mean (SD)	11.2 (2.6)	24.6 (6.2)	10.2 (1.3)	14.4 (1.5)	P < 0.01 /I-S*, S-A*, S-B*, A-B*
External rotation (°) at 90° of flexion					
1	6.0	16.0	15.0	16.0	
2	15.0	26.0	20.0	17.0	
3	20.0	36.0	27.0	25.0	
4	17.0	25.0	13.0	20.0	
5	17.0	30.0	19.0	23.0	
Mean (SD)	15.0 (5.3)	26.6 (7.3)	18.8 (5.4)	20.2 (3.8)	P <0.01 /I-S*, S-A*, S-B*, I-B*
Posterior translation (mm) at 30° of flexion					
1	2.0	4.0	3.0	4.0	
2	3.0	6.0	2.0	5.0	
3	6.0	14.0	8.0	9.0	
4	3.0	6.0	1.0	3.0	
5	3.0	7.0	3.0	4.0	
Mean (SD)	3.4 (1.5)	7.4 (3.8)	3.4 (2.7)	5.0 (2.3)	P < 0.01 /I-S*, S-A*, A-B*, I-B*
Posterior translation (mm) at 90° of flexion					
1	1.0	2.0	3.0	4.0	
2	3.0	5.0	3.0	3.0	
3	9.0	13.0	4.0	4.0	
4	2.0	1.0	0.0	1.0	
5	2.0	4.0	3.0	3.0	
Mean (SD)	3.4 (3.2)	5.0 (4.7)	2.6 (1.5)	3.0 (1.2)	No significant difference
Varus angulation (°) at 0° of flexion					
1	0.0	1.5	1.5	1.5	
2	1.0	4.5	1.5	0.5	
3	2.5	13.0	3.5	1.5	
4	2.5	7.5	0.0	0.5	
5	5.5	13.0	3.5	1.0	
Mean (SD)	2.3 (2.1)	7.9 (5.1)	2.0 (1.5)	1.0 (0.5)	P <0.01 /I-S*, S-A*, S-B*
Varus angulation (°) of 30° of flexion					
1	0.5	6.5	4.5	4.0	
2	4.0	9.0	4.0	9.5	
3	5.5	19.5	5.0	6.0	
4	1.0	11.5	1.5	4.5	
5	9.0	17.5	9.5	8.0	
Mean (SD)	4.0 (3.5)	12.8 (5.5)	4.9 (2.9)	6.4 (2.3)	P <0.01 /I-S*, S-A*

Abbreviations: I, intact; S, sectioned; A, technique A; B, technique B. * Statistically significant difference.

[a] P value of ANOVA for the four conditions. [b] Results of least-square difference post hoc pairwise comparison.

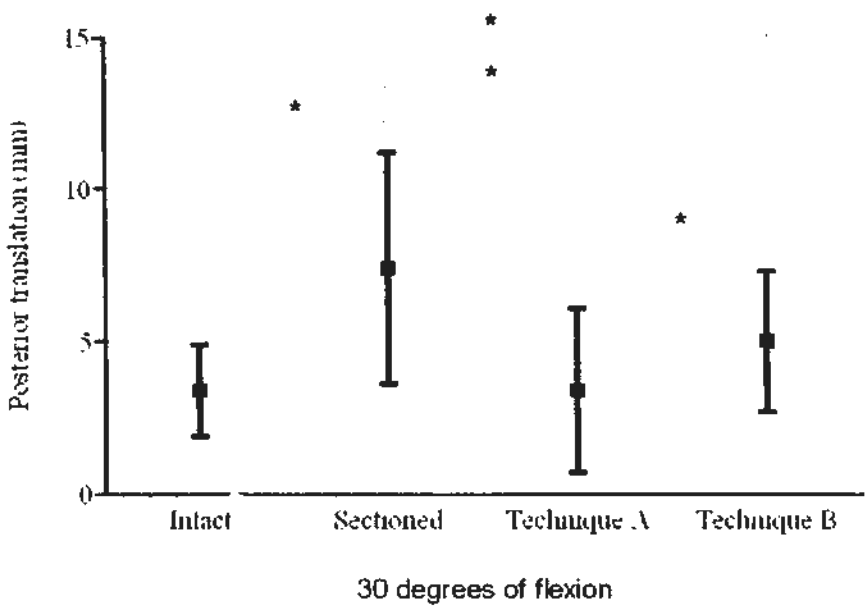


Figure 3.4 The posterior translation (mm) for each tested knee state (intact, sectioned, technique A [double-femoral tunnel technique], technique B [single-femoral tunnel technique]) at 30° of flexion. Asterisks indicate a significant difference ($p<0.05$).

3.3.2 External rotation

The external rotation of the intact knee was 11.2° (2.6°) and 15.0° (5.3°) at 30° and 90° of flexion, respectively (Figure 3.5). There was significant increase in external rotation after sectioning of the PLC structures, which measured as 24.6° (6.2°) at 30° of flexion ($p<0.05$) and 26.6° (7.3°) at 90° of flexion ($p<0.05$). Both PLC reconstruction techniques improved the rotational laxity when compared with the sectioned knee ($p<0.05$). Reconstruction by technique A improved the external rotation at 30° of flexion from 24.6° (6.2°) to 10.2° (1.3°), which was comparable to the intact knee ($p>0.05$). The reconstruction with technique A showed a better result than that of technique B, which measured 14.4° (1.5°) ($p<0.05$). There was no significant difference in external rotation at 90° of flexion between technique A and technique B ($p>0.05$).

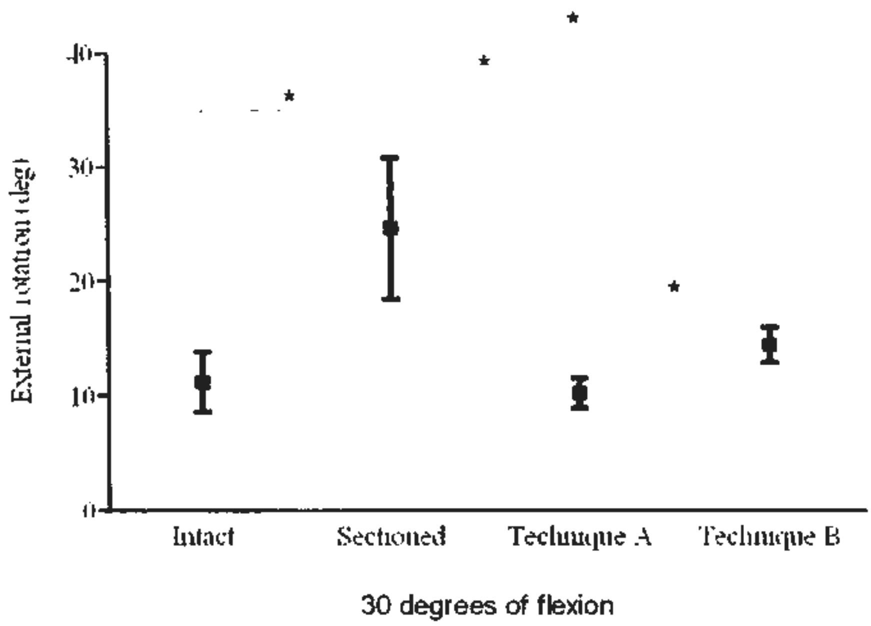


Figure 3.5 The external rotation (°) for each tested knee state (intact, sectioned, technique A [double-femoral tunnel technique], technique B [single-femoral tunnel technique]) at 30° of flexion. Asterisks indicate a significant difference ($p<0.05$).

3.3.3 Varus angulation

At 0° of flexion, varus angulation significantly increased from 2.3° (2.1°) to 7.9° (5.1°) after sectioning of the structures of the PLC ($p<0.05$). Both reconstruction techniques restored the varus laxity to 2.0° (1.5°) in technique A and 1.0° (0.5°) in technique B, with no significant difference between the reconstructed knees and the intact knee ($p>0.05$). However, there was no significant difference between the two reconstruction techniques ($p>0.05$). At 30° of flexion, the varus angulation significantly increased from 4.0° (3.5°) to 12.8° (5.5°) ($p<0.01$). After reconstruction by technique A, the varus laxity significantly decreased from 12.8° (5.5°) to 4.9° (2.9 °) ($p<0.05$). There was no significant difference between the sectioned knee and the reconstructed knee with technique B or between the reconstructed knees with both techniques.

3.4 Discussion

Numerous surgical techniques have been proposed in the literature for restoring PL instability, including acute repair, augmentation by the surrounding structures and reconstruction by use of allograft or autograft. In the 1980s, Hughston and Jacobsen (Hughston and Jacobson, 1985) used a lateral gastrocnemius, capsular, LCL and popliteus advancement procedure that relied on the integrity of PL structures. However, the result was not satisfactory. Clancy and coworkers (Clancy et al., 2003) diverted the biceps tendon and fixed it to the lateral femoral condyle by a screw and washer that aimed to reduce the external rotation of the knee, but the PLC function could not be completely restored. Muller (Muller, 1983) used a strip of the ilotibial band along the line of the popliteus tendon for a popliteal bypass procedure. The clinical outcomes and the degrees of residual laxity of this technique were not clearly reported.

In 1990s, Larson and coworkers (Larson et al., 1996) advocated a technique using a free semitendinosis graft as a figure of eight through a fibula tunnel and around a screw and washer in the lateral femoral condyle to reconstruct the LCL and the PFL. The tunnel technique was similar to the technique proposed by Kumar and coworkers (Kumar et al., 1999), but it was simplified so that the semitendinosis loop formed a triangle and was secured in the lateral epicondyle by use of an interference screw. In 2004, La Prade and coworkers (LaPrade et al., 2004) described a two-tail technique that offered a more anatomic reconstruction by adding a tibial tunnel to reconstruct the popliteus, which stressed the reconstruction of the three primary stabilizers (popliteus, PFL and LCL). Nau and coworkers (Nau et al., 2005) in 2005 compared the two-tail technique and the two-tunnel technique, which was similar to the technique A used in our experiment, It was criticized that the reconstruction by the two-tunnel technique only stressed the reconstruction of the static stabilizing structures of the PLC (LaPrade et al., 2004). However, both techniques restored the external rotation laxity at 30° and 90° of flexion, varus laxity at 0° and 30° of flexion, which showed no significant difference between the two techniques of reconstruction (Nau et al., 2005).

The anatomy over the lateral side of the knee was first described in 1982 and was divided into three layers from superficial to deep (Seebacher et al., 1982). The biomechanics of the PLC was then studied by sequential sectioning of the various structures in cadaver (Gollehon et al., 1987; Grood et al., 1988; Nielsen and Helmig, 1986; Nielsen et al., 1985; Nielsen et al., 1984; Seebacher et al., 1982; Shahane et al., 1999). From these studies, the LCL was found to be the primary restraint to varus movement. The PFL and popliteus tendon were reported to resist external rotation of the knee. Both the ACL and PCL served as the secondary restraint to varus angulation and external rotation. Moreover, the structures of the PLC were considered secondary restraints to posterior translation; our results showed increased posterior translation after sectioning of the PLC structures.

Brinkman and coworkers (Brinkman et al., 2005) quantitatively documented the insertion geometry of the LCL and popliteus tendon and found that the popliteus tendon inserted around 11 mm distally and 0.84 mm either anterior or posterior to the LCL. Therefore, it was concluded that single-femoral tunnel technique could not restore normal anatomy. Our results showed that single-femoral tunnel technique did not completely restore the rotational laxity in the sectioned knee and it was inferior to the double-femoral tunnels technique as well. There was no significance difference in external rotation and varus angulation between the intact knee and the reconstructed knee with double-femoral tunnel technique. The reconstruction with double-femoral tunnel technique included two femoral tunnels with two separate limbs of soft-tissue graft to simulate the function of the LCL and PFL, which explained the experimental results of better rotational control. Apart from using the tendon graft of the tibialis anterior for reconstruction, the literature has suggested using Achilles tendon allograft (Schechinger et al., 2009) or split Achilles tendon allograft (Sekiya and Kurtz, 2005) for reconstruction of the PLC with double-femoral tunnel technique.

The navigation system developed for ACL reconstruction would assist surgeon to evaluate AP translation and rotation displacement at 30° and 90° of flexion. Given the accurate measurement provided by the system, it was used in this experiment to measure knee kinematics. Another software program in the navigation system (BrainLab Total Knee Replacement System version 2.1) was used to evaluate the treatment's effect on varus angulation. The real-time changes in knee kinematics presented by the system provided valuable information for surgeon to examine the intact, sectioned and reconstructed knees under anesthesia. Therefore the navigation system may be useful in the clinical setting and this should be further studied.

The cadaveric knees in this experiment were fixed by formalin, which caused a limitation in the range of motion and the degree of ligament laxity. However, this negative effect was avoided by each specimen serving as its own control. The measurements were conducted in the same knee for four conditions including intact knee, sectioned knee and reconstructed knee with both techniques. Although allograft with same diameter was used in this experiment, we would suggest that artificial materials should be used in the future studies to control the thickness, preservation and elasticity. Another limitation in this experiment was that the biomechanical test was not able to fully simulate the in vivo conditions. Moreover, the function of the dynamic stabilizers was not addressed in this experiment. During PLC reconstruction in humans, the anterior limb of the graft was tunneled deep to the biceps femoris tendon insertion and adjacent to the native LCL, but this procedure could not be repeated in this experiment because the muscle tone of biceps was absent. Lastly, the graft healing and maturation, which are the most important clinical issues, were not investigated. In this experiment, the real physiological condition could not be simulated but the tested conditions could be isolated clearly. Therefore, the results were reproducible, which facilitated the experiment to determine the differences between the two reconstruction techniques.

3.5 Chapter conclusion

Both techniques of PLC reconstruction in this experiment showed improved stability compared with PLC sectioned knee. The PLC reconstruction with double-femoral tunnel technique showed better rotational stability and resistance to posterior translation than the single-femoral tunnel technique without compromising varus stability.

Chapter 4 The development of a biomechanical meter to quantify knee rotational laxity

Chapter summary

Biomechanical measurement tools have been developed and widely used to precisely quantify knee AP laxity after ACL injury. This chapter aims to develop a biomechanical meter to quantify knee rotational laxity under different applied torques (1-10 Nm) to the knee joint. The meter consisted of an ankle orthosis, torque sensor and one motion sensor, which would provide an objective and quantitative measurement of knee rotational laxity. It was hypothesized that the proposed meter would accurately and reliably measure tibial rotation in cadaveric model. Its reliability and validity were tested using cadaveric human specimens. Intra-rater and inter-rater reliability were quantified in terms of ICC coefficient among trials and between testers. Validity was verified by comparing data with a computer assisted navigation system. The intra-rater and inter-rater reliability achieved high correlation for both internal and external rotation, ranged from 0.959 to 0.992. For the validity, ICC for both internal and external rotation was 0.78 when compared with the gold standard measurement. The mean differences between the proposed meter and the navigation system were 2.3° and 2.5° for internal and external rotation, respectively. This simple meter might be useful in a wide field to document knee rotational laxity with various purposes, especially after ACL injury.

Publication: This chapter is submitted to Knee Surgery, Sports Traumatology, Arthroscopy.

Lam MH, Yung PSH, Fong DTP, Hung ASL, Chan WY, Chan KM (submitted). A biomechanical device to quantify knee rotational laxity: validity and reliability on human specimens. Knee Surgery, Sports Traumatology, Arthroscopy

Grant: This chapter is funded by HKSAR Innovation and Technology Commission.

Yung PSH, Fong DTP, Lam MH, Law BKY, Chan WY, Liao WH, Cheng CK, Chan KM. A knee rotational laxity meter to evaluate knee rotational stability. Innovation Technology Fund, 2009-2010, HKSAR Innovation and Technology Commission, ITS/039/09, HKD999,824; plus Internship Programme, InP/277/09 (HKD226,380), InP/313/09 (HKD214,200)

4.1 Introduction

The knee is the most commonly injured body site in sports, which accounts for 10-40% (Hinton et al., 2005; Louw et al., 2008). Among all sport-related knee injuries, around 45% is related to ligamentous injury (Ingram et al., 2008; Majewski et al., 2006). An accurate diagnosis of knee ligamentous injury relies on comprehensive physical examination, which relates to symptoms and functional instability of the injured patients (Kocher et al., 2004). Since some of the physical examinations for assessing AP laxity of the knee are greatly influenced by the examiners' experience and skill (Lubowitz et al., 2008), objective tools (Monaco et al., 2009; Schuster et al., 2004; Staubli and Jakob, 1991) have been developed and proven to precisely quantify knee laxity after ACL injury.

The restoration of knee rotational stability is recently being emphasized because anatomic double-bundle ACL reconstruction has been suggested to restore rotational stability better than single-bundle ACL reconstruction (Fu and Zelle, 2007). However, it is still highly controversial. Pivot shift test and dial test are often used by clinicians to measure knee rotational stability before and after ACL reconstruction (Kondo et al., 2008; Meredick et al., 2008; Yagi et al., 2007). Again, these manual examinations are subjective and dependent on examiners' experience and skill. Therefore, an objective tool that measures tibial rotation would be of great value to document knee rotational laxity of healthy and injured knees.

The procedures for measuring knee laxity should be simple, easy and practical in clinical setting. It may not be practical to use motion analysis system with skin marker, although it has been utilized in previous research to quantify tibial rotation (Ristanis et al., 2005; Waite et al., 2005). Motion sensor was used by a recent study

(Musahl et al., 2007), in which three EM sensors were attached to the lower limb to measure knee rotational laxity in a relaxed state. The device was only proven to be reliable on cadaver and human subjects (Tsai et al., 2008) but no validity data was presented. Besides, computer assisted navigation system (Bignozzi et al., 2010; Ferretti et al., 2009; Kanaya et al., 2009) has been used to measure intraoperative knee kinematics during ACL reconstruction. Though it was reported that the system could achieve an accuracy of 1° (Koh, 2005), the procedure is invasive to the patient as it involves rigid fixation of bone marker pins.

In this chapter, a new meter for measurement of tibial rotation was presented. The meter consisted of an ankle orthosis, torque sensor and one motion sensor. The orthosis design aimed to provide a more simple way to prevent any ankle motion over the previous boot design (Musahl et al., 2007). Furthermore, only one motion sensor was used to avoid calculation complexity among the three sensors reported previously. Torque and motion sensors were used to measure the applied torque and the corresponding tibial rotation. The objective was to measure the validity, inter-rater and intra-rater reliability of the proposed meter. It was hypothesized that the meter would accurately and reliably measure tibial rotation.

4.2 Method

4.2.1 Development of the proposed meter

The details of the knee rotational laxity meter, which aimed to measure external and internal tibial rotation, is presented here. The meter consisted of an ankle orthosis, a torque sensor with a handle bar and one motion sensor at the bottom of the meter (Figure 4.1). The orthosis is a common orthotic device that is used to immobilize the ankle joint of patients suffering from ankle related injuries. Three sizes of orthosis that accommodated patients with different sizes of foot were fabricated in the Department of Prosthetics and Orthotics. Next, a torque sensor (FUTEK, USA), which monitored the value of applied torque, was mounted at the bottom of each orthosis. A handle bar fixed on the torque sensor allowed tester to apply torques to the knee joint. One EM motion sensor with acquisition frequency of 120 Hz (trakSTAR Ascension Technologies Corporation, USA) was further attached to the other side of the torque sensor such that its longitudinal axis was along the tibia's axis of rotation. The motion sensor provided six DOF of its orientation (rotation angles) and position (three dimensional coordinates) with reference to a signal emitting frame through high speed electromagnetic transmission. The orientation data were outputted to a laptop computer. It was used to measure tibial rotation during the laxity test.

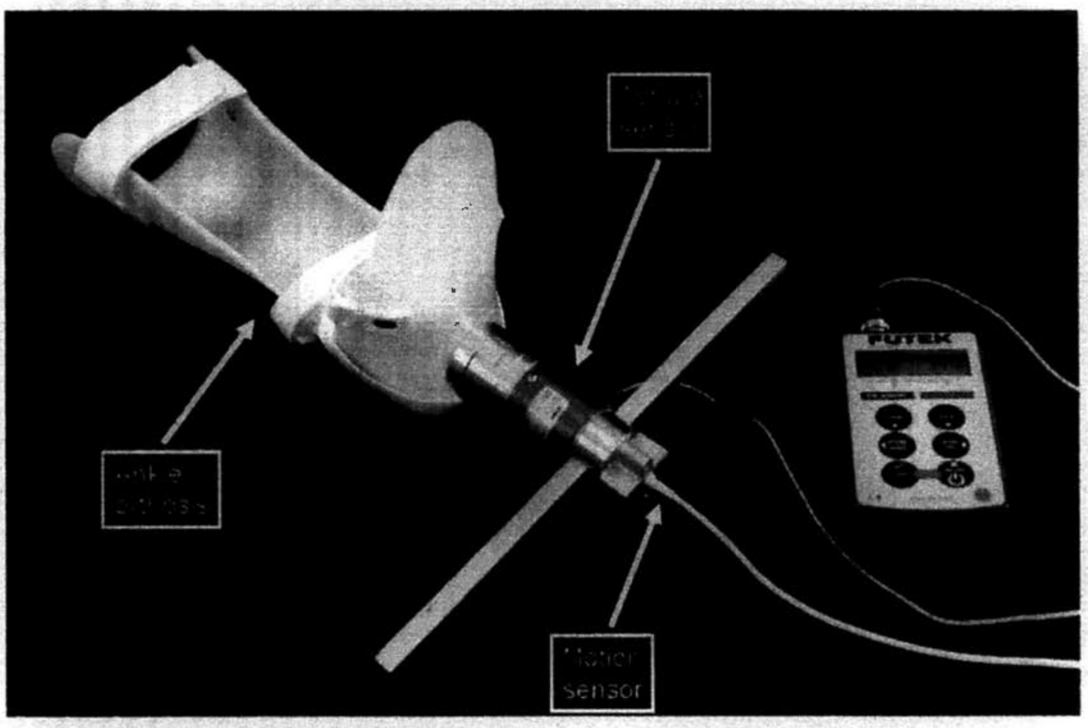


Figure 4.1 The rotational laxity meter, consisting of an ankle orthosis, a torque sensor with a handle bar and one motion sensor attached at the bottom.

4.2.2 Specimen preparation

In this experiment, three preserved human specimens of the lower extremity, including the hip, knee and ankle joints, were used. The experiment was conducted in mortuary of Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong. The specimens were checked by inspection, palpation and physical examination to exclude any obvious bony deformity, previous fracture, arthritic change and ligamentous hyper laxity.

For all specimens, the femur was sawed at 15 cm above the joint line. Two 30 cm long bone pins were drilled through the femur from medial to lateral side. It was then fixed on an autopsy table using two custom-made clamps that allowed free movement of tibia for conducting biomechanical testing. Two pairs of 4.5 mm pins were inserted over the anterior side of the distal femur and proximal tibia. These pins were used for anchoring trackers of the computer assisted navigation system.

4.2.3 Computer assisted navigation system

An intraoperative navigation system (BrainLAB, Germany) with ACL Reconstruction System Version 2.0 was used as a gold standard for measurement of internal and external tibial rotation with accuracy less than 1°. It was also used to monitor the knee flexion angle throughout the experiment. Before the start of the experiment, two sets of infrared optical motion trackers were fixed to the pins that had drilled into the femur and tibia previously. The trackers were oriented such that it could be visualized within the full range of motion by the navigation system camera. The system was calibrated by the use of an infrared pointer to digitize required points inside and outside the knee joint. A three dimensional model of the knee was calculated by the system that presented a real-time specific movement of the knee including flexion, extension, internal rotation and external rotation.

4.2.4 Testing protocol

Two independent testers were included in the experiment for measurement of knee laxity using the proposed meter. The orthosis was secured to the leg with a tourniquet and the leg was held at 30° of knee flexion and neutral position of rotation, which was determined by the navigation system. At this point, the reading of torque sensor was set to zero. Each tester applied external torque progressively to the handle bar with 1 Nm increment until 10 Nm torque was reached and then 1 Nm increment of internal rotation was applied until 10 Nm was reached (Figure 4.2). A maximum of 10 Nm torque was applied because human comfortable limit was reported to be between 5-10 Nm (Park et al., 2008). Ten reading measurements of each internal and external rotation were repeated three times for each tester. The first tester repeated the whole procedure for the rest of the knee specimens. The data from the navigation system was recorded by a technician while the EM sensor data were automatically recorded in the computer for further analysis.

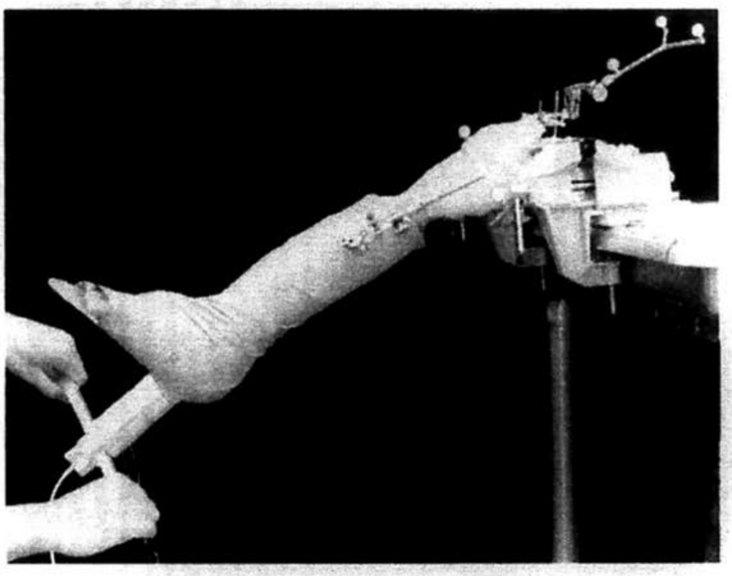


Figure 4.2 This figure shows the experimental setup for validation of knee rotational laxity meter.

4.2.5 Statistical analysis

For statistical analysis, single measures ICC with 95% CI was used to gauge intra-rater and inter-rater reliability and validity. For intra-rater reliability, the ICC across three trials was calculated for both testers. The average value of the three trials for tester 1 was compared to the average value of the three trials for tester 2 to determine inter-rater reliability. For validity, data from the proposed meter and the navigation system would be compared. Mean, SD and 95% CI of the difference as well as root mean square difference at different applied torques were calculated. All parameters were reported for internal and external rotations separately. A reliable correlation was shown if the single measures ICC was above 0.75.

4.3 Results

The EM sensor at the bottom of the proposed meter measured tibial rotation relative to the femur. The internal and external rotation angles increased with the applied torque to the knee for both the proposed meter and the navigation system (Figure 4.3). At 5 Nm applied torque, the total range of rotations measured from the proposed meter (from the navigation system) were 38.0°±2.0° (34.0°±2.6°) with 21.3°±0.6° (19.7°±1.5°) internal rotation and 16.7°±2.5° (14.3°±1.2°) external rotation. The highest applied torque of 10 Nm resulted in the total range of rotation of 59.3°±3.5° (43.3°±1.2°) with 32.7°±2.5° (24.0°±2.0°) internal rotation and 26.7°±3.2° (19.3°±1.2°) external rotation.

For reliability, intra-rater and inter-rater reliability achieved high correlation for both internal and external rotation, ranged from 0.959 to 0.992 (Table 4.1). For validity, when compared with the navigation system as a gold standard, ICC for both internal and external rotation was 0.78, which was regarded a reliable correlation. The mean differences between the proposed meter and the navigation system were 2.3° degrees and 2.5° for internal and external rotation respectively. The root mean square difference varied with the applied torque, which ranged from 1.0° to 8.8° (Table 4.2).

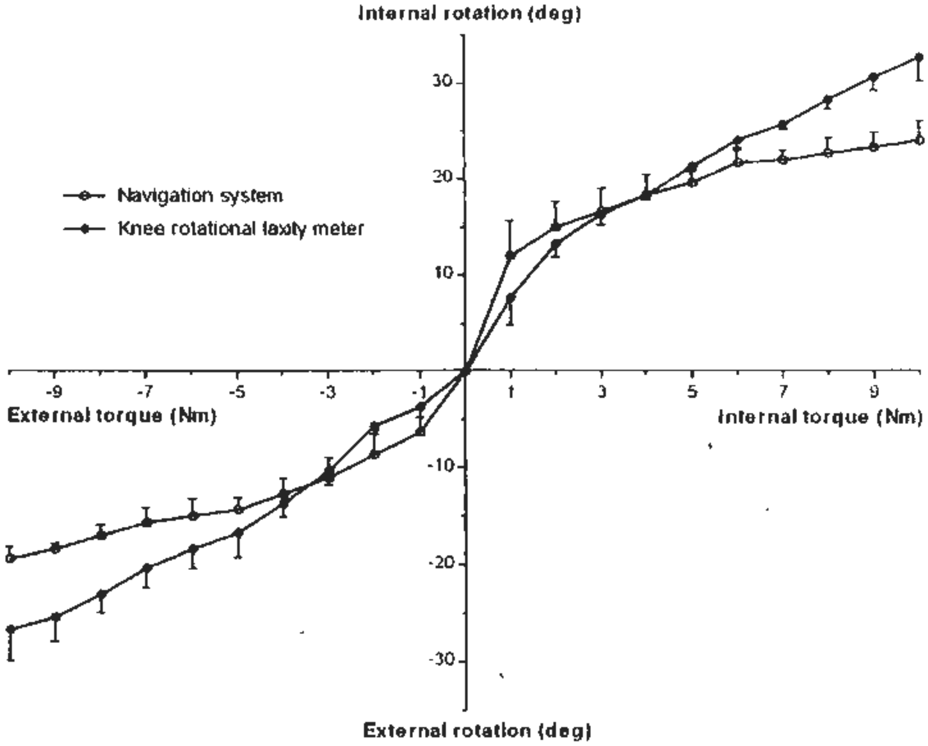


Figure 4.3 Internal and external rotational angle under different applied rotational torque (1-10 Nm).

Table 4.1 Reliability of knee rotational laxity meter.

	Intra-rater reliability				Inter-rater reliability	
	Tester 1		Tester 2		Tester 1 and 2	
	ICC	95% CI	ICC	95% CI	ICC	95% CI
Internal rotation	0.983	0.885,0.996	0.992	0.977,0.998	0.989	0.896,0.998
External rotation	0.959	0.566,0.992	0.972	0.857,0.993	0.990	0.958,0.998

ICC: intraclass correlation CI: confidence interval

Table 4.2 Validity of knee rotational laxity meter.

	Torque (Nm)	Internal rotation	External rotation
ICC		0.781	0.783
95% CI of ICC		0.589,0.889	0.592,0.890
Mean difference (°)		2.30	2.53
SD of difference (°)		4.15	4.17
95% CI of mean difference (°)		0.75,3.85	0.98,4.09
Root mean square difference (°) at different torques	1	4.80	2.83
	2	2.08	3.42
	3	1.00	1.83
	4	1.41	2.83
	5	1.91	3.70
	6	2.52	4.16
	7	3.70	5.10
	8	5.69	6.16
	9	7.44	7.19
	10	8.83	7.53

ICC: intraclass correlation CI: confidence interval SD: standard deviation

4.4 Discussion

In this experiment, a new biomechanical device for measuring knee rotational laxity was developed, and its reliability and validity were tested in a cadaveric model. Results showed that the correlations between and within subjects were high, which supported the hypothesis that the proposed meter was a reliable measurement tool. Though the validity correlation between the proposed meter and the navigation system was not as high as the reliability correlation, its ICC was above the pre-set value. Moreover, the mean difference for internal and external rotation between the two measurement tools was below 2.5°. The results also supported that the meter was an accurate device to measure tibial rotation for assessment of knee rotational laxity.

The overall reliability of the proposed meter was high and comparable to other previous studies. The ICC coefficient was reported to be above 0.94 for all intra-tester and inter-tester reliability in a similar cadaveric study in which a device for measurement of rotational knee laxity was developed (Musahl et al., 2007). With the same device, it was further applied on living human and revealed an ICC coefficient of 0.81-0.88 and 0.77 for inter-tester and test-retest reliability respectively (Tsai et al., 2008). Other studies reported the reliability from 0.86 to 0.98 depending on the value of applied torque, rotation direction and side of the knee (Lorbach et al., 2009; Shultz et al., 2007).

When checking criterion validity of a measurement tool, a comparative instrument as a gold standard should be used and the correlation coefficient between the two measurement tools should preferably be above 0.70 (Scholtes et al., in press). In this experiment, the navigation system was used as a gold standard for measurement of tibial rotation. Since the relative movement between the femur and tibia was based on two sets of bone pin markers, the navigation system has been regarded as an accurate method (Colombet et al., 2007; Pearle et al., 2007; Steckel et al., 2007). However, because of its invasive procedure, the validity of the proposed meter could only be achieved in a cadaveric model. That made our finding hardly comparable to others previous studies. Musahl and coworkers (Musahl et al., 2007) tested in a best case scenario for their new device, in which the EM sensors were directly fixed to the femur and tibia. Therefore, no validity was tested in their study. In another cadaveric study (Lorbach et al., 2009), a similar device was validated with a navigation system, and the correlation achieved was from 0.83 to 0.95. However, the tibial bone was fixed with screws to a metal bar which was cemented in a custom-made inside-boot. Conceivably, this allowed accurate measurement for bone motion (Musahl and Fu, 2010). In this experiment, the ICC coefficient between the proposed device and the navigation system was above the preferred value. Together with the low mean difference, we provided evidence of the validity of our proposed device.

When quantifying the validity of the proposed meter, lower extremity specimens including the knee and ankle joints, thigh, shank and foot segments were used to simulate a clinically relevant situation. To minimize ankle joint rotation and motion between the leg and the device when applying rotational torque, an orthosis was secured with a tourniquet such that the rotational torque was directly applied to the knee joint. The motion sensor was longitudinally placed at the bottom of the foot segment (attached to the device) such that its rotational axis was in line with the rotational axis of tibia. The assumption here was that the shank segment was cylindrical and therefore the motion sensor and the tibia rotated along the same axis. One advantage of this idea was to avoid placing the motion sensor directly on the skin, which would cause error up to 13° in measurement of rotation especially in obese patients (Benoit et al., 2006). In Figure 4.3, the error increased during small and high applied torques though the two measurement values were highly correlated. It was possibly because pre-loading was necessary before the motion sensor value became stable. This finding was also comparable to the previous study (Lorbach et al., 2009) that the error at 10 Nm applied torque was 8.4° and even up to 14.2° at 15 Nm. It suggested that the motion between the leg and the device would not be completely avoided, especially at large applied torque. Moreover, 5 Nm torque was commonly adopted in the previous studies for measurement of knee rotational laxity (Branch et al., 2010; Woo and Fisher, 2009). In consideration of clinical application, torque value ranged 4-6 Nm was suggested in future study using the proposed device because of its small error.

The proposed meter was designed to be clinically relevant. It would be a simple, easy operating and practical device for quantifying knee rotational laxity, especially for patients after ACL injuries in orthopaedic settings. This was why a new design was modified from previously study (Musahl et al., 2007). An ankle orthosis was used instead of an ankle boot because orthosis is easier for patients to put on and get secured with the tourniquet. Moreover, only one motion sensor was used in order to provide a real-time reading for operation. This is important since it allows a quick and simple assessment in orthopaedics clinic. In this experiment, 30° of knee flexion was chosen for validation of the device. One of the reasons was that this particular knee flexion angle might be sensitive to detect knee rotational laxity for healthy, ACL deficient and reconstructed patients since ACL has its maximum elongation peak at this flexion angle (Gabriel et al., 2004). Moreover, biomechanical investigations demonstrated that ACL injuries mostly occur in slight flexion angles (Koga et al., 2010). Furthermore, one should bear in mind that reproducibility should be verified again in human participants before applying this meter in clinical field. A standardized procedure for securing the orthosis to the leg as well as defining a neutral position should also be considered.

This experiment was limited by the fact that it was a cadaveric experimental test although the device would eventually be applied on living humans. However, as pointed out previously, it was not ethical to use invasive procedures in human participants when validating the device. The only way to conduct such kind of research was to apply on human cadaveric specimens. Although great efforts were made to simulate a clinically relevant situation, one limitation was that the femur was firmly attached to the autopsy table by bone bins and clamps, which was not possible when measuring laxity in real participants. Therefore, future studies were suggested to investigate a non-invasive way to stabilize the thigh and verify its effect in living human subjects. This would be important as minimizing the femur rotation would enhance accurate torque to be applied to the knee joint. Other limitations also included low sample size that existed in most cadaveric experiments. Due to the limited availability of fresh cadavers in different research centers, the specimen number was minimized to fulfill the statistical requirement.

4.5 Chapter conclusion

A biomechanical knee rotational laxity meter was proposed in this chapter. Its reliability and validity were verified in a cadaveric model by showing high correlation among trials and as compared with a gold standard measurement. This simple device might be useful in a wide field to document knee rotational laxity with various clinical purposes.

Chapter 5 The application of optical motion analysis system for functional assessment of patients before and after ACL reconstruction

Chapter summary

Based on the limitation that passive physical examination cannot produce force and stress that reflect real physical demand, this chapter aims to apply optical motion analysis system for assessment of dynamic knee rotational stability. Firstly, knee stability assessment after ACL injury was extensively reviewed. It included the stages of diagnosis, surgical treatment and long-term rehabilitation. Secondly, a high-demand jump-landing and pivoting task was adopted to functionally assess the knee rotational stability of patients before and after ACL reconstruction with two techniques. Twenty six men with unilateral ACL injury were treated with either single-bundle ACL reconstruction or anatomic double-bundle ACL reconstruction. All patients performed a functional task before and after ACL reconstruction with mean follow-up of 10.1 months. The range of tibial rotation of the injured, reconstructed and intact knees during the pivoting movement was measured by an optical motion analysis system. The results showed that the range of tibial rotation was higher in ACL deficient knee than the intact knee preoperatively. The increased rotation was reduced in the reconstructed knee after double-bundle techniques when compared with the deficient knee. There was no significant difference in the tibial rotation of the reconstructed knee between both surgical groups. By assessing with a dynamic functional pivoting movement, it was demonstrated that the anatomic double-bundle ACL reconstruction successfully restored knee rotational stability from an impaired level and the treatment effect for both techniques were similar with no superiority in anatomic double-bundle ACL reconstruction.

Publication: This chapter is published in Sports Medicine, Arthroscopy, Rehabilitation, Therapy and Technology (Appendix B), American Journal of Sports Medicine (Appendix C) and 實用關節鏡手術學 (Appendix D).

Lam MH, Fong DTP, Yung PSH, Ho EPY, Chan WY, Chan KM (2009). Knee stability assessment on anterior cruciate ligament injury: clinical and biomechanical approaches. Sports Medicine, Arthroscopy, Rehabilitation, Therapy and Technology, 1, 20

Lam MH, Fong DTP, Yung PSH, Ho EPY, Fung KY, Chan KM (2011). Knee rotational stability during pivoting movement is restored after anatomical double bundle anterior cruciate ligament reconstruction. American Journal of Sports Medicine, 39(5):1032-1038

林默涵、何鴻仁、羅勤業、張熙澤、陳啓明、容樹恆和方迪培 (2009)。前交叉韌帶損傷的膝關節運動學分析。輯於陳啓明著，實用關節鏡手術學(824-829頁)。中國：人民衛生出版社

5.1 Introduction

5.1.1 The knee and the ACL

The lower extremity is composed of three major joints: the hip joint, the knee joint and the ankle joint. Located in between the hip and ankle joint, the knee provides balance and transformation of body load especially for the movements that require a rapid change of speed and direction. It has shown that cutting maneuvers would increase the risk of non-contact knee ligamentous injury due to the increased varus/valgus and internal/external rotation moments (Besier et al., 2001). Even in straight running, the ground reaction force was reported as three times of the body weight (Cavanagh and Lafortune, 1980). Therefore, being as a function of supporting the entire body weight during stance phase, the knee is one of the most vulnerable joints suffering from acute injury (Adirim and Cheng, 2003) and long-term joint degeneration (DeHaven et al., 2003; Drawer and Fuller, 2001).

Theoretically, the knee joint allows six DOF movements, including both translation and rotation in three body planes. Clinically, abnormal excessive laxity in AP direction during physical examination may be an indication of ACL injury (Woo et al., 1999). The result of these assessments, however, is determined by the subjective feeling and experience of the examiners. Instead, biomechanical presentation of the knee motion provides precise information for comparison between the intact and deficient knees during knee stability assessment. To describe the geometric representation, Grood and Suntay (Grood and Suntay, 1983) proposed a joint coordinate system for measurement of three dimensional translation and rotation motions of the knee joint. This is essential when studying ligamentous injury as knee ligaments govern the motion of the knee.

The ACL is a band of dense connective tissue that courses from the femur to the tibia (Duthon et al., 2006). It is a major knee ligament to stabilize the joint movement against anterior tibial translation (Furman et al., 1976) and rotational loads (Fu and Zelle, 2007). While Norwood and Cross in 1979 suggested that the ACL has three separate bundles (Norwood and Cross, 1979), most anatomical studies have agreed that the AM and PL bundles are the only two components of the ACL (Figure 5.1) (Girgis et al., 1975; Lam, 1968). The AM and PL bundles behave differently in length (Hollis et al., 1991) and in situ force (Gabriel et al., 2004) during passive flexion. Due to the different attachments of the two bundles (Petersen and Zantop, 2007), the AM and PL bundles are responsible for resisting anterior tibial load and rotational load, respectively. Biomechanical studies have revealed that the ultimate load of the ACL to failure was three times of the body weight (Woo et al., 1991) and the time of ACL rupture was within 100 ms (Krosshaug et al., 2007). Therefore, it is suggested that there should be a huge explosive force acting to the knee joint during ACL injury.

Figure 5.1 An anterior view of the right knee, showing ACL with AM and PL bundles.

5.1.2 Knee stability assessment after ACL injury

About 70% of the ACL injury occurs in sports situation (Griffin et al., 2000). It often appears to occur in competitive sports such as soccer and handball, which involves landing, deceleration and rapid change of direction (Hughes and Watkins, 2006). When injury occurs during sports activity, athlete with ACL rupture is confirmed after an adequate diagnosis by orthopaedic specialist. Either operative or non-operative treatments (Beynnon et al., 2005) followed by a rehabilitation program (Myer et al., 2006) are advised to the injured patients before they can safe return-to-sports (Kvist, 2004). In this chapter, a management model is proposed (Figure 5.2).

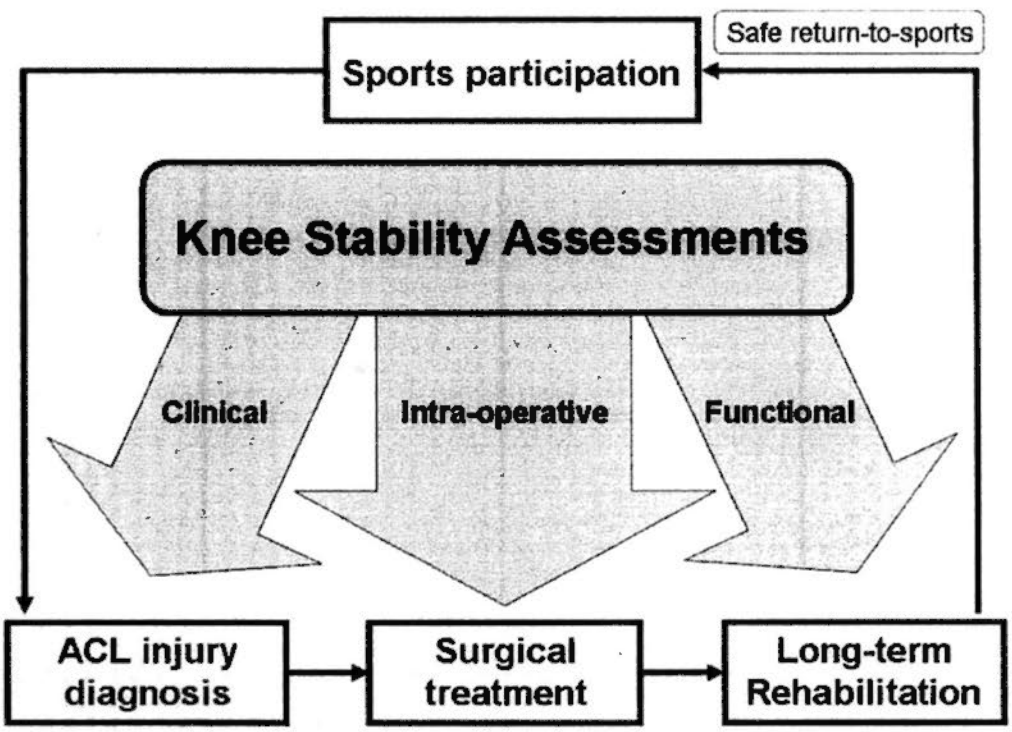


Figure 5.2 A management model after ACL injury, showing the contribution of knee stability assessment before safe return-to-sports. It includes clinical assessment, surgical treatment evaluation and long-term evaluation after rehabilitation.

Knee stability assessments contribute three main roles in the management model after ACL injury – (i) clinical assessment that provides a quick and reliable way for the diagnosis of ACL injury, (ii) surgical treatment evaluation that provides immediate assessment of operative treatment and comparison of different reconstruction techniques, (iii) long-term evaluation after rehabilitation that acts as a guideline after rehabilitation program, suggesting if the athlete is fully recovered in terms of knee stability compared with pre-injury activity level. The three main roles are elaborated in the following sections.

5.1.3 Diagnosis of ACL injury

Accurate diagnosis of ACL injury relies on injury history (Spindler and Wright, 2008), clinical assessment (Ostrowski, 2006) as well as advanced imaging technique (Klass et al., 2007). Being different from others, clinical assessment provides a passive laxity evaluation of the injured knee. The laxity varies considerably within the normal population and extreme value would be found in hyper-laxity or female group (Renstrom et al., 2008). Therefore, it is always recommended to compare the laxity of the injured side with the normal side if the patients have unilateral knee injury (Lubowitz et al., 2008). The potential limitations should be kept in mind, including the uncontrolled force applied and the reflex resistance of the patient because of anxiety and pain. Moreover, the first clinical examination after an acute knee trauma is suggested to have a low diagnostic value (Frobell et al., 2007). To enhance the accuracy, the clinical examination should be performed by skillful and experienced examiner.

Lachman test has a high accuracy for diagnosis of ACL injury (Jonsson et al., 1982).

Before the test, the examiner should ensure that the tibia does not sublux posteriorly to avoid false-positive result in a PCL deficient knee. The patient should lie supine with the testing knee flexed around 30°. The examiner stabilizes the femur and applies an anterior force on tibia without restraining axial rotation (Figure 5.3). A positive result from an ACL deficient patient will be known with proprioceptive or visible anterior translation of the tibia (Torg et al., 1976). The anterior translation of 1 mm to 5 mm is defined as grade I laxity, 6 mm to 10 mm as grade II, and greater than 10 mm or without a displacement limit as grade III (Lubowitz et al., 2008).

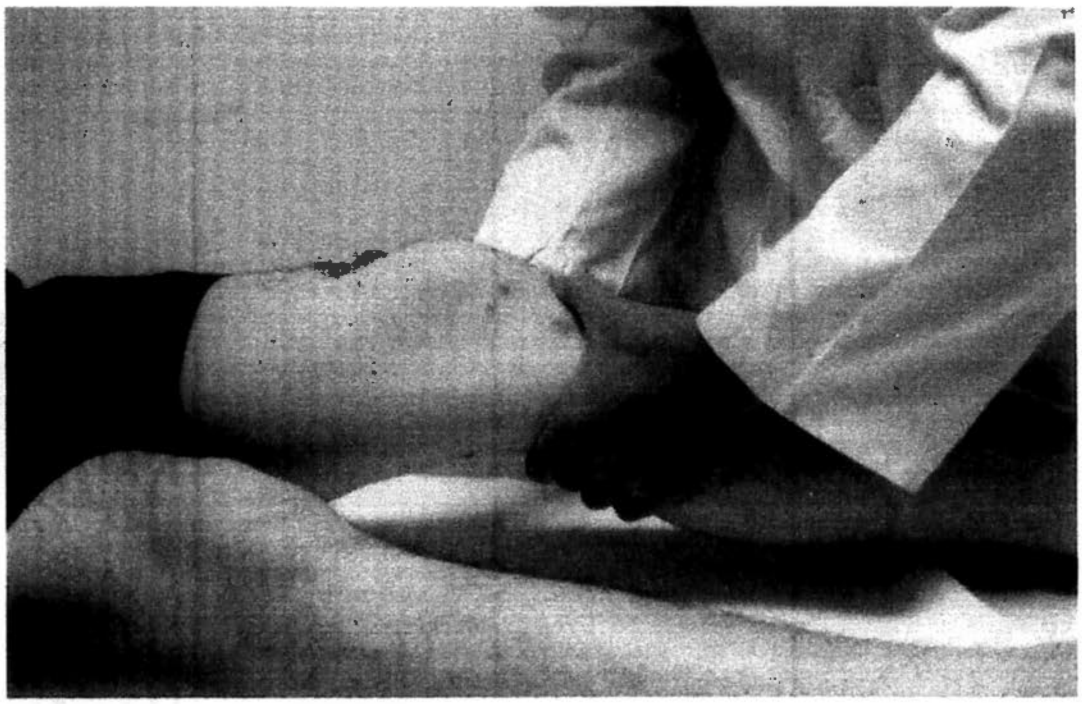


Figure 5.3 Lachman test.

Pivot shift test is relatively complex since it is a combination of internal rotation and valgus (Kanamori et al., 2002). This test is highly dependent to the technique and experience of the examiner. However, a positive result of this test is the best for ruling in an ACL rupture (Ostrowski, 2006). To perform the test, the basic principle is to apply valgus and internal rotation to the leg. The test starts with the knee in full extension and then gently flexion to about 40° (Figure 5.4). A positive pivot shift test is defined as a forward subluxation of tibia during sudden change in direction. It is a reproduction of event that occurs when the knee gives way because of the loss of ACL.

Figure 5.4 Pivot shift test

KT-1000 is an instrument that has been developed for an objective measurement for AP laxity on sagittal plane. The patient lies in a supine position with knee flexion of about 20° to 30°, support with a firm platform placed proximal to the popliteal space. The patient is told to relax in this position. The KT-1000 arthrometer is then placed above the tibia and attached firmly by two bands. After the zero adjustment, the arthrometer is pulled anteriorly to the tibia in order to provide an anterior force (Figure 5.5). An audible indication will be noticed at 15, 20 and 30 pounds of force. The anterior displacement is measured in millimeter while the laxity is often presented in side-to-side difference.

5.1.4 Treatment evaluation of ACL reconstruction

Computer assisted surgery has gone through lots of evolutions in recent 15 years. One of the technologies for orthopaedic surgery is navigation system, which has been applied in ACL reconstruction. In the following paragraph, fluoroscopic navigation system and image-free navigation system will be elaborated.

Fluoroscopic navigation system (Hufner et al., 2005; Shafizadeh et al., 2005) is based on the pre-imaging data (both AP and lateral views), such as computer tomography or radiograph shots, for the model formation to be displaced in the computer software. A pointer containing integrated reflective markers discs is also attached to the image. By holding the pointer to the known anatomical landmarks, the surgeon reviews the accuracy of the images when acquiring the AP and lateral images. To accurately locate the navigated tools in relationship to the selected anatomical landmarks, surgical instrument with passive marker spheres must be fixed securely to the patient's femur and tibia (Figure 5.7). Optoelectronic camera system with infrared light-emitting diodes tracks all passive markers throughout the surgical procedure. The line of sight must be guaranteed once after the navigated procedure starts.

Figure 5.5 KT-1000 to measure AP laxity of the knee

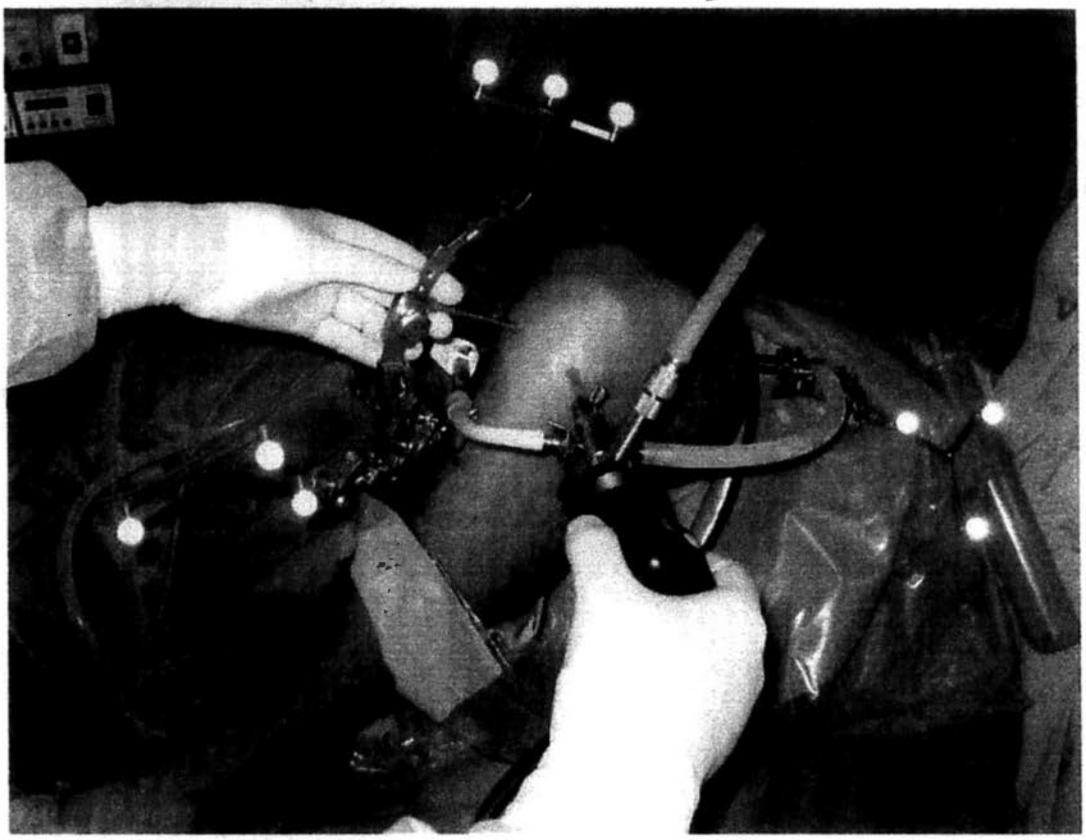


Figure 5.6 Femoral and tibial transmitters are inserted into the femur and tibia during navigation procedure.

Image-free navigation (Tsuda et al., 2007) has been widely established recently because of its simplified procedure. Based on the intraoperative knee alignment measurement such as knee axis and joint lines, the system provides virtual illustration of the anatomical structures. With the information after digitizing the cartilage surface of the femur and the tibia, this method combines the existing model and patient's knee information as defined by surface matching.

For both fluoroscopic and image-free navigations, since one reference marker set is fixed to each of the femur and the tibia the relative motion of these two segments can be measured precisely. Tsuda and coworkers validated the navigation system for femoral tunnel placement in double-bundle ACL reconstruction with optical motion analysis system (digital camera) (Tsuda et al., 2007). The average differences between the two measurement systems were less than 3% for both the AM and PL tunnels. Other studies have been reported that the navigation system is reliable to quantify knee kinematics during stability examinations, particularly in the setting of complex rotatory patterns such as pivot shift test (Colombet et al., 2007; Martelli et al., 2006; Pearle et al., 2007).

With the accurate and precise measurement of navigation systems, it improves the accuracy of the surgical procedures (Hufner et al., 2005). The computer provides information of the real-time relative positions of the instruments and the knee joint in order to assist surgeon during surgical procedures. Moreover, by locating joint center between two relative bodies, it accurately measures the knee kinematics in sagittal, coronal or transverse plane (Figure 5.6). Hence, the navigation system is also used to collect knee kinematics data for comparison before and after ACL reconstruction (Koh, 2005). It has become an objective way to assess immediate effect of ACL reconstruction, especially to compare single-bundle and double-bundle techniques in terms of anterior translation and tibial rotation.

5.1.5 Functional evaluation after long-term rehabilitation

By applying a certain force on specific direction to the relaxed knee, ligamentous injury would be identified if abnormal laxity is found when compared with the intact side. This is a usual practice for suspected knee injury without any patients' active movement. However, when it comes to the rehabilitation stage after surgical or non-surgical treatment, clinical examination does not produce sufficient force to simulate physical activity (Lubowitz et al., 2008). The ultimate goal for clinical treatment in sports medicine is to allow patients' safe return-to-sports. It has been suggested that functional knee stability should be one of the criteria that determine a safe return-to-sports (Kvist, 2004). On the other hand, dynamic functional test that mimics real game situation during sports involves patients' muscle strength and neuromuscular perception, demand of specific movement and confidence for performing. To monitor the knee stability during this specific dynamic movement, motion analysis is a good way to achieve.

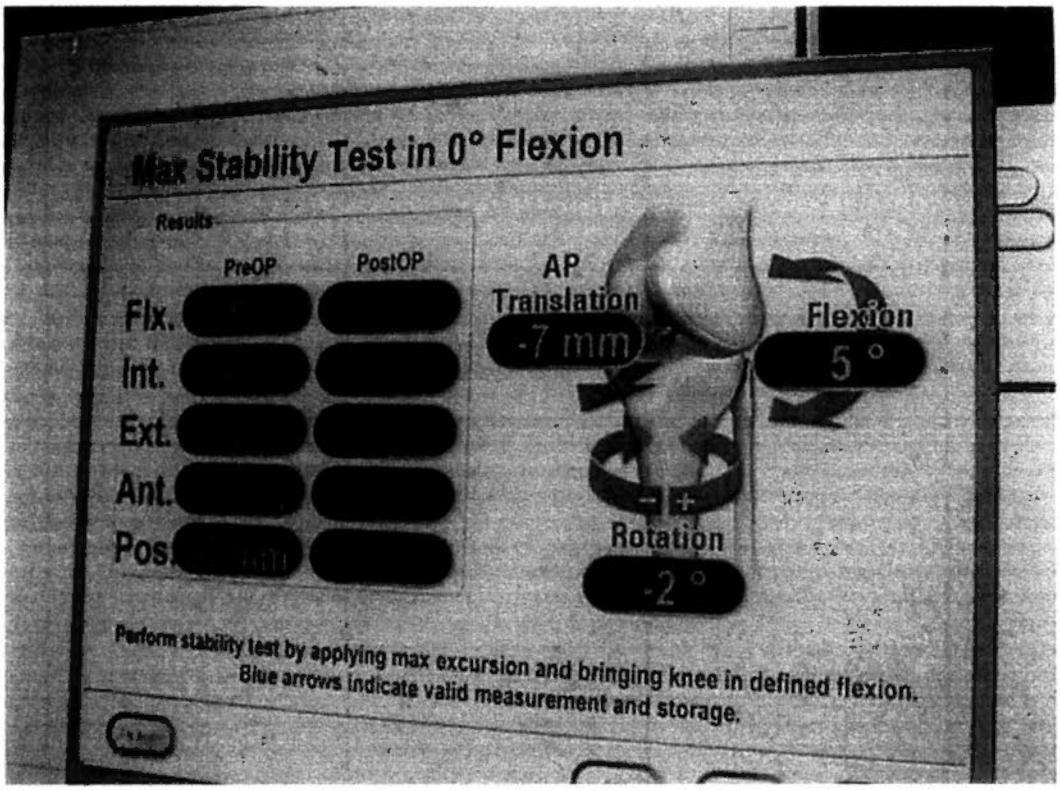


Figure 5.7 Kinematics evaluations during ACL reconstruction.

Patients with ACL injury can be assessed using motion analysis system before and after ACL reconstruction. The functional assessment is conducted in a gait laboratory (Figure 5.8), which is equipped of more than three high speed cameras and data processing software, providing 10x5 m^2 captured volume. The three dimensional coordinates of 9 mm reflective markers can be recognized in the captured volume by means of infra-red light emitting cameras. In the center of the captured volume, force plates are placed on floor level to collect ground reaction force during the movement.

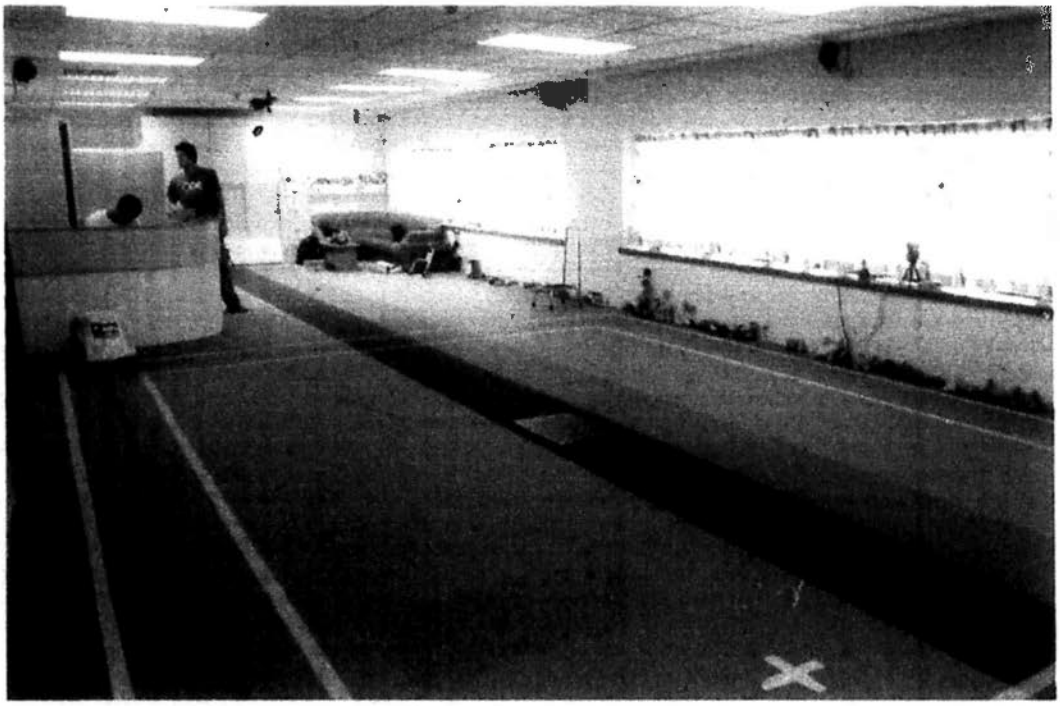


Figure 5.8 A standard gait laboratory.

Marker model is essential for motion analysis. It consists of several reflective skin markers that depend on the outcome parameters. Ristanis and coworkers (Ristanis et al., 2005) adopt the method described by Vaughan (Vaughan et al., 1992) for measurement of knee kinematics. Fifteen markers are stuck on anatomical landmarks of lower extremities including ASIS, greater trochanter, lateral femoral epicondyle, tibial tubercle, lateral malleolus, heel, fifth metatarsal head on both sides and sacrum (Figure 5.9). Before capturing the dynamic movement, anthropometric data which include weight, ASIS breadth and thigh length, mid-thigh circumference, calf length, calf circumference, knee diameter, foot length, malleolus height, malleolus diameter, foot breadth on both sides, are collected.

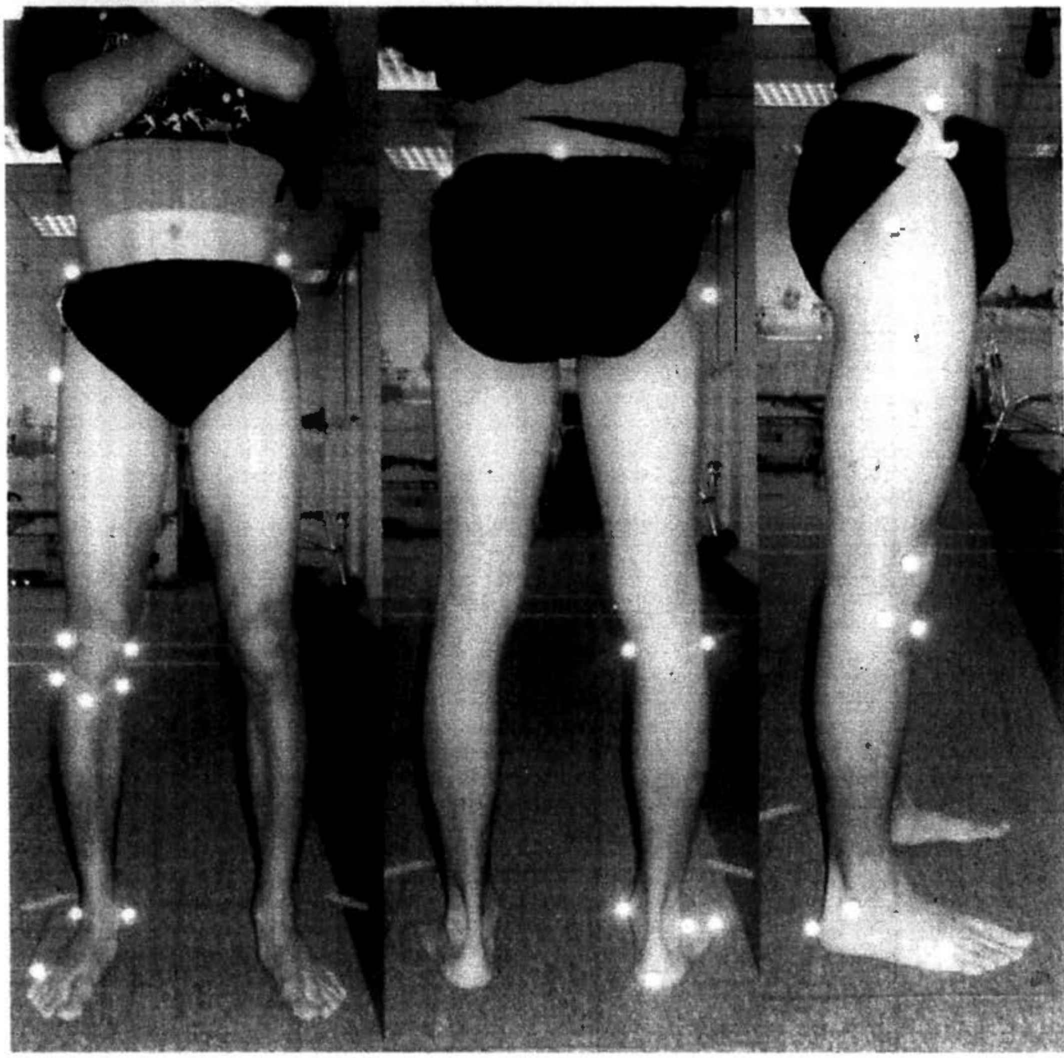


Figure 5.9 Marker set of motion analysis assessment (left to right: anterior view, posterior view and lateral view).

After data collection, the evaluation period should be well defined and trimmed. In clinical practice, stance phase is chosen for evaluation due to the landing risk factor of non-contact ACL injury. A standing trial with anatomical position is needed to define the offset degree for all segmental movements in all planes. Anthropometric measurements combined with three dimensional coordinates from the standing trial provide calculations of joint center and axe of rotation. Kinematics of knee joint such as flexion angle, tibial rotation and valgus angle are calculated using self-compiled programming software.

Several kinematics studies, which used different dynamic movements, investigated patients with unilateral ACL injury. Andriacchi and Dyrby (Andriacchi and Dyrby, 2005) reported that the external rotation and anterior translation were different between the ACL deficient and intact knees in swing phase during walking. On treadmill running, tibial rotation increased with speed in both the injured and normal knees (Czerniecki et al., 1988). The difference between the knees, however, was not significant. Waite and coworkers (Waite et al., 2005) suggested that low demand activity such as walking and running did not produce sufficient stress to initiate knee instability in ACL deficient knee. In a study of assessing functional stability with a high demanding movement, tibial rotation was found not to be restored after single-bundle ACL reconstruction with hamstring or patellar tendon autograft (Georgoulis et al., 2007). Dynamic movement should be clinically based and specific to the research objective. For example, if a study is designed to investigate knee rotational stability, movement that gives a rotational stress to the knee should be considered. In a study that aimed to assess knee rotational stability of ACL deficient and reconstructed patients, a combination movement of jumping, landing and pivoting was used (Ristanis et al., 2005). The movement was regarded as a high-demand of activity because the patients had to resist a high rotational stress at the knee joint during pivoting.

The injury mechanism is one of the implications of how functional movement is designed. It is reported that over 70% of ACL injuries occur in non-contact situation (Figure 8.10), which involves landing, decelerating and changing direction (Griffin et al., 2000). If a patient has good stability during these 'high risk' movements, it would be an important indication for safe return-to-sports. Therefore, movements such as

3-way cutting (Waite et al., 2005) and 4-way jumping (Sell et al., 2006) maneuvers are useful to assess the knee stability. Furthermore, a real game element should also be considered in designing movement task in functional stability assessment. In most situations during sports, movements such as landing and sudden change of direction are often unexpected. It has been suggested that planned laboratory task and actual movement in real game competition would have different biomechanical parameters (Besier et al., 2001). Further, biomechanical study has also shown that unplanned cutting is identified as a risk factor of non-contact ACL injury (Landry et al., 2007). In order to mimic the real game situation, anticipation effect should be brought into the laboratory. It can be achieved by placing photo cell receiver with a light source across the runway. When the participants pass through the device, a randomized signal will be triggered in the monitor screen that provides a visual cue for the cutting and jumping directions. This setting aims to allow a short time decision so that a game-like situation is reproduced in the laboratory.

Figure 5.10 Non-contact ACL injury.

5.1.6 Controversy in ACL reconstruction

In-vitro studies showed that anatomic double-bundle ACL reconstruction using hamstring graft restored both AP translation and axial rotation stability (Mae et al., 2001; Yagi et al., 2002). With this current technique, clinical studies reported good restoration of joint stability and patient-reported outcomes after a short-term follow-up (Fu et al., 2008; Toritsuka et al., 2009). Moreover, a few studies (Aglietti et al., 2010; Jarvela, 2007; Kondo et al., 2008; Yagi et al., 2007), which used subjective clinical tests and questionnaires for evaluation, compared between double-bundle and single-bundle ACL reconstruction. However, among these studies, there is limited knowledge of rotational stability as investigated by objective assessment after anatomic double-bundle ACL reconstruction. On the other hand, there were studies (Ristanis et al., 2005; Tashman et al., 2004), using dynamic functional activity, reported that single-bundle ACL reconstruction could not restore rotational stability. Therefore, the purpose of this chapter was to prospectively investigate the effect of single-bundle and double-bundle ACL reconstruction on the knee rotational stability during a high-demand pivoting task. It was hypothesized that both techniques would restore knee rotational stability to a normal level compared with the intact knee.

5.2 Method

5.2.1 Participants

Twenty six men with unilateral ACL injury were recruited for the study (11 right knees and 15 left knees; age, 25.5±4.6 years; height, 1.73±0.08 m; body mass, 66.8±10.6 kg). All participants were recruited in our sports clinic. When patients were confirmed with unilateral ACL rupture, they were scanned with exclusion criteria. ACL rupture was confirmed either by arthroscopy, MRI or clinical examination. Exclusion criteria included the presence of bone fractures, complex meniscal injury, ligamentous injuries of the involved knee and previous surgery on either knee. All participants reported knee joint instability during sports and all were recommended to receive surgical treatment. The surgical treatment would be either single-bundle ACL reconstruction or anatomic double-bundle ACL reconstruction, depending on surgeon's decision during operation. All injuries were sport related, and all participants participated in their sports at least one time per week before the injury. The preoperative clinical data was shown in Table 5.1. The university ethics committee approved the study. Informed consents were obtained from each subject before the study.

Table 5.1 Preoperative clinical data of all participants

No.	Injured knee	Time (month)[a]	Preoperative assessment					
			IKDC	Lysholm	KT-1000 (mm)[b]	Lachman	Anterior drawer	Pivot shift
1	L	11	47.1	90	8.5	3	2	2
2	L	3	74.7	85	6.0	3	3	3
3	L	10	74.7	80	7.0	2	2	2
4	L	5	82.8	95	4.5	3	3	2
5	R	3	74.7	85	4.5	3	3	2
6	L	2	50.6	63	3.0	2	3	2
7	L	5	74.7	85	5.5	3	2	2
8	R	3	82.8	95	7.0	2	2	0
9	R	3	83.9	100	4.0	2	2	2
10	L	4	74.7	80	2.5	3	3	2
11	R	6	30.0	36	6.0	3	2	3
12	R	5	54.7	85	4.5	3	3	2
13	L	5	73.6	90	4.0	2	3	1
14	L	10	67.4	100	5.5	2	2	1
15	R	9	74.7	85	8.5	3	2	3
16	R	5	79.3	84	0.0	3	2	2
17	L	5	69.0	80	3.5	2	2	1
18	L	3	67.4	65	5.0	2	3	2
19	R	6	69.0	80	6.0	3	3	2
20	R	4	73.6	80	4.5	3	3	2
21	L	9	52.9	65	9.5	3	3	3
22	L	4	73.6	65	3.5	2	2	2
23	L	2	69.0	65	8.0	3	3	3
24	R	2	73.6	75	5.5	3	3	3
25	R	3	66.7	85	7.0	3	3	2
26	L	5	82.8	85	4.0	3	3	2
Mean(SD)		5.1(2.6)	69.2(12.6)	80(14)	5.3(2.1)	-	-	-

[a]Time from injury to preoperative assessment.

[b]Differences between both knees when assessed with 30 lb of anterior forces

5.2.2 Surgical techniques

In all participants, either single-bundle ACL reconstruction or anatomic double-bundle ACL reconstructions were performed by two orthopaedics surgeons who have more than 10 years experiences performing ACL reconstruction. The operating knee was put on the operating table with a foot rest and lateral thigh support at 90° of flexion. The operation was performed after inflating the tourniquet. The hamstring grafts (gracilis and semi-tendinosus) were harvested through an incision over the ipsilateral tibia and braided with Ultrabraid 2 (Smith & Nephew Endoscopy, Massachusetts, USA) to each tendon grafts. A diagnostic arthroscopy was performed by using the anterolateral and AM portals. After confirming the rupture of AM and PL bundles, the ACL stump was debrided and the foot prints of AM and PL bundles were identified and marked by radiofrequency probe. When deciding the surgical techniques anatomical structures including graft size and original insertion site area would be considered (Martins et al., 2009). After ACL reconstruction, all patients completed a standard rehabilitation program (Shelbourne and Nitz, 1990).

5.2.2.1 Anatomic double-bundle ACL reconstruction

The footprint of the ACL was identified by locating the lateral intercondylar ridge and the lateral bifurcate ridge, as suggested by previous studies (Kopf et al., 2009; Martins et al., 2009). The AM femoral tunnel was prepared through the AM portal with the aid of a 6 mm offset guide; the guide pin was placed at the footprint of AM bundle and reamed to 4.5 mm diameter for the passage of the Endobutton (Smith & Nephew Endoscopy). The AM tunnel was further reamed to 6 mm or 7 mm diameter, and the integrity of the outer cortex was preserved. The diameter and length of the tunnel depended on the graft size and the patient's anatomy. After the tunnel for AM bundle was created, the knee was then flexed to 110°. An accessory AM portal was created according to the guidance of a spinal needle, which was used to aim the footprint of the PL bundle. A 2.4 mm guide pin was inserted according to the footprint of the PL bundle. The PL femoral tunnel, which varied from 5 mm to 6 mm in diameter, was then created through the accessory AM portal by the Endobutton reamer and the 5 mm or 6 mm reamer. The bone bridge between the two tunnels was at least 2 mm.

For the tibial tunnels of AM and PL bundles, 45° and 55° tibial jig (Smith & Nephew Endoscopy) was used, respectively. The ACL remnant was used as a guide to identify the footprint of ACL. The tibial tunnel of the PL bundle was created by inserting a 2.4 mm guide pin through a 55° tibial jig. The guide pin was aimed to the footprint of the ACL, about 6 mm to 7 mm anterior to the PCL. Another 2.4 mm guide pin was inserted through a 45° tibial jig, aimed about 9mm away (anterior and medial) from the guide pin for the PL tunnel. According to the size of the graft, it was then further reamed to 5 or 6 mm and 6 or 7 mm in diameter, respectively. The tunnels were designed to create a bone bridge of about 2 mm between the two tibial tunnels.

Double gracilis and semitendinosis tendons were used for the PL and AM bundle reconstructions, respectively. Graft passage was completed for the PL bundle, followed by the AM bundle. On the femoral side, the PL bundle was fixed by 15 mm Endobutton loop (Smith & Nephew Endoscopy), whereas the AM bundle was fixed by 15 mm or 20 mm Endobutton loop. The PL bundle was tensioned at 15° of flexion and the AM bundle at 60° of flexion. On the tibial side, bioabsorbable interference screws were used to fix each bundle individually, and staples were used to fix both grafts over the medial surface of the tibia. Figure 5.11 shows the arthroscopic images and postoperative radiograph.

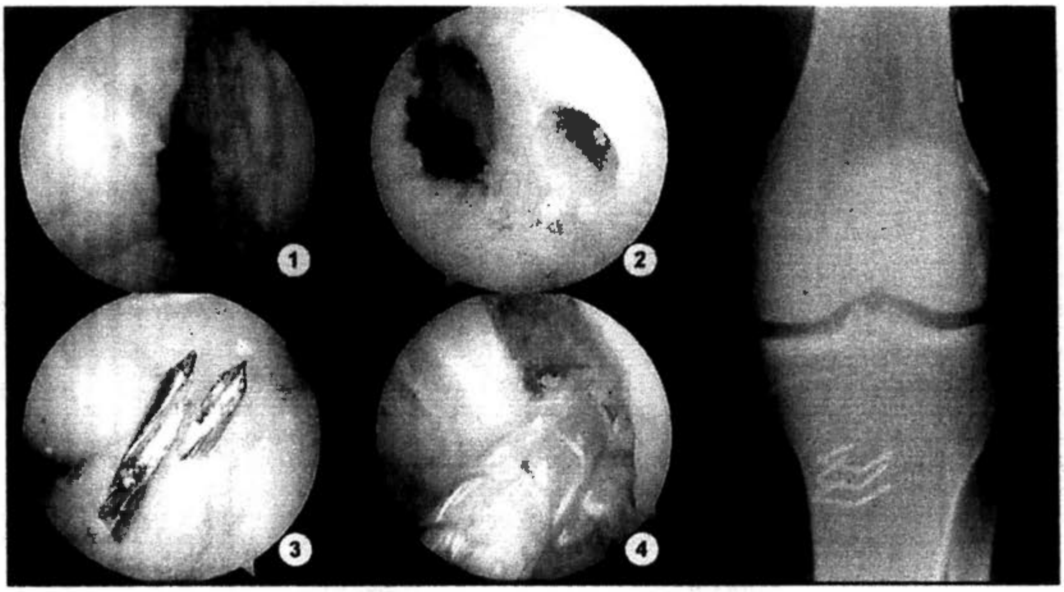


Figure 5.11 The arthroscopic images of the anatomic double-bundle ACL reconstruction, with postoperative radiograph: 1, ACL footprint of femoral side at 90° of knee flexion; 2, femoral tunnels at 110° of knee flexion, viewed from AM portal; 3, tibial tunnels created by inserting two guide pins with tibial jig at 55° and 45° for PL and AM bundles, respectively; 4, graft passage viewed from anterolateral portal. The postoperative radiograph shows the position of both the AM and PL tunnels in the distal femur and proximal tibia, with Endobutton fixation on the femoral side and bioabsorbable screws and bone staples on the tibial side.

5.2.2.2 Single-bundle ACL reconstruction

The footprint of the ACL was identified by locating the lateral intercondylar ridge and the lateral bifurcate ridge. The femoral tunnel was prepared through the AM portal with the aid of a 6 mm offset guide; the guide pin was placed at the footprint of the ACL and reamed to 4.5 mm diameter for the passage of the Endobutton (Smith & Nephew Endoscopy). The femoral tunnel was further reamed to a diameter varying from 7 mm to 10 mm and the integrity of the outer cortex was preserved. The diameter and length of the tunnel depended on the graft size and the patient's anatomy. For the tibial tunnel, the ACL remnant was used as a guide to identify the footprint of the ACL. The tibial tunnel was created by inserting a 2.4 mm guide pin through a 45° tibial jig (Smith & Nephew Endoscopy). The guide pin was aimed to the footprint of the ACL, about 8mm anterior to the PCL. According to the size of the graft, it was then further reamed to match the size of femoral tunnel. Quadrupled gracilis and semitendinosis tendons were used for single-bundle ACL reconstructions. On the femoral side, the graft was fixed by 15 mm or 20 mm Endobutton loop (Smith & Nephew Endoscopy), whereas on the tibial side, staples were used to fix over the medial surface of the tibia. Bioabsorbable interference screws were used to fix the graft on both femoral and tibial sides. The graft was tensioned at 60° of flexion.

5.2.3 Experimental procedure

All participants were assessed before and after ACL reconstruction with a follow-up of 10.1±2.9 months. An optical motion analysis system with eight cameras (VICON 624, Vicon Motion System Ltd, Oxford, United Kingdom) was used to record the three dimensional rotation movements of lower extremities at a capturing frequency of 120 Hz. The system was calibrated on the same day of testing and the mean residual was less than 1 mm. If it was not, the system was recalibrated. Synchronized force plate (model OR6-7 AMTI, Watertown, Massachusetts, USA) data was collected at the center of the capture volume at 1080 Hz. A 15-marker model (Davis et al., 1991) was adopted to collect lower limb kinematics during movements. Skin reflective markers with 9 mm diameter were placed at anatomic landmarks including ASIS, sacrum, greater trochanter, femoral epicondyle, tibial tubercle, lateral malleolus, heel and fifth metatarsal head on both limbs. Anthropometric data were measured for kinematics calculation, including body mass, ASIS breadth, thigh and calf length, midthigh and calf circumference, knee diameter, foot breadth and length, malleolus height and diameter. The reliability of the overall procedure has been reported to be less than 2.4° for within-day measures (Webster et al., 2010).

5.2.4 Experimental task

Before the movement was performed, a trial of standing anatomic position was recorded. Every participant was instructed by the same tester to stand with both feet in shoulder width and to align the shank and foot segment to a neutral position. This calibration file provided a definition of 0° for all segmental movements. Both limbs were tested individually. The subjects were asked to jump off a platform, 40 cm in height and 10 cm behind the force plate, and to land with both feet on the ground, with only the testing foot on the force plate. After the foot contact, they were to pivot 90° to the lateral side of the testing leg, which acted as the core leg during pivoting. They were then instructed to run away with their maximum effort for three steps after completing the pivoting movement (Figure 5.12).

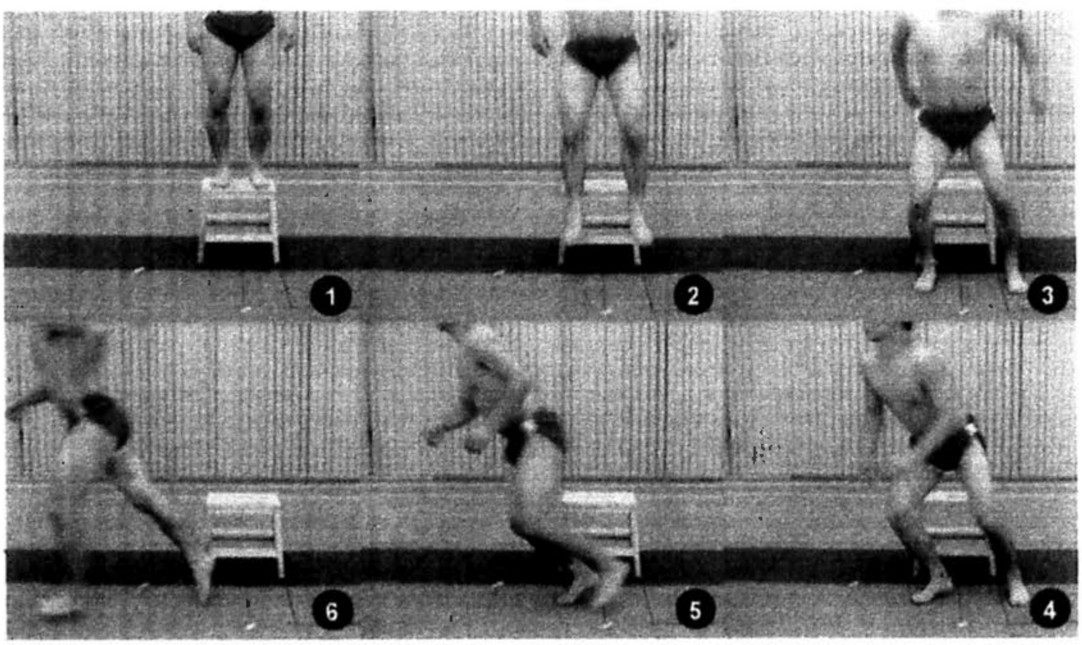


Figure 5.12 The video sequence of the jump-landing and pivoting task, assessing the right knee of the patient: 1, initial position; 2, jumping; 3, landing; 4, pivoting; 5, push-off; 6, running.

5.2.5 Data collection and reduction

The evaluation period was defined from the first foot contact to the takeoff of the testing leg on the ground. Foot contact was determined by the force plate when the vertical ground reaction force exceeded 5% of the participant's body weight. Three dimensional coordinates of every marker were exported from the VICON software. With the anthropometric measurements, knee joint kinematics was then calculated (Davis et al., 1991). All calculations were conducted using self-compiled program (Mathworks, Natick, Massachusetts, USA). The main dependent variable was range of tibial rotation during pivoting movement, which was defined as the difference between the lowest tibial internal rotation after landing and the highest tibial internal rotation within the foot contact period (Ristanis et al., 2005).

5.2.6 Data analysis

Independent t-tests were used to compare the preoperative demographic data and postoperative clinical data of the two surgical groups. For the biomechanical data, paired t-tests were performed to investigate any significant difference between the two limbs pre-operatively and post-operatively, and within the injured limb before and after the ACL reconstruction, separately for the two surgical groups. The postoperative injured knee was also compared between the two surgical groups by independent t-tests. Power analysis was conducted if there was no significant difference between the reconstructed knee and the intact knee after reconstruction, and between two groups on the postoperative injured knee. The level of significance and study power were set at 0.05 and 0.8 respectively.

5.3 Results

Sixteen and ten participants received single-bundle and double-bundle ACL reconstruction, respectively. Table 5.2 showed the demographic data and preoperative clinical data of the two groups. There was no significant difference on the subjective questionnaires (IKDC and Lysholm) and the objective clinical test (KT-1000) postoperatively. Table 5.3 showed the postoperative clinical data of the two groups.

Table 5.2 Demographic data and preoperative clinical data of the two surgical groups.

	Single-bundle group	Double-bundle group	Independent t-test
Age (year)	24.4±4.4	27.2±4.7	p=0.131
Height (m)	1.71±0.07	1.76±0.10	p=0.134
Weight (kg)	65.3±11.5	69.1±9.2	p=0.396
IKDC	68.1±14.6	70.8±9.0	p=0.607
Lysholm	78.4±17.3	82.9±4.2	p=0.331
KT-1000 (mm)[a]	5.5±1.8	5.0±2.6	p=0.592

[a]Differences between both knees when assessed with 30 lb of anterior forces.

For the biomechanical data, the tibia internally rotated to a maximum degree during the pivoting phase (Figure 5.13). For the range of tibial rotation in the group of single-bundle ACL reconstruction, there was a significant increase in the deficient knee (15.0°±5.5°) when compared with the intact knee (7.2°±2.6°) preoperatively. This increased tibial rotation significantly decreased in the reconstructed knee (8.5°±5.3°) and did not differ from that of the intact knee (7.8°±3.2°) after ACL reconstruction. For the group of anatomic double-bundle ACL reconstruction, similar results were obtained. The range of tibial rotation of the preoperative deficient and intact knees, and the postoperative reconstructed and intact knees were 12.6°±4.5°, 7.9°±3.1°, 8.9°±3.0°, 8.2°±2.6°, respectively (Figure 5.14). Regarding over constraining, we compared the reconstructed and intact knees after surgery and did not find any case demonstrating this problem for both groups. Because there was no significant difference between the reconstructed knee and the intact knee of single-bundle and double-bundle surgical groups, and between the two groups of the injured knee after reconstruction, power analysis was conducted (3° true difference) and the statistical power were reported to be 0.74, 0.82 and 0.51, respectively.

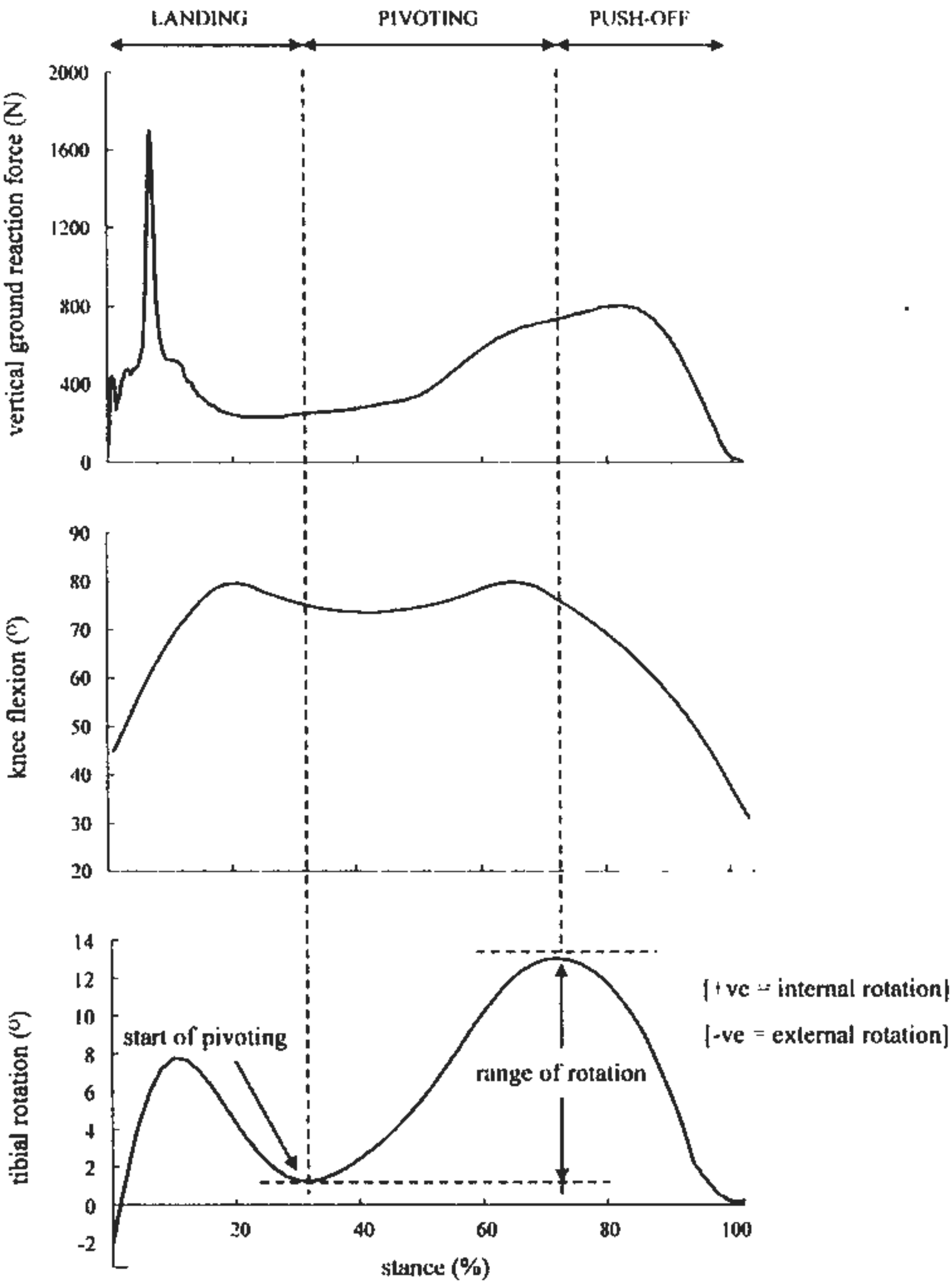


Figure 5.13 Vertical ground-reaction force (top), knee flexion (middle), and tibial rotation (bottom) during the entire stance phase of the high-demand jump-landing and pivoting task from a typical ACL-deficient knee.

Table 5.3 Postoperative clinical data of all participants

No.	Injured knee	Time (month)[a]	Postoperative assessment					
			IKDC	Lysholm	KT-1000 (mm)[b]	Lachman	Anterior drawer	Pivot shift
Single-bundle group								
2	L	7	88.5	100	2.0	0	0	0
3	L	12	94.0	100	2.0	0	1	0
4	L	12	83.9	89	2.0	0	1	0
6	L	10	94.0	95	0.5	0	1	0
8	R	10	95.4	100	3.0	0	0	0
9	R	13	79.3	95	0.0	0	0	0
11	R	9	80.5	70	1.0	0	0	1
12	R	9	100.0	100	7.5	1	1	1
13	L	12	94.8	98	1.0	0	0	0
14	L	10	94.8	100	0.5	0	0	0
18	L	12	88.5	89	2.0	1	1	0
19	R	13	93.4	95	2.5	0	0	0
21	L	7	94.0	95	2.0	1	1	0
22	L	10	80.5	70	1.0	0	0	0
23	L	7	85.1	90	1.5	0	0	0
26	L	6	95.4	100	1.0	1	1	1
Mean(SD)		9.9(2.3)	90.1(6.5)	93(10)	1.8(1.7)	-	-	-
Double-bundle group								
1	L	7	100	99	1.5	0	0	0
5	R	18	100	100	0	0	0	0
7	L	10	79.3	99	1.5	0	0	0
10	L	12	80.5	100	2.5	0	0	0
15	R	7	74.8	90	3	1	1	0
16	R	15	100	98	1	0	0	0
17	L	7	100	100	1.5	0	1	1
20	R	12	93.3	98	1.5	0	0	0
24	R	7	100	100	1	0	0	0
25	R	8	93.3	90	6	1	1	1
Mean(SD)		10.3(3.9)	92.1(10.1)	97.4(4.0)	2.0(1.6)	-	-	-

[a]Time from surgery to postoperative assessment.

[b]Differences between both knees when assessed with 30 lb of anterior forces.

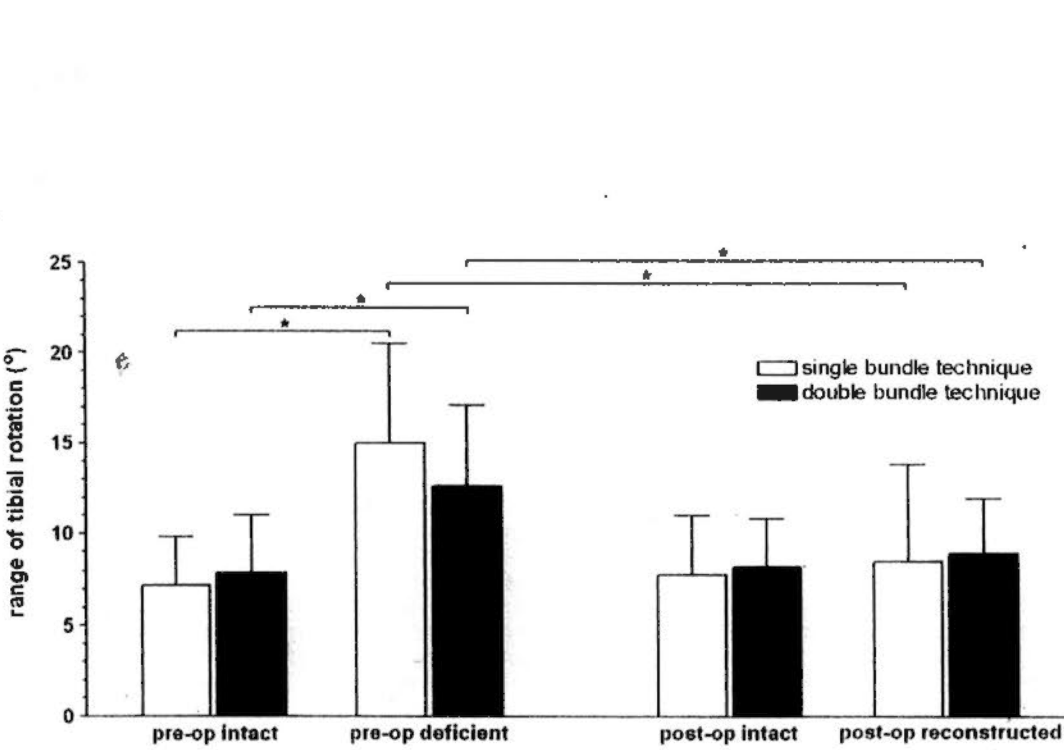


Figure 5.14 Range of tibial internal rotation during pivoting movement before and after ACL reconstruction of the two surgical techniques. *Significant difference as suggested by the paired t test between preoperatively intact and preoperatively deficient, and between preoperatively deficient and postoperatively reconstructed for both the surgical groups.

5.4 Discussion

In this chapter, the increased tibial rotational movement in ACL deficient knee and the restoration of this movement after ACL reconstruction were demonstrated. For the anatomic double-bundle ACL reconstruction, our results of significant decrease of tibial rotation in the reconstructed knee and no significant difference when compared with the intact knee after surgery with adequate statistical power supported that this surgical technique would restore knee rotational stability to the normal level of the intact knee. However, we were lack of evidence to prove that single-bundle technique would restore knee rotational stability and that the treatment effect of both techniques on knee rotational stability would be the same because of inadequate statistical power.

Our findings supported previous studies (Deneweth et al., 2010; Georgoulis et al., 2007; Ristanis et al., 2005; Tashman et al., 2004) that showed knee rotational instability of ACL deficient knee and reconstructed knee with single-bundle technique. In two studies with protocols similar to those of the present chapter (Georgoulis et al., 2007; Ristanis et al., 2005), the tibial rotation of deficient knee was significantly higher than that of intact knee. Whereas those subjects were instructed to walk after pivoting movement, ours were instructed to run. We believe that the task in this chapter provides a higher rotational stress to the knee. However, the increased tibial rotation found in the current chapter was not as high as that in either of the two previous studies, perhaps because of the difference in the time from injury to assessment. The cases in this chapter were based on acute injury, whereas those in the two studies were based on chronic injury. Our participants might have performed cautiously in the preoperative assessment. Other studies employing different functional activities, such as downhill running (Tashman et al., 2004) and single leg hopping (Deneweth et al., 2010), have showed abnormal rotational motion after ACL reconstruction. Regarding study design, all the participants in this chapter were assessed prospectively, before and after ACL reconstruction. The variations between the study group and the control group were minimized because the contralateral intact knee was used as a control.

Anatomic ACL reconstruction (Karlsson, 2010) aims to reconstruct the original ACL with normal kinematics in all six DOF, including mediolateral and AP translation, and axial rotation. However, in vitro (Colombet et al., 2007; Li et al., 2006; Woo et al., 2002) and in vivo (Deneweth et al., 2010; Georgoulis et al., 2007; Ristanis et al., 2005; Tashman et al., 2004) studies showed that tibial rotation is not restored by single-bundle ACL reconstruction. One of the suggested reasons is that only the AM bundle is replicated, thereby resulting in insufficient rotational control of the knee;

another is that the single-bundle techniques tested may not have been completely anatomic. In the current chapter, ten patients were treated with anatomic double-bundle ACL reconstruction, in which AM and PL bundles were both reconstructed to mimic the original ACL anatomy. In addition to the AM bundle, the PL bundle might provide a role in the stabilization of the knee against a combined rotatory load (Gabriel et al., 2004). In evaluating double-bundle ACL reconstruction with a high-demand movement, the significant decrease in range of tibial rotation of the reconstructed knee suggests the effectiveness of rotational control of such an anatomic reconstruction. For the sixteen patients who received single-bundle ACL reconstruction, the graft was reconstructed in a more horizontal way when compared with the original AM bundle. This orientation of the graft might provide some of the rotational controls that the PL bundle should be provided. However, we did not statistically have enough evidence that the knee rotational stability is restored by single-bundle ACL reconstruction. When comparing the two surgical techniques, we also did not demonstrate the superiority of the double-bundle technique. Post statistical analysis showed that sample size has to be increased to at least 30 subjects in each surgical group such that the power obtained would be above 0.8. The current result was also in line with a recent systemic review that showed the reviewed papers did not support the theory that double-bundle reconstruction better controls knee rotation (Meredick et al., 2008). This first attempt to evaluate different techniques of ACL reconstruction with functional assessment provides a suitable platform for future study with large-scale randomized controlled trials comparing the effect of single-bundle and double-bundle ACL reconstruction on functional stability.

Functional test should be the ultimate step for evaluating ACL reconstruction, given that it involves real-life loading that human joints are exposed in daily activities or even sport motion. Although dynamic functional test was commonly employed (Fitzgerald et al., 2001), previous studies have mainly focused on functional performance. Muscle strength is one of the performance indexes during rehabilitation, in which there is a positive association between thigh muscles and functional outcome of the knee (Moisala et al., 2007). Other functional tests have been used as assessment after ACL reconstruction, such as vertical jump, figure of eight and stairs running (Risberg and Ekeland, 1994). All were expressed as strength and ability that a patient would achieve. Instead, joint functional stability should be investigated through function test such as running (Tashman et al., 2004) and jumping (Deneweth et al., 2010). In this chapter, a high-demand sports movement was used to investigate the effect of anatomic double-bundle ACL reconstruction on knee rotational stability. The stability was expressed as tibial rotation during a pivoting movement, and the result of excessive rotation before ACL reconstruction was in line with previous study (Risberg and Ekeland, 1994). Functional test with motion analysis would be a good tool to evaluate patients with knee instability, after knee ligamentous injury, for example.

The limitations in this experiment included known drawbacks of motion analysis, including the movement of skin markers (Reinschmidt et al., 1997). However, the marker model was validated (Davis et al., 1991) and employed by other researchers for similar movement (Ristanis et al., 2005; Webster et al., 2010; Yu et al., 2005). During the procedure, the inter-tester error was minimized by having the same technician place the skin markers and measure all anthropometric data. A standing offset trial to define 0° for all segmental movements was collected to avoid subtle misalignment of the knee joint. Moreover, tibial rotation was reliably measured in a similar previous study (Webster et al., 2010), and typical error values (<2.9°) were less than the usual group differences in rotational excursion as reported in the literature. Furthermore, to avoid variation among surgeons in the complicated surgical technique (Karlsson, 2010), two experienced orthopaedic surgeons preformed all reconstructions. Lastly, to avoid unnecessarily subject variations, we employed a prospective design in which the same injury knee was compared before and after the reconstruction. The intact knee of the same individual was used as a control.

5.5 Chapter conclusion

The ACL deficient knee demonstrated increased tibial rotation. By using a dynamic functional biomechanical assessment, it is demonstrated that the anatomic double-bundle ACL reconstruction successfully restores functional knee rotational stability during a pivoting movement. When comparing the single-bundle and double-bundle techniques, the results showed a trend that both reconstructions have similar effect on knee rotational stability with no superiority in anatomic double-bundle ACL reconstruction.

Chapter 6 The application of optical motion analysis system to investigate anticipation effect during stop-jumping functional task

Chapter summary

The last chapter demonstrates how a high-demand pivoting task is adopted in a functional assessment to evaluate knee rotational stability. Knee stability during functional assessment such as stop-jumping task is a key factor to determine if an athlete is adequately rehabilitated after knee ligamentous injury. This chapter aims to investigate the effect of anticipation on landing maneuvers during planned and unplanned stop-jumping tasks. Knee kinematics of ten healthy male participants was collected using an optical motion analysis system during planned and unplanned stop-jumping tasks. A photocell gate was set on the walkway in laboratory such that an instruction signal was triggered on a monitor when the participants passed through the gate. Data at the time of foot strike were considered for investigation of the anticipation effect during the stop-jumping tasks. Knee kinematics data were compared between planned and unplanned tasks. External rotational angle showed significant decreased in unplanned stop-jumping task during forward and right jump when compared with that of planned tasks. Flexion angle and abduction angle during forward, vertical and right jump were significantly decreased in the unplanned tasks. It was concluded that anticipation effect significantly influenced the landing maneuvers of stop-jumping task and it was suggested that both planned and unplanned stop-jumping tasks should be considered when monitoring the rehabilitation progress after knee ligamentous injury.

Publication: This chapter is in revision in Sports Biomechanics.

Lam MH, Lai PK, Fong DTP, Yung PSH, Fung KY, Chan KM (in revision). Effect of anticipation on landing maneuver during stop-jumping task. Sports Biomechanics

Grant: This chapter is funded by The Chinese University of Hong Kong, Direct Grant for Research.

Fong DTP, Chan KM, Yung PSH, Lam MH. Anticipation effect on knee rotational stability during planned and un-planned movement tests in laboratory. The Chinese University of Hong Kong, Direct Grant for Research, 2008.2.020, HKD34,000

6.1 Introduction

Knee ligament reconstruction such as ACL reconstruction aims to restore the functional stability and allows athletes to return to sports activity (Myklebust and Bahr, 2005). Therefore, functional test is used during follow-up consultation to evaluate if an athlete is adequately rehabilitated (Risberg and Ekeland, 1994). The movement tasks vary with different purposes, for example running (Tashman et al., 2007) is used to evaluate gait pattern while hopping (Fitzgerald et al., 2001) is used to test muscle power. However, knee stability is seldom considered during high-demand functional task.

Knee stability is usually evaluated by clinicians and athletes themselves through subjective assessments such as clinical examination and questionnaire (Moller et al., 2009; Stengel et al., 2009; Tegner and Lysholm, 1985; Tyler et al., 1999). Objective assessments have been developed for assessing AP translation (Monaco et al., 2009) and axial rotation (Musahl et al., 2007) of the knee. However, these measurement tools are limited to passive laxity test. Knee rotational stability in terms of tibial rotation has been investigated during dynamic functional tasks (Georgoulis et al., 2007; Ristanis et al., 2005). These studies evaluated tibial rotation during a high-demand pivoting task before and after ACL reconstruction. Besides pivoting, stop-jumping task (Sell et al., 2006; Yu et al., 2005) and cutting task (Beaulieu et al., 2008; Besier et al., 2001; Houck et al., 2007; Pollard et al., 2007) have been used in kinematics studies but no study focused on knee rotational stability.

Anticipation effect refers to the phenomenon that individuals change their motion pattern when potential threats or dangers are expected (Cham and Redfern, 2002). It involves in most of the sport movements and research has revealed that unplanned movement is more danger than planned movement (Besier et al., 2001). Possible reasons suggest quick and unplanned movement affect muscle activation patterns and result abnormal joint kinematics (Beaulieu et al., 2008; Sell et al., 2006). For example, Besier and coworkers (Besier et al., 2001) suggested that unplanned cutting maneuvers would increase the risk of non-contact ACL injury and Sell and coworkers (Sell et al., 2006) found lateral jump was the most dangerous among 3-direction stop-jumping tasks. However, there is limited knowledge if the unplanned tasks would affect the knee rotational stability during functional tasks. This information would be important to decide if anticipation effect should be considered during dynamic functional assessment after knee ligamentous injury.

This chapter aims to investigate the anticipation effect on knee rotational stability during stop-jumping tasks in laboratory. Kinematics at foot strike (Cham and Redfern, 2002) was considered as ACL injury was reported to occur 17-50 ms after initial foot strike during landing (Krosshaug et al., 2007). It is hypothesized that there is a significant difference for landing maneuver in terms of tibial rotation between planned and unplanned stop-jumping tasks. Since returning to sport is the ultimate goal of knee ligament reconstruction, such information is important for sport biomechanists to design functional test protocol for assessing knee stability during and after rehabilitation of the reconstructed athletes.

6.2 Method

6.2.1 Participants

Ten healthy male participants without any injury history on lower limbs were recruited. They were recreational athletes, currently participating at least two times of their sports per week. The mean age, body mass and height of the participants were 26.4±1.8 years, 70.9±15.6 kg and 1.73±0.72 m respectively. The university ethics committee approved the study. Informed consents were obtained from each participant before the experiment.

6.2.2 Experimental task

A series of stop-jumping tasks were performed in planned and unplanned manners randomly for each participant. For each task, the participant was instructed to run straight on a 10 m walkway approaching a ground mounted force plate, with a running speed of 3.1 m/s to 3.5 m/s (De Cock et al., 2005), as monitored by the forward speed of the sacrum marker by a motion analysis system (VICON 624, Vicon Motion System Ltd, Oxford, United Kingdom). Trials with the running speed out of the range were discarded.

In the planned tasks, the participants were instructed to stop with both feet, with the testing foot on the force plate, and then jump immediately to one of the four directions (forward, vertical, left and right) as far as they could. In the unplanned tasks, a photocell gate was set at the participants' hip height and at a distance of 0.7 m in front of the force plate, allowing approximate 0.2 s to react and perform the jump. When the participant passed through the gate, a voltage signal was delivered to a computer to trigger an instruction of the movement direction as shown on a 17-inch monitor in front of the walkway. The participant then stepped on the force plate and jumped to the instructed direction in the shortest time he could (Figure 6.1). The four-direction instructions were delivered to the participant in a random sequence.

6.2.3 Experimental procedure

All experiments were conducted in the Gait Laboratory of Alice Ho Miu Ling

Nethersole Hospital, Hong Kong. An optical motion analysis system with eight cameras was used to collect three dimensional rotation movements of lower extremities at 120 Hz capturing frequency. The system was calibrated on the same day of testing and the mean residual was less than 1 mm. If it was not, the system was recalibrated. A synchronized force plate (model OR6-7 AMTI, Watertown, Massachusetts, USA) was used to record complete ground reaction force data at 1080 Hz at the centre of the capture volume of about 3x3x3 m^3.

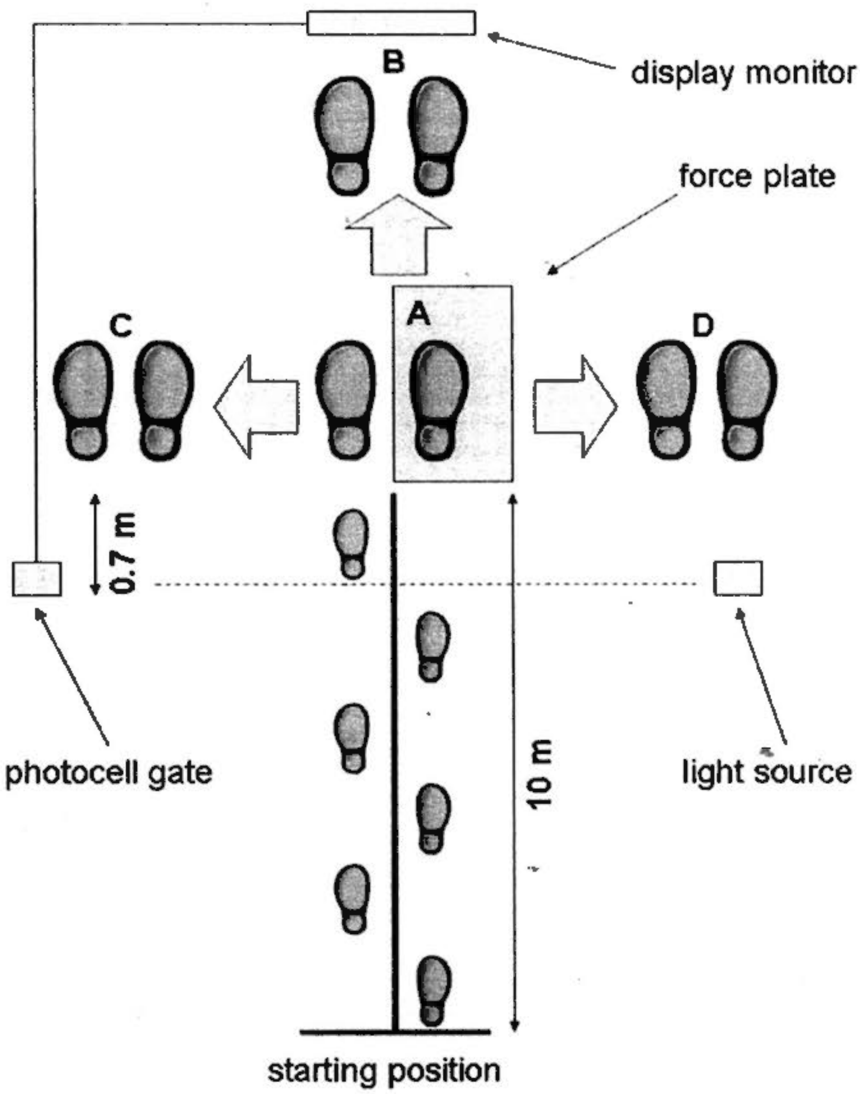


Figure 6.1 Laboratory setting of planned and unplanned stop-jumping tasks (Vertical jump: A to A; Forward jump: A to B; Left jump: A to C; Right jump: A to D)

After explanation of study procedures, anthropometric measurements including body height and mass, ASIS breadth, high and calf length, midthigh and calf circumference, knee diameter, foot breadth and length, malleolus height and diameter were measured. A 15-marker model was adopted to collect lower limb kinematics during stop-jumping movements. The markers were secured with double-sided tape to the participants' bony landmarks, including sacrum, ASIS, greater trochanter, femoral epicondyle, tibial tubercle, lateral malleolus, heel and fifth metatarsal head on both limbs (Davis et al., 1991). All the procedures were managed by one tester.

A trial of standing anatomical position was captured. Each participant was instructed by the same tester to stand with both feet in shoulder width and align the shank and foot segment to a neutral position. This calibration file provided a definition of 0° for all joint angles in all planes. Video demonstration of stop-jumping tasks was shown to all participants. They were allowed to practise a series of planned and unplanned stop-jumping tasks until they were comfortable to start the test. Each participant was told to begin the task at the designated starting point, run straight towards the force plate, stop with both feet and jump as high as possible for the vertical jump and as far as possible for the forward, left and right jumps. Thirty seconds of rest was allowed between each jump and one minute of rest was also given to subjects between the planned and the unplanned tasks.

6.2.4 Data collection and reduction

Three successful trials for each direction for planned and unplanned tasks were collected. For each successful trial, data from the motion analysis system were trimmed before and after the time of foot strike. A foot contact was determined by the force plate when the vertical ground reaction force exceeded 5% of the participants' body weight. Three dimensional coordinates of every marker were exported from the VICON software. The knee joint kinematics was calculated with the anthropometric data measured previously (Davis et al., 1991). All calculations were conducted using self-compiled program (Mathworks, Natick, Massachusetts, USA). The main dependent variable was knee external rotational angle. Knee flexion angle and knee abduction angle were also calculated at the time of foot strike (Cham and Redfern, 2002), as this suggested if the anticipation effect was significant to the preparatory stage of the stop-jumping task.

6.2.5 Data analysis

All data were analyzed for the right side only and were averaged across three trials for each condition. Two-way multivariate ANOVA with repeated measures was used to examine the interactive effects (anticipation effect x direction) of knee kinematics. If the interactive effect was found, stratified paired t-tests were conducted for each parameter to demonstrate the anticipation effect at each jumping direction. The level of significance was set at 0.05.

6.3 Results

Multivariate ANOVA showed significant interactive effect (Wilks' Lambda value = 0.353, $F = 3.614$, $p<0.05$). Therefore, stratified paired t-tests were conducted for each parameter between planned and unplanned tasks. The result of the knee kinematics at the time of foot strike was summarized in the Table 6.1. Besides left jump, all variables of the planned jumps were larger than the unplanned jumps. Significant differences were found in the external rotation angle during the forward and right jumps, the abduction angle during the forward, vertical and right jumps, and the flexion angle during the right jump.

Table 6.1 Paired t-test results of knee kinematics on the anticipation effect for all jumping directions.

Direction	Knee kinematics (+ve)	Planned	Unplanned	Significant difference
	Flexion	25.8° (7.4°)	23.8° (7.4°)	No
Forward	Abduction	9.4° (8.9°)	6.0° (10.9°)	Yes ($p<0.05$)
	External rotation	20.2° (8.8°)	13.9° (6.4°)	Yes ($p<0.05$)
	Flexion	27.0° (12.0°)	23.5° (6.5°)	No
Vertical	Abduction	9.1° (10.5°)	6.1° (7.9°)	Yes ($p<0.05$)
	External rotation	17.4° (8.8°)	14.1° (5.4°)	No
	Flexion	29.5° (3.7°)	23.0° (7.1°)	Yes ($p<0.05$)
Right	Abduction	9.9° (10.4°)	6. 5° (10.0°)	Yes ($p<0.05$)
	External rotation	19.6° (8.6°)	13.3° (3.8°)	Yes ($p<0.05$)
	Flexion	21.4° (4.4°)	22.4° (4.5°)	No
Left	Abduction	5.7° (10.3°)	7.9° (8. 9°)	No
	External rotation	11.5° (10.6°)	16.2° (6.8°)	No

6.4 Discussion

In laboratory setting, functional test allows participants to pre-plan the movement pattern and it may not reflect the real movement pattern in real game competition during which athletes must react to unanticipated events (Besier et al., 2001). Currently, research investigating anticipation effect on knee kinematics during stop-jumping tasks is limited. Pollard et al. (Pollard et al., 2007) and Landry et al. (Landry et al., 2007) reported that both male and female performed similarly in a random cued cutting maneuver. However, neither of the research groups focused on stop-jumping tasks, in which most of the ACL injuries occurs during sudden stop-landing movement with a change in direction. Sell and co-workers (Sell et al.,

2006) did comparison between planned and unplanned stop-jumping tasks and demonstrated increased knee joint loading characteristics such as greater knee valgus and flexion moments. The authors suggested that directional and reactive jumps should be included in research methodology based on the knee joint loading data. In a recent study, it has been suggested that unanticipated landing induces modifications in landing biomechanics that may increase the risk of ACL injury (Brown et al., 2009). However, this unanticipated effect is not well-understood in terms of knee rotational kinematics.

In this chapter, knee rotational stability was investigated in terms of knee external rotation angle. For three of the four directions (forward, vertical and right), our participants demonstrated decreased knee external rotation angle during unplanned stop-jumping tasks. Significant differences between planned and unplanned tasks were found in the forward ($p<0.05$) and right ($p<0.05$) stop-jumping tasks. The external rotation angles were 20.2° and 13.9° for the forward jump, and 19.6° and 13.3° for the right jump in the planned and unplanned situations, respectively. It was surprised that the results did not support previous studies (Besier et al., 2001; Brown et al., 2009), suggesting unplanned tasks would generate more demanding stress to the knee. One of the reasons was that our participants performed the tasks cautiously due to the nature of the unplanned task, which involved short time decision and multi-directional jumps. However, without hesitation, participants performed confidently and showed increased knee rotation for planned tasks since enough time was allowed for them to pre-program their movement patterns before making the jump.

Athletes tend to pre-program their landing maneuver during preparation stage, which is regarded as the flight phase before landing (Chappell et al., 2007). Research has been suggested ACL injuries typically occur at the time of foot strike (Krosshaug et al., 2007). In this experiment, the kinematics difference between planned and unplanned jump at the time of foot strike suggested that athletes would modify their strategies before landing on the ground. In contrast to the previous studies (Sell et al., 2006; Yu et al., 2005), our participants had a decreased abduction angle during the unplanned tasks. Chappell et al. (Chappell et al., 2007) reported that female would have smaller flexion angle than male at the end of preparation stage. Our participants also demonstrated similar result, showing smaller flexion angle during the unplanned right jump (23.0°) than the planned right jump (29.5°). It may increase the knee joint loading and further increase the risk of ACL injury. Participants in this experiment performed differently in knee kinematics between the planned and the unplanned stop-jumping tasks during the forward, vertical and right jump. The results suggested that anticipation effect would affect landing maneuver and hence it should be considered if stop-jumping task is used during functional assessment.

None of the previous studies evaluate knee rotational stability during unplanned landing maneuver. Knee rotational displacement, which is one of the major laxities in knee ligamentous injury athletes, was measured in this experiment. Previous study (Chappell et al., 2007) showed that there was a gender difference in knee rotation during preparation stage of vertical stop-jumping task. In this experiment, the healthy participants demonstrated significant decreased knee kinematics for unplanned tasks in the forward, vertical and right jump. A series of high risk movements of ACL injury was incorporated, including a sharp deceleration, a sudden stop landing maneuver and a sudden change in direction. Since knee stability is one of the major considerations to determine if athletes could return to sports after ligament reconstruction, it would be of great value for evaluation of knee stability of the ligament reconstructed athletes with functional assessment such as stop-jumping task with anticipation effect.

The limitation in this experiment involved known drawbacks of motion analysis, including the movement of skin markers (Reinschmidt et al., 1997). During the experimental procedure, the inter-tester error was minimized by having the same technician place the skin markers and measure all anthropometric data. A standing offset trial to define 0° for all segmental movements was collected to avoid subtle misalignment of the knee joint. Moreover, as this experiment investigated the anticipation effect on knee kinematics in healthy participants jumping height and distance were not considered. It would be suggested that other parameters reflecting functional stability and muscles strength such as ground reaction force and electromyography data should be included in future studies for assessing athletes after ligament reconstruction.

6.5 Chapter conclusion

This chapter provided specific knee kinematics information during stop-jumping tasks, especially the anticipation effect on knee rotational stability. It was concluded that anticipation would affect landing manuever during stop-jumping tasks by showing different knee kinematics between planned and unplanned tasks in healthy male participants. It was suggested that both planned and unplanned stop-jumping tasks should be considered as one of the functional assessments to monitor the rehabilitation progress after knee ligamentous injury.

Chapter 7 Discussion

In chapter two, varies biomechanical techniques to quantify knee rotational stability were summarized. Different techniques in the literature for three situations under which the knee was examined were reported. The practicability, accuracy, invasiveness, others pros and cons of these biomechanical techniques were extensively discussed. To choose a suitable technique for a specific clinical application, it is recommended that the study's propose should be considered, as well as the experimental setup and the stress applied on the knee. It would be better to quantify the effectiveness of a new designed surgical technique by using a cadaveric model before application to living human subjects for intra-operative evaluation or long time functional stability assessment.

This piece of work provides useful information to choose suitable techniques when we consider investigating knee rotational stability in the following chapters. Intra-operative navigation system was used in chapter three to evaluate knee rotational stability of a double femoral-tunnel PLC reconstruction technique. In chapter four, one motion sensor was used for measurement of tibial rotation in developing a knee rotational laxity meter. At the same time, navigation system was used again as a gold standard measurement. Further, an optical motion analysis system was used in chapter five and six, to document the dynamic knee rotational stability. By using a high-demand pivoting task, we demonstrated the effect of ACL reconstruction and also the anticipation effect in laboratory as an extension to provide suggestion if anticipation should be considered for future functional assessments.

Biomechanical technique is only a tool of measurement. In the field of orthopaedics sports medicine scientists make use of these techniques to solve clinical problems. Therefore, two controversial issues in sports medicine were chosen in this dissertation. The first issue regarded the reconstruction technique of the PLC. In the literatures, it was suggested that the single isometric femoral tunnel did not address the different insertion sites of the popliteus tendon and LCL. Later, another technique that aims to provide a more anatomic reconstruction of the PLC by re-creating the insertion sites of the LCL and the popliteus tendon on the femur using a dual-femoral sockets technique was suggested (Arciero, 2005). In chapter three, we compared the immediate effect of double-femoral tunnel technique and single-femoral tunnel technique for PLC reconstruction on knee kinematics, using an isolated cadaveric injury model. The cadaveric model was used not only because the muscle effect could be removed during experiment but also a preliminary consensus could be obtained before a clinical trial can be conducted in the future. During the experiment, a controlled torque was applied at the knee joint to simulate a rotational stress. At the same time, a navigation system was used to quantify knee internal and external rotation. In this design, the effect of the two reconstruction techniques would be tested in a well-controlled condition.

The second clinical problem in this dissertation was the rotational control of the anatomic double-bundle ACL reconstruction. Previous studies have suggested that the double-bundle technique was proven to have a better rotational control over single-bundle technique in cadaveric model (Mae et al., 2001; Yagi et al., 2002). With the fundamental support in the literature, we decide to conduct a clinical trial to investigate the effect of ACL reconstruction on knee rotational stability. In this case, clinical assessments such as physical examination and questionnaire were no longer our research focus. Dynamic functional assessment, instead, was used as a platform to evaluate knee rotational stability. In chapter five, by means of optical motion analysis system, we demonstrated that knee rotational stability was restored by anatomic double-bundle ACL reconstruction. However, the superiority of rotational control over single-bundle technique was remained questionable. Future study should be conducted with large-scale randomized controlled trials comparing the effect of single-bundle and double-bundle ACL reconstruction on functional stability during dynamic task.

In view of the biomechanical techniques used in this dissertation, navigation system would be a simple and accurate measurement tool to quantify knee rotational laxity, regardless of its invasiveness and equipment cost. It was suggested to consider using navigation system when in vitro kinematics would be of interest in the future research design. Since the navigation system has been developed to provide guidelines of specific surgical procedure such as tunnel placement of ACL reconstruction, some investigators utilized the extra kinematics measurement function for assessing knee rotational laxity during operation (Bignozzi et al., 2010; Hofbauer et al., 2010; Song et al., 2009). For any research study that involves invasive procedure to patients, prior approval should be obtained from the ethical committee of their institutions. Another concern for using navigation system is that the equipment cost may be too expensive in some of the research centers. We suggest using two or more high speed cameras and a motion analysis software to achieve the same data collection function of the navigation system. This methodology would provide an alternative way with lower equipment cost but a longer data processing time.

Another biomechanical technique that used in this dissertation was the optical motion analysis system. The knee movement of the patients was based on three dimensional coordinate of the skin markers attached to the patients' anatomical bony landmarks. This kind of motion analysis system is well equipped in most of the standardized gait laboratories. However, its accuracy has been a concern because of the skin movement during dynamic task. By considering the validity of the skin marker model, the reported typical error value and the availability of equipment in our own center, optical motion analysis system was chosen to measure tibial rotation during dynamic functional task in this dissertation. As reported in chapter two, radiographic measurement was another option for dynamic assessment of knee rotational stability. This technique was considered to be invasive since bone marker had to be implemented prior the functional test. The radiographic capturing frequency was reported to be 2-4 Hz, which was very low when compared with the optical high speed camera. This disadvantage highly restricts the motion of the dynamic task. However, similar technique was developed to improve these limitations of radiographic measurement (Tashman et al., 2007). The invasiveness is minimized by having a computerized tomography scan prior to the assessment so that the pre-scanned image can be matched with the radiograph. Also, the capturing frequency highly increases to 250 Hz, which allows a smooth continuous kinematics data collection during most of the human dynamic movements. However, to the author's knowledge, there is only one center that equips this advanced technique although some centers equip computerized tomography matching technique but with low radiographic capturing frequency. All in all, it would be great in terms of accuracy to apply the current radiographic measurement techniques for assessment of knee rotational stability during dynamic functional task regardless of the equipment cost.

In orthopaedics sports medicine, ligamentous reconstruction aims to restore functional stability and allow patients safe return-to-sports. Therefore, functional stability should be considered as an ultimate assessment to determine if the patient is able to return-to-sports. In chapter six, the anticipation effect was proved to have effect on knee rotational stability during stop-jumping task. It is suggested including this real game effect when assessing functional stability during dynamic task. However, the functional stability assessment may not be practical in every orthopaedics center because of the time consuming assessment. A simple, practical and objective assessment tool that reflects functional stability would be of great interest. In chapter four, a handle and simple device was developed for measurement of knee rotational laxity. Validity and reliability were verified in a cadaveric model. This biomechanical meter was designed to use in clinical setting with quick, reliable and objective measurement of knee rotational laxity.

In this dissertation, we have demonstrated different applications and development of biomechanical techniques for measurement of knee rotational stability. Future studies are suggested as below.

- Develop a thigh fixation device for the use in patients when documenting knee rotational laxity using the validated meter proposed in this dissertation.
- Check reliability for the proposed meter when applying to patients who have knee ligamentous injury.
- Determine a threshold that represents a significant difference between the injured knee and the intact knee when documenting knee rotational laxity using the proposed meter.
- Investigate the knee rotational stability of patients with knee ligamentous injury

during unanticipated high-demand functional task.

- Develop a model consisting simple and practical measurement tool to reflect knee functional stability during dynamic task.

Chapter 8 Conclusion

This dissertation presented various biomechanical techniques to quantify knee rotational stability that have been currently used in the literatures. Different techniques were chosen to apply on current clinical problems in the field of orthopaedics sports medicine in order to supplement the limitation of physical examination. The PLC reconstruction with double-femoral tunnel technique showed better rotational stability and resistance to posterior translation than the single-femoral tunnel technique without compromising varus stability. Next, a simple biomechanical meter to document knee rotational laxity was proposed and verified in cadaveric model. Further, it was shown that anatomic double-bundle ACL reconstruction successfully restored functional knee rotational stability during the high-demand pivoting movement. When comparing the single-bundle and double-bundle techniques, the results showed a trend that both reconstructions have similar effect on knee rotational stability with no superiority in anatomic double-bundle ACL reconstruction. Lastly, anticipation effect was shown to affect landing manuever during stop-jumping tasks by showing different knee kinematics between planned and unplanned tasks in healthy male participants. It was suggested that both planned and unplanned stop-jumping tasks should be considered as one of the functional assessments to monitor the rehabilitation progress after knee ligamentous injury.

REFERENCES

Abernethy, L. and D. MacAuley (2003). "Impact of school sports injury." British Journal of Sports Medicine 37(4): 354-5.

Adirim, T. A. and T. L. Cheng (2003). "Overview of injuries in the young athlete." Sports Medicine 33(1): 75-81.

Allen, C. R., E. K. Wong, G. A. Livesay, M. Sakane, F. H. Fu and S. L. Woo (2000). "Importance of the medial meniscus in the anterior cruciate ligament-deficient knee." Journal of Orthopaedic Research 18(1): 109-15.

Andersen, H. N. and P. Dyhre-Poulsen (1997). "The anterior cruciate ligament does play a role in controlling axial rotation in the knee." Knee Surgery, Sports Traumatology, Arthroscopy 5(3): 145-9.

Anderson, C. J., B. D. Westerhaus, S. D. Pietrini, C. G. Ziegler, C. A. Wijdicks, S. Johansen, L. Engebretsen and R. F. Laprade (2010). "Kinematic impact of anteromedial and posterolateral bundle graft fixation angles on double-bundle anterior cruciate ligament reconstructions." American Journal of Sports Medicine 38(8): 1575-83.

Anderson, K., E. M. Wojtys, P. V. Loubert and R. E. Miller (1992). "A biomechanical evaluation of taping and bracing in reducing knee joint translation and rotation." American Journal of Sports Medicine 20(4): 416-21.

Andriacchi, T. P. and E. J. Alexander (2000). "Studies of human locomotion: past, present and future." Journal of Biomechanics 33(10): 1217-24.

Andriacchi, T. P., E. J. Alexander, M. K. Toney, C. Dyrby and J. Sum (1998). "A point cluster method for in vivo motion analysis: applied to a study of knee kinematics." Journal of Biomechanical Engineering 120(6): 743-9.

Andriacchi, T. P., P. L. Briant, S. L. Bevill and S. Koo (2006). "Rotational changes at the knee after ACL injury cause cartilage thinning." Clinical Orthopaedics and Related Research 442: 39-44.

Andriacchi, T. P. and C. O. Dyrby (2005). "Interactions between kinematics and loading during walking for the normal and ACL deficient knee." Journal of Biomechanics 38(2): 293-8.

Apsingi, S., T. Nguyen, A. M. Bull, A. Unwin, D. J. Deehan and A. A. Amis (2008). "Control of laxity in knees with combined posterior cruciate ligament and posterolateral corner deficiency: comparison of single-bundle versus double-bundle posterior cruciate ligament reconstruction combined with modified Larson posterolateral corner reconstruction." American Journal of Sports Medicine 36(3): 487-94.

Apsingi, S., T. Nguyen, A. M. Bull, A. Unwin, D. J. Deehan and A. A. Amis (2008). "The role of PCL reconstruction in knees with combined PCL and posterolateral corner deficiency." Knee Surgery, Sports Traumatology, Arthroscopy **16**(2): 104-11.

Apsingi, S., T. Nguyen, A. M. Bull, A. Unwin, D. J. Deehan and A. A. Amis (2009). "A comparison of modified Larson and 'anatomic' posterolateral corner reconstructions in knees with combined PCL and posterolateral corner deficiency." Knee Surgery, Sports Traumatology, Arthroscopy **17**(3): 305-12.

Arciero, R. A. (2005). "Anatomic posterolateral corner knee reconstruction." Arthroscopy **21**(9): 1147.

Arnason, A., S. B. Sigurdsson, A. Gudmundsson, I. Holme, L. Engebretsen and R. Bahr (2004). "Risk factors for injuries in football." American Journal of Sports Medicine **32**(1 Suppl): 5S-16S.

Baxter, M. P. (1988). "Assessment of normal pediatric knee ligament laxity using the genucom." Journal of Pediatric Orthopedics **8**(5): 546-50.

Beaulieu, M. L., M. Lamontagne and L. Xu (2008). "Gender differences in time-frequency EMG analysis of unanticipated cutting maneuvers." Medicine and Science in Sports and Exercise **40**(10): 1795-804.

Benoit, D. L., D. K. Ramsey, M. Lamontagne, L. Xu, P. Wretenberg and P. Renstrom (2006). "Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo." Gait and Posture **24**(2): 152-64.

Besier, T. F., D. G. Lloyd, T. R. Ackland and J. L. Cochrane (2001). "Anticipatory effects on knee joint loading during running and cutting maneuvers." Medicine and Science in Sports and Exercise **33**(7): 1176-81.

Beynnon, B. D., R. J. Johnson, J. A. Abate, B. C. Fleming and C. E. Nichols (2005). "Treatment of anterior cruciate ligament injuries, part 2." American Journal of Sports Medicine **33**(11): 1751-67.

Beynnon, B. D., R. J. Johnson, J. A. Abate, B. C. Fleming and C. E. Nichols (2005). "Treatment of anterior cruciate ligament injuries, part I." American Journal of Sports Medicine **33**(10): 1579-602.

Bignozzi, S., S. Zaffagnini, N. Lopomo, F. H. Fu, J. J. Irrgang and M. Marcacci (2010). "Clinical relevance of static and dynamic tests after anatomical double-bundle ACL reconstruction." Knee Surgery, Sports Traumatology, Arthroscopy **18**(1): 37-42.

Brady, M. F., M. P. Bradley, B. C. Fleming, P. D. Fadale, M. J. Hulstyn and R. Banerjee (2007). "Effects of initial graft tension on the tibiofemoral compressive forces and joint position after anterior cruciate ligament reconstruction." American Journal of Sports Medicine **35**(3): 395-403.

Branch, T. P., J. E. Browne, J. D. Campbell, R. Siebold, H. I. Freedberg, E. A. Arendt, F. Lavoie, P. Neyret and C. A. Jacobs (2010). "Rotational laxity greater in patients with contralateral anterior cruciate ligament injury than healthy volunteers." Knee Surgery, Sports Traumatology, Arthroscopy **18**(10): 1379-84.

Brandsson, S., J. Karlsson, B. I. Eriksson and J. Karrholm (2001). "Kinematics after tear in the anterior cruciate ligament: dynamic bilateral radiostereometric studies in 11 patients." Acta Orthopaedica Scandinavica **72**(4): 372-8.

Brandsson, S., J. Karlsson, L. Sward, J. Kartus, B. I. Eriksson and J. Karrholm (2002). "Kinematics and laxity of the knee joint after anterior cruciate ligament reconstruction: pre- and postoperative radiostereometric studies." American Journal of Sports Medicine **30**(3): 361-7.

Brinkman, J. M., P. J. Schwering, L. Blankevoort, J. G. Kooloos, J. Luites and A. B. Wymenga (2005). "The insertion geometry of the posterolateral corner of the knee.[erratum appears in J Bone Joint Surg Br. 2006 Jun;88(6):837 Note: Koolos, JG [corrected to Kooloos, JG]]." Journal of Bone and Joint Surgery - British Volume **87**(10): 1364-8.

Brophy, R. H., J. E. Voos, F. J. Shannon, C. C. Granchi, T. L. Wickiewicz, R. F. Warren and A. D. Pearle (2008). "Changes in the length of virtual anterior cruciate ligament fibers during stability testing: a comparison of conventional single-bundle reconstruction and native anterior cruciate ligament." American Journal of Sports Medicine **36**(11): 2196-203.

Brown, T. N., R. M. Palmieri-Smith and S. G. McLean (2009). "Differences between Sexes and Limbs in Hip and Knee Kinematics and Kinetics during Anticipated and Unanticipated Jump Landings: Implications for ACL injury." British Journal of Sports Medicine.

Bull, A. M., H. N. Andersen, O. Basso, J. Targett and A. A. Amis (1999). "Incidence and mechanism of the pivot shift. An in vitro study." Clinical Orthopaedics and Related Research(363): 219-31.

Butler, D. L., F. R. Noyes and E. S. Grood (1980). "Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study." Journal of Bone and Joint Surgery - American Volume **62**(2): 259-70.

Cavanagh, P. R. and M. A. Lafortune (1980). "Ground reaction forces in distance running." Journal of Biomechanics **13**(5): 397-406.

Cham, R. and M. S. Redfern (2002). "Changes in gait when anticipating slippery floors." Gait and Posture **15**(2): 159-71.

Chappell, J. D., R. A. Creighton, C. Giuliani, B. Yu and W. E. Garrett (2007). "Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury." American Journal of Sports Medicine **35**(2): 235-41.

Clancy, W. G., Jr., M. F. Shepard and E. L. Cain, Jr. (2003). "Posterior lateral corner reconstruction." American Journal of Orthopedics **32**(4): 171-6.

Colombet, P., J. Robinson, P. Christel, J. P. Franceschi and P. Djian (2007). "Using navigation to measure rotation kinematics during ACL reconstruction." Clinical Orthopaedics and Related Research **454**: 59-65.

Consultancy Study on Sport for All (2009). "Participation Patterns of Hong Kong People in Physical Activities."

Coobs, B. R., C. A. Wijdicks, B. M. Armitage, S. I. Spiridonov, B. D. Westerhaus, S. Johansen, L. Engebretsen and R. F. Laprade (2010). "An in vitro analysis of an anatomical medial knee reconstruction." American Journal of Sports Medicine **38**(2): 339-47.

Covey, D. C. (2001). "Injuries of the posterolateral corner of the knee." Journal of Bone and Joint Surgery - American Volume **83-A**(1): 106-18.

Czerniecki, J. M., F. Lippert and J. E. Olerud (1988). "A biomechanical evaluation of tibiofemoral rotation in anterior cruciate deficient knees during walking and running." American Journal of Sports Medicine **16**(4): 327-31.

Daniel, D. M., W. H. Akeson and J. J. O'Connor (1990). "Knee ligaments: structure, function, injury and repair." Raven Press, New York.

Darcy, S. P., R. H. Kilger, S. L. Woo and R. E. Debski (2006). "Estimation of ACL forces by reproducing knee kinematics between sets of knees: A novel non-invasive methodology." Journal of Biomechanics **39**(13): 2371-7.

Davis, R. B., S. Ounpuu, D. Tyburski and J. R. Gage (1991). "A gait analysis data collection and reduction technique." Human Movement Science **10**(5): 575-587.

De Cock, A., D. De Clercq, T. Willems and E. Witvrouw (2005). "Temporal characteristics of foot roll-over during barefoot jogging: reference data for young adults." Gait and Posture **21**(4): 432-439.

de Loes, M. (1990). "Medical treatment and costs of sports-related injuries in a total population." International Journal of Sports Medicine **11**(1): 66-72.

de Loes, M. and I. Goldie (1988). "Incidence rate of injuries during sport activity and physical exercise in a rural Swedish municipality: incidence rates in 17 sports." International Journal of Sports Medicine **9**(6): 461-7.

Defrate, L. E., R. Papannagari, T. J. Gill, J. M. Moses, N. P. Pathare and G. Li (2006). "The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis.[see comment]." American Journal of Sports Medicine **34**(8): 1240-6.

DeHaven, K. E., A. J. Cosgarea and W. J. Sebastianelli (2003). "Arthrofibrosis of the knee following ligament surgery." Instructional Course Lectures **52**: 369-81.

Deneweth, J. M., M. J. Bey, S. G. Mclean, T. R. Lock, P. A. Kolowich and S. Tashman (2010). "Tibiofemoral Joint Kinematics of the Anterior Cruciate Ligament-Reconstructed Knee During a Single-Legged Hop Landing."

American Journal of Sports Medicine **38**(9): 1820-1828.

Drawer, S. and C. W. Fuller (2001). "Propensity for osteoarthritis and lower limb joint pain in retired professional soccer players." British Journal of Sports Medicine **35**(6): 402-8.

Duthon, V. B., C. Barea, S. Abrassart, J. H. Fasel, D. Fritschy and J. Menetrey (2006). "Anatomy of the anterior cruciate ligament." Knee Surgery, Sports Traumatology, Arthroscopy **14**(3): 204-213.

Dyrby, C. O. and T. P. Andriacchi (2004). "Secondary motions of the knee during weight bearing and non-weight bearing activities." Journal of Orthopaedic Research **22**(4): 794-800.

Engebretsen, L., W. D. Lew, J. L. Lewis, R. E. Hunter and P. Benum (1990). "Anterolateral rotatory instability of the knee. Cadaver study of extraarticular patellar-tendon transposition." Acta Orthopaedica Scandinavica **61**(3): 225-30.

Fahlstrom, M., J. S. Yeap, H. Alfredson and K. Soderman (2006). "Shoulder pain - a common problem in world-class badminton players." Scandinavian Journal of Medicine and Science in Sports **16**(3): 168-73.

Fanelli, G. C., B. F. Giannotti and C. J. Edson (1996). "Arthroscopically assisted combined posterior cruciate ligament/posterior lateral complex reconstruction." Arthroscopy **12**(5): 521-30.

Ferrari, A., M. G. Benedetti, E. Pavan, C. Frigo, D. Bettinelli, M. Rabuffetti, P. Crenna and A. Leardini (2008). "Quantitative comparison of five current protocols in gait analysis." Gait and Posture **28**(2): 207-16.

Ferrari, D. A., D. R. Wilson and W. C. Hayes (2003). "The effect of release of the popliteus and quadriceps force on rotation of the knee." Clinical Orthopaedics & Related Research(412): 225-33.

Ferrari, D. A., D. R. Wilson and W. C. Hayes (2003). "The effect of release of the popliteus and quadriceps force on rotation of the knee." Clinical Orthopaedics and Related Research(412): 225-33.

Ferretti, A., E. Monaco, L. Labianca, A. De Carli, B. Maestri and F. Conteduca (2009). "Double-bundle anterior cruciate ligament reconstruction: a comprehensive kinematic study using navigation." American Journal of Sports Medicine **37**(8): 1548-53.

Fitzgerald, G. K., S. M. Lephart, J. H. Hwang and R. S. Wainner (2001). "Hop tests as predictors of dynamic knee stability." Journal of Orthopaedic and Sports Physical Therapy **31**(10): 588-97.

Fong, D. T. P., C. Y. Man, P. S. H. Yung, S. Y. Cheung and K. M. Chan (2008). "Sport-related ankle injuries attending an accident and emergency department." Injury **39**(10): 1222-7.

Friden, T., D. Roberts, E. Ageberg, M. Walden and R. Zatterstrom (2001). "Review of knee proprioception and the relation to extremity function after an anterior cruciate ligament rupture." Journal of Orthopaedic and Sports Physical Therapy **31**(10): 567-76.

Frobell, R. B., L. S. Lohmander and H. P. Roos (2007). "Acute rotational trauma to the knee: poor agreement between clinical assessment and magnetic resonance imaging findings." Scandinavian Journal of Medicine and Science in Sports **17**(2): 109-14.

Fu, F. H. and B. A. Zelle (2007). "Rotational instability of the knee: editorial comment." Clinical Orthopaedics and Related Research **454**: 3-4.

Furman, W., J. L. Marshall and F. G. Girgis (1976). "The anterior cruciate ligament - A functional analysis based on postmortem studies." Journal of Bone and Joint Surgery - American Volume **58**(2): 179-185.

Gaasbeek, R. D., R. T. Welsing, N. Verdonschot, W. J. Rijnberg, C. J. van Loon and A. van Kampen (2005). "Accuracy and initial stability of open- and closed-wedge high tibial osteotomy: a cadaveric RSA study." Knee Surgery, Sports Traumatology, Arthroscopy **13**(8): 689-94.

Gabriel, M. T., E. K. Wong, S. L. Woo, M. Yagi and R. E. Debski (2004). "Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads." Journal of Orthopaedic Research **22**(1): 85-9.

Georgoulis, A. D., A. Papadonikolakis, C. D. Papageorgiou, A. Mitsou and N. Stergiou (2003). "Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking." American Journal of Sports Medicine **31**(1): 75-9.

Georgoulis, A. D., S. Ristanis, V. Chouliaras, C. Moraiti and N. Stergiou (2007). "Tibial rotation is not restored after ACL reconstruction with a hamstring graft." Clinical Orthopaedics and Related Research **454**: 89-94.

Girgis, F. G., J. L. Marshall and A. Monajem (1975). "The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis." Clinical Orthopaedics and Related Research(106): 216-31.

Gollehon, D. L., P. A. Torzilli and R. F. Warren (1987). "The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study." Journal of Bone and Joint Surgery - American Volume **69**(2): 233-42.

Granberry, W. M., P. C. Noble and G. W. Woods (1990). "Evaluation of an electrogoniometric instrument for measurement of laxity of the knee.[see comment]." Journal of Bone and Joint Surgery - American Volume **72**(9): 1316-22.

Griffith, C. J., R. F. LaPrade, S. Johansen, B. Armitage, C. Wijdicks and L. Engebretsen (2009). "Medial knee injury: Part 1, static function of the individual components of the main medial knee structures." American Journal of Sports Medicine **37**(9): 1762-70.

Grood, E. S., S. F. Stowers and F. R. Noyes (1988). "Limits of movement in the human knee. Effect of sectioning the posterior cruciate ligament and posterolateral structures." Journal of Bone and Joint Surgery - American Volume **70**(1): 88-97.

Grood, E. S. and W. J. Suntay (1983). "A joint coordinate system for the clinical description of three-dimensional motions: application to the knee." Journal of Biomechanical Engineering **105**(2): 136-44.

Gupte, C. M., A. M. Bull, R. D. Thomas and A. A. Amis (2003). "The meniscofemoral ligaments: secondary restraints to the posterior drawer. Analysis of anteroposterior and rotary laxity in the intact and posterior-cruciate-deficient knee." Journal of Bone and Joint Surgery - British Volume **85**(5): 765-73.

Hagemeister, N., N. Duval, L. Yahia, W. Krudwig, U. Witzel and J. A. de Guise (2002). "Comparison of two methods for reconstruction of the posterior cruciate ligament using a computer based method: quantitative evaluation of laxity, three-dimensional kinematics and ligament deformation measurement in cadaver knees." Knee **9**(4): 291-9.

Hagemeister, N., N. Duval, L. Yahia, W. Krudwig, U. Witzel and J. A. de Guise (2003). "Computer based method for the three-dimensional kinematic analysis of combined posterior cruciate ligament and postero-lateral complex reconstructions on cadaver knees." Knee **10**(3): 249-56.

Hara, K., T. Kubo, T. Suginoshita, C. Shimizu and Y. Hirasawa (2000). "Reconstruction of the anterior cruciate ligament using a double bundle." Arthroscopy **16**(8): 860-4.

Harreld, K., J. Nyland, B. Cottrell and D. N. Caborn (2006). "Self-reported patient outcomes after ACL reconstruction with allograft tissue." Medicine and Science in Sports and Exercise **38**(12): 2058-67.

Hinton, R. Y., A. E. Lincoln, J. L. Almquist, W. A. Douoguih and K. M. Sharma (2005). "Epidemiology of lacrosse injuries in high school-aged girls and boys: a 3-year prospective study." American Journal of Sports Medicine **33**(9): 1305-14.

Hofbauer, M., P. Valentin, R. Kdolsky, R. C. Ostermann, A. Graf, M. Figl and S. Aldrian (2010). "Rotational and translational laxity after computer-navigated single- and double-bundle anterior cruciate ligament reconstruction." Knee Surgery, Sports Traumatology, Arthroscopy **18**(9): 1201-7.

Hofmann, A. A., R. W. Wyatt, M. H. Bourne and A. U. Daniels (1984). "Knee stability in orthotic knee braces." American Journal of Sports Medicine **12**(5):

371-4.

Hoher, J., C. D. Harner, T. M. Vogrin, G. H. Baek, G. J. Carlin and S. L. Woo (1998). "In situ forces in the posterolateral structures of the knee under posterior tibial loading in the intact and posterior cruciate ligament-deficient knee." Journal of Orthopaedic Research **16**(6): 675-81.

Hollis, J. M., S. Takai, D. J. Adams, S. Horibe and S. L. Woo (1991). "The effects of knee motion and external loading on the length of the anterior cruciate ligament (ACL): a kinematic study." Journal of Biomechanical Engineering **113**(2): 208-14.

Hong Kong Amateur Athletic Association (2010). "Event history of Standard Chartered Hong Kong Marathon."

Hong Kong Department of Health (2010). "Injury Survey 2008."

Houck, J. and H. J. Yack (2001). "Giving way event during a combined stepping and crossover cutting task in an individual with anterior cruciate ligament deficiency." Journal of Orthopaedic and Sports Physical Therapy **31**(9): 481-9; discusssion 490-5.

Houck, J. R., K. E. De Haven and M. Maloney (2007). "Influence of anticipation on movement patterns in subjects with ACL deficiency classified as noncopers." Journal of Orthopaedic and Sports Physical Therapy **37**(2): 56-64.

Hsu, W. H., J. A. Fisk, Y. Yamamoto, R. E. Debski and S. L. Woo (2006). "Differences in torsional joint stiffness of the knee between genders: a human cadaveric study." American Journal of Sports Medicine **34**(5): 765-70.

Hufner, T., R. Meller, D. Kendoff, J. Zeichen, B. A. Zelle, F. H. Fu and C. Krettek (2005). "The role of navigation in knee surgery and evaluation of three-dimensional knee kinematics." Operative Techniques in Orthopaedics **15**(1): 64-69.

Hughes, G. and J. Watkins (2006). "A risk-factor model for anterior cruciate ligament injury." Sports Medicine **36**(5): 411-28.

Hughston, J. C. and K. E. Jacobson (1985). "Chronic posterolateral rotatory instability of the knee." Journal of Bone and Joint Surgery - American Volume **67**(3): 351-9.

Hurd, W. J. and L. Snyder-Mackler (2007). "Knee instability after acute ACL rupture affects movement patterns during the mid-stance phase of gait." Journal of Orthopaedic Research **25**(10): 1369-77.

Ingram, J. G., S. K. Fields, E. E. Yard and R. D. Comstock (2008). "Epidemiology of knee injuries among boys and girls in US high school athletics." American Journal of Sports Medicine **36**(6): 1116-22.

Irrgang, J. J., A. F. Anderson, A. L. Boland, C. D. Harner, M. Kurosaka, P. Neyret, J. C. Richmond and K. D. Shelborne (2001). "Development and validation of the international knee documentation committee subjective knee form." American Journal of Sports Medicine **29**(5): 600-13.

Ishibashi, Y., E. Tsuda, A. Fukuda, H. Tsukada and S. Toh (2008). "Intraoperative biomechanical evaluation of anatomic anterior cruciate ligament reconstruction using a navigation system: comparison of hamstring tendon and bone-patellar tendon-bone graft." American Journal of Sports Medicine **36**(10): 1903-12.

Ishibashi, Y., E. Tsuda, K. Tazawa, H. Sato and S. Toh (2005). "Intraoperative evaluation of the anatomical double-bundle anterior cruciate ligament reconstruction with the OrthoPilot navigation system." Orthopedics **28**(10 Suppl): s1277-82.

Ishibashi, Y., E. Tsuda, Y. Yamamoto, H. Tsukada and S. Toh (2009). "Navigation evaluation of the pivot-shift phenomenon during double-bundle anterior cruciate ligament reconstruction: is the posterolateral bundle more important?" Arthroscopy **25**(5): 488-95.

Jarvela, T. (2007). "Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective, randomize clinical study." Knee Surgery, Sports Traumatology, Arthroscopy **15**(5): 500-7.

Johannsen, H. V., T. Lind, B. W. Jakobsen and K. Kroner (1989). "Exercise-induced knee joint laxity in distance runners." British Journal of Sports Medicine **23**(3): 165-8.

Jonsson, H. and J. Karrholm (1990). "Brace effects on the unstable knee in 21 cases. A roentgen stereophotogrammetric comparison of three designs." Acta Orthopaedica Scandinavica **61**(4): 313-8.

Jonsson, T., B. Althoff, L. Peterson and P. Renstrom (1982). "Clinical diagnosis of ruptures of the anterior cruciate ligament: a comparative study of the Lachman test and the anterior drawer sign." American Journal of Sports Medicine **10**(2): 100-2.

Kanamori, A., J. Zeminski, T. W. Rudy, G. Li, F. H. Fu and S. L. Woo (2002). "The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test." Arthroscopy **18**(4): 394-8.

Kanaya, A., M. Ochi, M. Deie, N. Adachi, M. Nishimori and A. Nakamae (2009). "Intraoperative evaluation of anteroposterior and rotational stabilities in anterior cruciate ligament reconstruction: lower femoral tunnel placed single-bundle versus double-bundle reconstruction." Knee Surgery, Sports Traumatology, Arthroscopy **17**(8): 907-13.

Kaneda, Y., H. Moriya, K. Takahashi, Y. Shimada and T. Tamaki (1997). "Experimental study on external tibial rotation of the knee." American

Journal of Sports Medicine **25**(6): 796-800.

Karlsson, J. (2010). "ACL injuries: unanswered questions--are there any solutions?" Knee Surgery, Sports Traumatology, Arthroscopy **18**(3): 275-6.

Karlsson, J. (2010). "Anatomy is the key." Knee Surgery, Sports Traumatology, Arthroscopy **18**(1): 1.

Karrholm, J., L. G. Elmqvist, G. Selvik and L. I. Hansson (1989). "Chronic anterolateral instability of the knee. A roentgen stereophotogrammetric evaluation." American Journal of Sports Medicine **17**(4): 555-63.

Kendoff, D., R. Meller, M. Citak, A. Pearle, S. Marquardt, C. Krettek and T. Hufner (2007). "Navigation in ACL reconstruction - comparison with conventional measurement tools." Technology and Health Care **15**(3): 221-30.

Klass, D., A. P. Toms, R. Greenwood and P. Hopgood (2007). "MR imaging of acute anterior cruciate ligament injuries." Knee **14**(5): 339-47.

Knowles, S. B., S. W. Marshall, T. Miller, R. Spicer, J. M. Bowling, D. Loomis, R. W. Millikan, J. Yang and F. O. Mueller (2007). "Cost of injuries from a prospective cohort study of North Carolina high school athletes." Injury Prevention **13**(6): 416-21.

Knutzen, K. M., B. T. Bates, P. Schot and J. Hamill (1987). "A biomechanical analysis of two functional knee braces." Medicine and Science in Sports and Exercise **19**(3): 303-9.

Kocher, M. S., J. R. Steadman, K. K. Briggs, W. I. Sterett and R. J. Hawkins (2004). "Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction." American Journal of Sports Medicine **32**(3): 629-34.

Koga, H., A. Nakamae, Y. Shima, J. Iwasa, G. Myklebust, L. Engebretsen, R. Bahr and T. Krosshaug (2010). "Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball." American Journal of Sports Medicine **38**(11): 2218-25.

Koh, J. (2005). "Computer-assisted navigation and anterior cruciate ligament reconstruction: accuracy and outcomes." Orthopedics **28**(10 Suppl): S1283-7.

Kondo, E., A. M. Merican, K. Yasuda and A. A. Amis (2010). "Biomechanical comparisons of knee stability after anterior cruciate ligament reconstruction between 2 clinically available transtibial procedures: anatomic double bundle versus single bundle." American Journal of Sports Medicine **38**(7): 1349-58.

Kondo, E., K. Yasuda, H. Azuma, Y. Tanabe and T. Yagi (2008). "Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients."

American Journal of Sports Medicine 36(9): 1675-87.

Kopf, S., V. Musahl, S. Tashman, M. Szczodry, W. Shen and F. H. Fu (2009). "A systematic review of the femoral origin and tibial insertion morphology of the ACL." Knee Surgery, Sports Traumatology, Arthroscopy 17(3): 213-9.

Krosshaug, T., J. R. Slauterbeck, L. Engebretsen and R. Bahr (2007). "Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences." Scandinavian Journal of Medicine and Science in Sports 17(5): 508-19.

Krudwig, W. K., U. Witzel and K. Ullrich (2002). "Posterolateral aspect and stability of the knee joint. II. Posterolateral instability and effect of isolated and combined posterolateral reconstruction on knee stability: a biomechanical study." Knee Surgery, Sports Traumatology, Arthroscopy 10(2): 91-5.

Kubo, S., H. Muratsu, S. Yoshiya, K. Mizuno and M. Kurosaka (2007). "Reliability and usefulness of a new in vivo measurement system of the pivot shift." Clinical Orthopaedics and Related Research 454: 54-58.

Kumar, A., S. Jones and D. R. Bickerstaff (1999). "Posterolateral reconstruction of the knee: a tunnel technique for proximal fixation." Knee 6(4): 257-260.

Kvist, J. (2004). "Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation." Sports Medicine 34(4): 269-80.

Lam, S. J. S. (1968). "Reconstruction of the anterior cruciate ligament using the Jones Procedure and its Guy's Hospital Modification." Journal of Bone and Joint Surgery - American Volume 50(6): 1213-1224.

Landry, S. C., K. A. McKean, C. L. Hubley-Kozey, W. D. Stanish and K. J. Deluzio (2007). "Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver." American Journal of Sports Medicine 35(11): 1888-900.

LaPrade, R., B. Konowalchuk and F. Wentorf (2002). "Posterolateral corner injuries." Monograph Series: Multiple Ligamentous Injuries of the Knee in the Athlete: 53-71.

Laprade, R. F., L. Engebretsen, S. Johansen, F. A. Wentorf and C. Kurtenbach (2008). "The effect of a proximal tibial medial opening wedge osteotomy on posterolateral knee instability: a biomechanical study." American Journal of Sports Medicine 36(5): 956-60.

LaPrade, R. F., S. Johansen, F. A. Wentorf, L. Engebretsen, J. L. Esterberg and A. Tso (2004). "An analysis of an anatomical posterolateral knee reconstruction: an in vitro biomechanical study and development of a surgical technique.[see comment]." American Journal of Sports Medicine 32(6): 1405-14.

LaPrade, R. F., C. Muench, F. Wentorf and J. L. Lewis (2002). "The effect of injury to the posterolateral structures of the knee on force in a posterior cruciate ligament graft: a biomechanical study." American Journal of Sports Medicine 30(2): 233-8.

LaPrade, R. F. and F. Wentorf (2002). "Diagnosis and treatment of posterolateral knee injuries." Clinical Orthopaedics and Related Research(402): 110-21.

LaPrade, R. F., F. A. Wentorf, E. J. Olson and C. S. Carlson (2006). "An in vivo injury model of posterolateral knee instability." American Journal of Sports Medicine 34(8): 1313-21.

Larson, R., J. Sidles and T. Beals (1996). "Isometry of the lateral collateral and popliteofibular ligaments and a technique for reconstruction." University of Washington Orthopedic Research Report: 42–44.

Leadbeater, B., S. Babul, M. Jansson, G. Scime and I. Pike (2010). "Youth injuries in British Columbia: type, settings, treatment and costs, 2003-2007." International Journal of Injury Control and Safety Promotion 17(2): 119-27.

Leven, H. (1978). "Radiologic determination of rotational instability of the knee joint." Acta Radiologica: Diagnosis 19(4): 599-608.

Li, G., T. J. Gill, L. E. DeFrate, S. Zayontz, V. Glatt and B. Zarins (2002). "Biomechanical consequences of PCL deficiency in the knee under simulated muscle loads--an in vitro experimental study." Journal of Orthopaedic Research 20(4): 887-92.

Li, G., R. Papannagari, L. E. DeFrate, J. D. Yoo, S. E. Park and T. J. Gill (2006). "Comparison of the ACL and ACL graft forces before and after ACL reconstruction: an in-vitro robotic investigation." Acta Orthopaedica Scandinavica 77(2): 267-74.

Li, G., R. Papannagari, M. Li, J. Bingham, K. W. Nha, D. Allred and T. Gill (2008). "Effect of posterior cruciate ligament deficiency on in vivo translation and rotation of the knee during weightbearing flexion." American Journal of Sports Medicine 36(3): 474-9.

Lie, D. T., A. M. Bull and A. A. Amis (2007). "Persistence of the mini pivot shift after anatomically placed anterior cruciate ligament reconstruction." Clinical Orthopaedics and Related Research 457: 203-9.

Logerstedt, D. S., L. Snyder-Mackler, R. C. Ritter and M. J. Axe (2010). "Knee pain and mobility impairments: meniscal and articular cartilage lesions." Journal of Orthopaedic and Sports Physical Therapy 40(6): A1-A35.

Lohmander, L. S., P. M. Englund, L. L. Dahl and E. M. Roos (2007). "The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis." American Journal of Sports Medicine 35(10): 1756-69.

Lorbach, O., P. Wilmes, S. Maas, T. Zerbe, L. Busch, D. Kohn and R. Seil (2009). "A non-invasive device to objectively measure tibial rotation: verification of the device." Knee Surgery, Sports Traumatology, Arthroscopy 17(7): 756-62.

Lorbach, O., P. Wilmes, D. Theisen, M. Brockmeyer, S. Maas, D. Kohn and R. Seil (2009). "Reliability testing of a new device to measure tibial rotation." Knee Surgery, Sports Traumatology, Arthroscopy 17(8): 920-6.

Louie, J. K. and C. D. Mote, Jr. (1987). "Contribution of the musculature to rotatory laxity and torsional stiffness at the knee." Journal of Biomechanics 20(3): 281-300.

Louw, Q. A., J. Manilall and K. A. Grimmer (2008). "Epidemiology of knee injuries among adolescents: a systematic review." British Journal of Sports Medicine 42(1): 2-10.

Lubowitz, J. H., B. J. Bernardini and J. B. Reid, 3rd (2008). "Current concepts review: comprehensive physical examination for instability of the knee." American Journal of Sports Medicine 36(3): 577-94.

Lundberg, M. and K. Messner (1994). "Decrease in valgus stiffness after medial knee ligament injury. A 4-year clinical and mechanical follow-up study in 38 patients." Acta Orthopaedica Scandinavica 65(6): 615-9.

Mae, T., K. Shino, T. Miyama, H. Shinjo, T. Ochi, H. Yoshikawa and H. Fujie (2001). "Single- versus two-femoral socket anterior cruciate ligament reconstruction technique: Biomechanical analysis using a robotic simulator." Arthroscopy 17(7): 708-16.

Majewski, M., H. Susanne and S. Klaus (2006). "Epidemiology of athletic knee injuries: A 10-year study." Knee 13(3): 184-8.

Mann, B. J., W. A. Grana, P. A. Indelicato, D. F. O'Neill and S. Z. George (2007). "A survey of sports medicine physicians regarding psychological issues in patient-athletes." American Journal of Sports Medicine 35(12): 2140-7.

Mannel, H., F. Marin, L. Claes and L. Durselen (2004). "Anterior cruciate ligament rupture translates the axes of motion within the knee." Clinical Biomechanics 19(2): 130-5.

Marchi, A. G., D. Di Bello, G. Messi and G. Gazzola (1999). "Permanent sequelae in sports injuries: a population based study." Archives of Disease in Childhood 81(4): 324-8.

Markolf, K. L., S. R. Jackson and D. R. McAllister (2010). "A comparison of 11 o'clock versus oblique femoral tunnels in the anterior cruciate ligament-reconstructed knee: knee kinematics during a simulated pivot test." American Journal of Sports Medicine 38(5): 912-7.

Marshall, S. W. and K. M. Guskiewicz (2003). "Sports and recreational injury: the hidden cost of a healthy lifestyle." Injury Prevention 9(2): 100-2.

Martelli, S., S. Zaffagnini, S. Bignozzi, M. Bontempi and M. Marcacci (2006). "Validation of a new protocol for computer-assisted evaluation of kinematics of double-bundle ACL reconstruction." Clinical Biomechanics **21**(3): 279-87.

Martelli, S., S. Zaffagnini, S. Bignozzi, N. Lopomo and M. Marcacci (2007). "Description and validation of a navigation system for intra-operative evaluation of knee laxity." Computer Aided Surgery **12**(3): 181-8.

Martins, C. A. Q., E. J. Kropf, W. Shen, C. F. van Eck and F. H. Fu (2009). "The Concept of Anatomic Anterior Cruciate Ligament Reconstruction." Operative Techniques in Sports Medicine **16**(3): 104-115.

Matsumoto, H. (1990). "Mechanism of the pivot shift." Journal of Bone and Joint Surgery - British Volume **72**(5): 816-21.

McCarthy, M., L. Camarda, C. A. Wijdicks, S. Johansen, L. Engebretsen and R. F. Laprade (2010). "Anatomic posterolateral knee reconstructions require a popliteofibular ligament reconstruction through a tibial tunnel." American Journal of Sports Medicine **38**(8): 1674-81.

Meredick, R. B., K. J. Vance, D. Appleby and J. H. Lubowitz (2008). "Outcome of single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a meta-analysis." American Journal of Sports Medicine **36**(7): 1414-21.

Miura, K., Y. Ishibashi, E. Tsuda, A. Fukuda, H. Tsukada and S. Toh (2010). "Intraoperative comparison of knee laxity between anterior cruciate ligament-reconstructed knee and contralateral stable knee using navigation system." Arthroscopy **26**(9): 1203-11.

Moisala, A. S., T. Jarvela, P. Kannus and M. Jarvinen (2007). "Muscle strength evaluations after ACL reconstruction." International Journal of Sports Medicine **28**(10): 868-72.

Moller, E., L. Weidenhielm and S. Werner (2009). "Outcome and knee-related quality of life after anterior cruciate ligament reconstruction: a long-term follow-up." Knee Surgery, Sports Traumatology, Arthroscopy **17**(7): 786-94.

Monaco, E., L. Labianca, B. Maestri, A. De Carli, F. Conteduca and A. Ferretti (2009). "Instrumented measurements of knee laxity: KT-1000 versus navigation." Knee Surgery, Sports Traumatology, Arthroscopy **17**(6): 617-21.

Mueller, C. A., C. Eingartner, E. Schreitmueller, S. Rupp, J. Goldhahn, F. Schuler, K. Weise, U. Pfister and N. P. Suedkamp (2005). "Primary stability of various forms of osteosynthesis in the treatment of fractures of the proximal tibia." Journal of Bone and Joint Surgery - British Volume **87**(3): 426-32.

Muller, W. (1983). Form, function, and ligament reconstruction. The knee. Berlin, Springer.

Musahl, V., K. M. Bell, A. G. Tsai, R. S. Costic, R. Allaire, T. Zantop, J. J. Irrgang and F. H. Fu (2007). "Development of a simple device for measurement of rotational knee laxity." Knee Surgery, Sports Traumatology, Arthroscopy

15(8): 1009-12.

Musahl, V. and F. H. Fu (2010). "Influence of the anteromedial and posterolateral bundles of the anterior cruciate ligament on external and internal tibiofemoral rotation." American Journal of Sports Medicine **38**(9): NP1; author reply NP1-2.

Myer, G. D., M. V. Paterno, K. R. Ford, C. E. Quatman and T. E. Hewett (2006). "Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase." Journal of Orthopaedic and Sports Physical Therapy **36**(6): 385-402.

Myklebust, G. and R. Bahr (2005). "Return to play guidelines after anterior cruciate ligament surgery." British Journal of Sports Medicine **39**(3): 127-31.

Nau, T., Y. Chevalier, N. Hagemeister, J. A. Deguise and N. Duval (2005). "Comparison of 2 surgical techniques of posterolateral corner reconstruction of the knee." American Journal of Sports Medicine **33**(12): 1838-45.

Nau, T., Y. Chevalier, N. Hagemeister, N. Duval and J. A. deGuise (2005). "3D kinematic in-vitro comparison of posterolateral corner reconstruction techniques in a combined injury model." Knee Surgery, Sports Traumatology, Arthroscopy **13**(7): 572-80.

Nielsen, S. and P. Helmig (1986). "The static stabilizing function of the popliteal tendon in the knee. An experimental study." Archives of Orthopaedic and Traumatic Surgery **104**(6): 357-62.

Nielsen, S., J. Ovesen and O. Rasmussen (1985). "The posterior cruciate ligament and rotatory knee instability. An experimental study." Archives of Orthopaedic and Traumatic Surgery **104**(1): 53-6.

Nielsen, S., O. Rasmussen, J. Ovesen and K. Andersen (1984). "Rotatory instability of cadaver knees after transection of collateral ligaments and capsule." Archives of Orthopaedic and Traumatic Surgery **103**(3): 165-9.

Norwood, L. A. and M. J. Cross (1979). "Anterior cruciate ligament: functional anatomy of its bundles in rotatory instabilities." American Journal of Sports Medicine **7**(1): 23-6.

Noyes, F. R. (2010). "Noyes' Knee Disorders: Surgery, Rehabilitation, Clinical Outcomes." Saunders, an imprint of Elsevier Inc.: 48.

Noyes, F. R., E. S. Grood, D. L. Butler and M. Malek (1980). "Clinical laxity tests and functional stability of the knee: biomechanical concepts." Clinical Orthopaedics and Related Research(146): 84-9.

Orchard, J. and W. Hoskins (2007). "For debate: consensus injury definitions in team sports should focus on missed playing time." Clinical Journal of Sport Medicine **17**(3): 192-6.

Ostrowski, J. A. (2006). "Accuracy of 3 diagnostic tests for anterior cruciate ligament tears." Journal of Athletic Training **41**(1): 120-1.

Papannagari, R., T. J. Gill, L. E. Defrate, J. M. Moses, A. J. Petruska and G. Li (2006). "In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation." American Journal of Sports Medicine **34**(12): 2006-12.

Park, H. S., N. A. Wilson and L. Q. Zhang (2008). "Gender differences in passive knee biomechanical properties in tibial rotation." Journal of Orthopaedic Research **26**(7): 937-44.

Pearle, A. D., D. J. Solomon, T. Wanich, A. Moreau-Gaudry, C. C. Granchi, T. L. Wickiewicz and R. F. Warren (2007). "Reliability of navigated knee stability examination: a cadaveric evaluation." American Journal of Sports Medicine **35**(8): 1315-20.

Petersen, W. and T. Zantop (2007). "Anatomy of the anterior cruciate ligament with regard to its two bundles." Clinical Orthopaedics and Related Research **454**: 35-47.

Picard, F., A. M. DiGioia, J. Moody, V. Martinek, F. H. Fu, M. Rytel, C. Nikou, R. S. LaBarca and B. Jaramaz (2001). "Accuracy in tunnel placement for ACL reconstruction. Comparison of traditional arthroscopic and computer-assisted navigation techniques." Computer Aided Surgery **6**(5): 279-89.

Plaweski, S., J. Cazal, P. Rosell and P. Merloz (2006). "Anterior cruciate ligament reconstruction using navigation: a comparative study on 60 patients." American Journal of Sports Medicine **34**(4): 542-52.

Pollard, C. D., S. M. Sigward and C. M. Powers (2007). "Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver." Clinical Journal of Sport Medicine **17**(1): 38-42.

Quigley, F. (2000). "A survey of the causes of sudden death in sport in the Republic of Ireland." British Journal of Sports Medicine **34**(4): 258-61.

Reinschmidt, C., A. J. van den Bogert, B. M. Nigg, A. Lundberg and N. Murphy (1997). "Effect of skin movement on the analysis of skeletal knee joint motion during running." Journal of Biomechanics **30**(7): 729-32.

Risberg, M. A. and A. Ekeland (1994). "Assessment of functional tests after anterior cruciate ligament surgery." Journal of Orthopaedic and Sports Physical Therapy **19**(4): 212-7.

Ristanis, S., N. Stergiou, K. Patras, H. S. Vasiliadis, G. Giakas and A. D. Georgoulis (2005). "Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction." Arthroscopy **21**(11): 1323-9.

Robinson, J. R., A. M. Bull, R. R. Thomas and A. A. Amis (2006). "The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity." American Journal of Sports Medicine 34(11): 1815-23.

Rudy, T. W., G. A. Livesay, S. L. Woo and F. H. Fu (1996). "A combined robotic/universal force sensor approach to determine in situ forces of knee ligaments." Journal of Biomechanics 29(10): 1357-60.

Sallis, R. E. (2009). "Exercise is medicine and physicians need to prescribe it!" British Journal of Sports Medicine 43(1): 3-4.

Samuelson, M., L. F. Draganich, X. Zhou, P. Krumins and B. Reider (1996). "The effects of knee reconstruction on combined anterior cruciate ligament and anterolateral capsular deficiencies." American Journal of Sports Medicine 24(4): 492-7.

Scarvell, J. M., P. N. Smith, K. M. Refshauge, H. Galloway and K. Woods (2005). "Comparison of kinematics in the healthy and ACL injured knee using MRI." Journal of Biomechanics 38(2): 255-62.

Schechinger, S. J., B. A. Levy, K. A. Dajani, J. P. Shah, D. A. Herrera and R. G. Marx (2009). "Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner." Arthroscopy 25(3): 232-42.

Scholtes, V. A., C. B. Terwee and R. W. Poolman (in press). "What makes a measurement instrument valid and reliable?" Injury.

Schuster, A. J., M. J. McNicholas, S. W. Wachtl, D. W. McGurty and R. P. Jakob (2004). "A new mechanical testing device for measuring anteroposterior knee laxity." American Journal of Sports Medicine 32(7): 1731-5.

Scopp, J. M., L. E. Jasper, S. M. Belkoff and C. T. Moorman, 3rd (2004). "The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts." Arthroscopy 20(3): 294-9.

Seebacher, J. R., A. E. Inglis, J. L. Marshall and R. F. Warren (1982). "The structure of the posterolateral aspect of the knee." Journal of Bone and Joint Surgery - American Volume 64(4): 536-41.

Sekiya, J. K. and C. A. Kurtz (2005). "Posterolateral corner reconstruction of the knee: surgical technique utilizing a bifid Achilles tendon allograft and a double femoral tunnel." Arthroscopy 21(11): 1400.

Sekiya, J. K., D. R. Whiddon, C. T. Zehms and M. D. Miller (2008). "A clinically relevant assessment of posterior cruciate ligament and posterolateral corner injuries. Evaluation of isolated and combined deficiency." Journal of Bone and Joint Surgery - American Volume 90(8): 1621-7.

Sell, T. C., C. M. Ferris, J. P. Abt, Y. S. Tsai, J. B. Myers, F. H. Fu and S. M. Lephart (2006). "The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism." American Journal of Sports Medicine 34(1): 43-54.

Shafizadeh, S., H. J. Huver, S. Grote, J. Hoeher, T. Paffrath, T. Tiling and B. Bouillon (2005). "Principles of fluoroscopic-based navigation in anterior cruciate ligament reconstruction." Operative Techniques in Orthopaedics **15**(1): 70-75.

Shahane, S. A., C. Ibbotson, R. Strachan and D. R. Bickerstaff (1999). "The popliteofibular ligament. An anatomical study of the posterolateral corner of the knee." Journal of Bone and Joint Surgery - British Volume **81**(4): 636-42.

Shelbourne, K. D. and P. Nitz (1990). "Accelerated rehabilitation after anterior cruciate ligament reconstruction." American Journal of Sports Medicine **18**(3): 292-9.

Shelburne, K. B., M. R. Torry and M. G. Pandy (2005). "Effect of muscle compensation on knee instability during ACL-deficient gait." Medicine and Science in Sports and Exercise **37**(4): 642-8.

Shephard, R. J. (2003). "Can we afford to exercise, given current injury rates?" Injury Prevention **9**(2): 99-100.

Shoemaker, S. C. and K. L. Markolf (1982). "In vivo rotatory knee stability. Ligamentous and muscular contributions." Journal of Bone and Joint Surgery - American Volume **64**(2): 208-16.

Shoemaker, S. C. and K. L. Markolf (1985). "Effects of joint load on the stiffness and laxity of ligament-deficient knees. An in vitro study of the anterior cruciate and medial collateral ligaments." Journal of Bone and Joint Surgery - American Volume **67**(1): 136-46.

Shultz, S. J. and R. J. Schmitz (2009). "Effects of transverse and frontal plane knee laxity on hip and knee neuromechanics during drop landings." American Journal of Sports Medicine **37**(9): 1821-30.

Shultz, S. J., Y. Shimokochi, A. D. Nguyen, R. J. Schmitz, B. D. Beynnon and D. H. Perrin (2007). "Measurement of varus-valgus and internal-external rotational knee laxities in vivo--Part II: relationship with anterior-posterior and general joint laxity in males and females." Journal of Orthopaedic Research **25**(8): 989-96.

Song, E. K., J. K. Seon, S. J. Park, C. I. Hur and D. S. Lee (2009). "In vivo laxity of stable versus anterior cruciate ligament-injured knees using a navigation system: a comparative study." Knee Surgery, Sports Traumatology, Arthroscopy **17**(8): 941-5.

Spindler, K. P. and R. W. Wright (2008). "Clinical practice. Anterior cruciate ligament tear." New England Journal of Medicine **359**(20): 2135-42.

Stannard, J. P., S. L. Brown, J. T. Robinson, G. McGwin, Jr. and D. A. Volgas (2005). "Reconstruction of the posterolateral corner of the knee." Arthroscopy **21**(9): 1051-9.

Staubli, H. U. and R. P. Jakob (1991). "Anterior knee motion analysis. Measurement and simultaneous radiography." American Journal of Sports Medicine **19**(2): 172-7.

Steckel, H., P. E. Murtha, R. S. Costic, J. E. Moody, B. Jaramaz and F. H. Fu (2007). "Computer evaluation of kinematics of anterior cruciate ligament reconstructions." Clinical Orthopaedics and Related Research **463**: 37-42.

Stengel, D., F. Klufmoller, G. Rademacher, S. Mutze, K. Bauwens, K. Butenschon, J. Seifert, M. Wich and A. Ekkernkamp (2009). "Functional outcomes and health-related quality of life after robot-assisted anterior cruciate ligament reconstruction with patellar tendon grafts." Knee Surgery, Sports Traumatology, Arthroscopy **17**(5): 446-55.

Stoller, D. W., K. L. Markolf, S. A. Zager and S. C. Shoemaker (1983). "The effects of exercise, ice, and ultrasonography on torsional laxity of the knee." Clinical Orthopaedics and Related Research(174): 172-80.

Tashiro, Y., K. Okazaki, H. Miura, S. Matsuda, T. Yasunaga, M. Hashizume, Y. Nakanishi and Y. Iwamoto (2009). "Quantitative assessment of rotatory instability after anterior cruciate ligament reconstruction." American Journal of Sports Medicine **37**(5): 909-16.

Tashman, S., D. Collon, K. Anderson, P. Kolowich and W. Anderst (2004). "Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction." American Journal of Sports Medicine **32**(4): 975-83.

Tashman, S., P. Kolowich, D. Collon, K. Anderson and W. Anderst (2007). "Dynamic function of the ACL-reconstructed knee during running." Clinical Orthopaedics and Related Research **454**: 66-73.

Taylor, W. R., R. M. Ehrig, G. N. Duda, H. Schell, P. Seebeck and M. O. Heller (2005). "On the influence of soft tissue coverage in the determination of bone kinematics using skin markers." Journal of Orthopaedic Research **23**(4): 726-34.

Tegner, Y. and J. Lysholm (1985). "Rating systems in the evaluation of knee ligament injuries." Clinical Orthopaedics and Related Research(198): 43-9.

Thambyah, A., P. Thiagarajan and J. Goh Cho Hong (2004). "Knee joint moments during stair climbing of patients with anterior cruciate ligament deficiency." Clinical Biomechanics **19**(5): 489-96.

Torg, J. S., W. Conrad and V. Kalen (1976). "Clinical diagnosis of anterior cruciate ligament instability in the athlete." American Journal of Sports Medicine **4**(2): 84-93.

Tsai, A. G., V. Musahl, H. Steckel, K. M. Bell, T. Zantop, J. J. Irrgang and F. H. Fu (2008). "Rotational knee laxity: reliability of a simple measurement device in vivo." BMC Musculoskeletal Disorders **9**: 35.

Tsai, A. G., C. A. Wijdicks, M. P. Walsh and R. F. Laprade (2010). "Comparative kinematic evaluation of all-inside single-bundle and double-bundle anterior cruciate ligament reconstruction: a biomechanical study." American Journal of Sports Medicine **38**(2): 263-72.

Tsuda, E., Y. Ishibashi, A. Fukuda, H. Tsukada and S. Toh (2007). "Validation of computer-assisted double-bundle anterior cruciate ligament reconstruction." Orthopedics **30**(10 Suppl): S136-40.

Tsuda, E., Y. Ishibashi, A. Fukuda, H. Tsukada and S. Toh (2009). "Comparable results between lateralized single- and double-bundle ACL reconstructions." Clinical Orthopaedics and Related Research **467**(4): 1042-55.

Tyler, T. F., M. P. McHugh, G. W. Gleim and S. J. Nicholas (1999). "Association of KT-1000 measurements with clinical tests of knee stability 1 year following anterior cruciate ligament reconstruction." Journal of Orthopaedic and Sports Physical Therapy **29**(9): 540-5.

Ullrich, K., W. K. Krudwig and U. Witzel (2002). "Posterolateral aspect and stability of the knee joint. I. Anatomy and function of the popliteus muscle-tendon unit: an anatomical and biomechanical study." Knee Surgery, Sports Traumatology, Arthroscopy **10**(2): 86-90.

US Department of Health and Human Services (1996). "Physical activity and health: a report from the Surgeon General." Atlanta, GA: Centers for Desease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion.

Van de Velde, S. K., T. J. Gill, L. E. DeFrate, R. Papannagari and G. Li (2008). "The effect of anterior cruciate ligament deficiency and reconstruction on the patellofemoral joint." American Journal of Sports Medicine **36**(6): 1150-9.

Vaughan, C. L., B. L. Davis and J. C. O'Conner (1992). Dynamics of Human Gait, Human Kinetics Publishers Champaign.

Veltri, D. M., X. H. Deng, P. A. Torzilli, R. F. Warren and M. J. Maynard (1995). "The role of the cruciate and posterolateral ligaments in stability of the knee. A biomechanical study." American Journal of Sports Medicine **23**(4): 436-43.

Veltri, D. M. and R. F. Warren (1994). "Operative treatment of posterolateral instability of the knee." Clinics in Sports Medicine **13**(3): 615-27.

Waite, J. C., D. J. Beard, C. A. Dodd, D. W. Murray and H. S. Gill (2005). "In vivo kinematics of the ACL-deficient limb during running and cutting." Knee Surgery, Sports Traumatology, Arthroscopy **13**(5): 377-84.

Webster, K. E., J. A. McClelland, J. E. Wittwer, K. Tecklenburg and J. A. Feller (2010). "Three dimensional motion analysis of within and between day repeatability of tibial rotation during pivoting." Knee **17**(5): 329-333.

Whiddon, D. R., C. T. Zehms, M. D. Miller, J. S. Quinby, S. L. Montgomery and J. K.

Sekiya (2008). "Double compared with single-bundle open inlay posterior cruciate ligament reconstruction in a cadaver model." Journal of Bone and Joint Surgery - American Volume **90**(9): 1820-9.

Wojcik, K., R. Nowak and D. Polak (2010). "The value of computed tomography with 3D reconstruction for the diagnosis of pelvic and spine fractures following a sports injury - a case report." Ortop Traumatol Rehabil **12**(5): 459-66.

Wojtys, E. M., S. A. Goldstein, M. Redfern, E. Trier and L. S. Matthews (1987). "A biomechanical evaluation of the Lenox Hill knee brace." Clinical Orthopaedics and Related Research(220): 179-84.

Wojtys, E. M., P. V. Loubert, S. Y. Samson and D. M. Viviano (1990). "Use of a knee-brace for control of tibial translation and rotation. A comparison, in cadavera, of available models.[see comment]." Journal of Bone and Joint Surgery - American Volume **72**(9): 1323-9.

Woo, S. L., S. S. Chan and T. Yamaji (1997). "Biomechanics of knee ligament healing, repair and reconstruction." Journal of Biomechanics **30**(5): 431-9.

Woo, S. L., R. E. Debski, J. D. Withrow and M. A. Janaushek (1999). "Biomechanics of knee ligaments." American Journal of Sports Medicine **27**(4): 533-43.

Woo, S. L. and M. B. Fisher (2009). "Evaluation of knee stability with use of a robotic system." Journal of Bone and Joint Surgery - American Volume **91 Suppl 1**: 78-84.

Woo, S. L., J. M. Hollis, D. J. Adams, R. M. Lyon and S. Takai (1991). "Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation." American Journal of Sports Medicine **19**(3): 217-25.

Woo, S. L., A. Kanamori, J. Zeminski, M. Yagi, C. Papageorgiou and F. H. Fu (2002). "The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon . A cadaveric study comparing anterior tibial and rotational loads." Journal of Bone and Joint Surgery - American Volume **84-A**(6): 907-14.

Woo, S. L. Y., C. Wu, O. Dede, F. Vercillo and S. Noorani (2006). "Biomechanics and anterior cruciate ligament reconstruction." Journal of Orthopaedic Surgery and Research **1**: 2.

Wu, G. and P. R. Cavanagh (1995). "ISB recommendations for standardization in the reporting of kinematic data." Journal of Biomechanics **28**(10): 1257-61.

Yagi, M., R. Kuroda, K. Nagamune, S. Yoshiya and M. Kurosaka (2007). "Double-bundle ACL reconstruction can improve rotational stability." Clinical Orthopaedics and Related Research **454**: 100-107.

Yagi, M., E. K. Wong, A. Kanamori, R. E. Debski, F. H. Fu and S. L. Woo (2002).

"Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction." American Journal of Sports Medicine 30(5): 660-6.

Yamamoto, Y., W. H. Hsu, J. A. Fisk, A. H. Van Scyoc, K. Miura and S. L. Woo (2006). "Effect of the iliotibial band on knee biomechanics during a simulated pivot shift test." Journal of Orthopaedic Research 24(5): 967-73.

Yamamoto, Y., W. H. Hsu, S. L. Woo, A. H. Van Scyoc, Y. Takakura and R. E. Debski (2004). "Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement." American Journal of Sports Medicine 32(8): 1825-32.

Yu, B., S. B. McClure, J. A. Onate, K. M. Guskiewicz, D. T. Kirkendall and W. E. Garrett (2005). "Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task." American Journal of Sports Medicine 33(9): 1356-64.

Zaffagnini, S., D. Bruni, S. Martelli, N. Imakiire, M. Marcacci and A. Russo (2008). "Double-bundle ACL reconstruction: influence of femoral tunnel orientation in knee laxity analysed with a navigation system - an in-vitro biomechanical study." BMC Musculoskeletal Disorders 9: 25.

Zantop, T., M. Herbort, M. J. Raschke, F. H. Fu and W. Petersen (2007). "The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation." American Journal of Sports Medicine 35(2): 223-7.

Zehms, C. T., D. R. Whiddon, M. D. Miller, J. S. Quinby, S. L. Montgomery, R. B. Campbell and J. K. Sekiya (2008). "Comparison of a double bundle arthroscopic inlay and open inlay posterior cruciate ligament reconstruction using clinically relevant tools: a cadaveric study." Arthroscopy 24(4): 472-80.

List of publications

Full-length manuscripts published/accepted in journals/book chapter

1. **Lam MH**, Fong DTP, Yung PSH, Ho EPY, Chan WY, Chan KM (2009). Knee stability assessment on anterior cruciate ligament injury: clinical and biomechanical approaches. Sports Medicine, Arthroscopy, Rehabilitation, Therapy and Technology, 1, 20
2. Ho EPY, **Lam MH**, Chung MML, Fong DTP, Law BKY, Yung PSH, Chan WY, Chan KM (2011). Comparison of two surgical techniques for reconstructing posterolateral corner of the knee - a cadaveric study evaluated by navigation system. Arthroscopy, 27(1):89-96
3. **Lam MH**, Fong DTP, Yung PSH, Ho EPY, Fung KY, Chan KM (2011). Knee rotational stability during pivoting movement is restored after anatomical double bundle anterior cruciate ligament reconstruction. American Journal of Sports Medicine, 39(5):1032-1038
4. **林默涵**、何鴻仁、羅勤業、張熙澤、陳啓明、容樹恆和方迪培 (2009)。前交叉韌帶損傷的膝關節運動學分析。輯於陳啓明著，實用關節鏡手術學 (824-829 頁)。中國：人民衛生出版社

Full-length manuscripts submitted/revision in journals

1. **Lam MH**, Fong DTP, Yung PSH, Chan KM (2nd revision). A systematic review on the biomechanical techniques to evaluate tibial rotation. Knee Surgery, Sports Traumatology, Arthroscopy
2. **Lam MH**, Yung PSH, Fong DTP, Hung ASL, Chan WY, Chan KM (submitted). A biomechanical device to quantify knee rotational laxity: validity and reliability on human specimens. Knee Surgery, Sports Traumatology,

Arthroscopy

3. **Lam MH**, Lai PK, Fong DTP, Yung PSH, Fung KY, Chan KM (in revision). Effect of anticipation on landing maneuver during stop-jumping task. Sports Biomechanics

List of presentations in international and local conferences

1. **Lam MH**, Fong DTP, Yung PSH, Chan KM (2008) Biomechanics techniques to evaluate knee rotational stability. In Proceedings of International Convention on Science Education and Medicine in Sport (vol 1, pp 281), Guangzhou, China. [Aug 1-4, 2008]
2. **Lam MH**, Yung PSH, Chan KM (2008) A biomechanical study of anterior cruciate ligament deficient knee during landing and pivoting movements. In Proceedings of 2nd HKASMSS Student Conference on Sport Medicine, Rehabilitation and Exercise Science (pp. 32), Hong Kong, China [Nov 1, 2008]
3. **Lam MH**, Yung PSH, Fong DTP, Fung KY, Chan KM (2008) Motion analysis to assess knee rotation stability of anterior crucitate ligament deficient knee. Hong Kong Journal of Orthopaedic Surgery, 12(Supp), 122. [Nov 29-30, 2008]
4. Yung PSH, **Lam MH**, Fong DTP, Chan KM (2009) Motion analysis to assess knee rotational stability of anterior cruciate ligament deficient knee, with application in studying the kinematics change of double bundle ACL reconstruction versus single bundle reconstruction. In proceedings of The 7th Biennial ISAKOS Congress (#595), Osaka, Japan. [Apr 5-9, 2009]
5. **Lam MH**, Fong, DTP, Chan KM (2009) Anticipation Effect on knee joint stability during planned and un-planned movement tests in laboratory. Departmental Research Day, Department of Orthopaedics and Traumatology, The Chinese University of Hong Kong, China. [Jun 16, 2009]
6. **Lam MH**, Lai PK, Fong, DTP, Chan KM (2009) Anticipation Effect on knee joint stability during planned and un-planned movement tests in laboratory. In proceedings of XXVII International Symposium on Biomechanics in Sports (pp.232), Limerick, Ireland [Aug 17-21, 2009]

7. Ho EPY, **Lam MH**, Chung MML, Fong DTP, Law BKY, Yung PSH, Chan KM (2009) Comparison of two surgical techniques of posterolateral corner reconstruction of the knee, evaluated by image-free navigation system. Hong Kong Journal of Orthopaedic Surgery, 13(Supp), 77. [Nov 28-29, 2009]

8. **Lam MH**, Lai PK, Fong DTP, Yung PSH, Fung KY, Chan KM (2009). Anticipatory effect on knee kinematics during planned and un-planned stop-jumping tasks. Hong Kong Journal of Orthopaedic Surgery, 13(Supp), 121. [Nov 28-29, 2009].

9. **Lam MH**, Chan KM (2010). Excessive tibial rotation is restored after anatomical double bundle anterior cruciate ligament reconstruction. In Proceedings of The 3rd HKASMSS Student Conference on Sport Medicine, Rehabilitation and Exercise Science (pp. 5-7), Hong Kong, China. [Jun 19, 2010].

10. **Lam MH**, Fong DTP, Yung PSH, Ho EPY, Fung KY, Chan KM (2010). Excessive tibial rotation is improved after anatomical double bundle ACL reconstruction. In Proceedings of the combined 7th Biennial Meeting of Asia-Pacific Orthopaedic Society for Sports Medicine and the 2nd Annual Meeting of Japanese Orthopaedic Society of Knee, Arthroscopy and Sports Medicine (pp. 70), Okinawa, Japan. [Jul 2, 2010].

11. Ho EPY, **Lam MH**, Chung MML, Fong DTP, Law BKY, Yung PSH, Chan KM (2010). Comparison of 2 surgical techniques of posterolateral corner reconstruction. In Proceedings of the combined 7th Biennial Meeting of Asia-Pacific Orthopaedic Society for Sports Medicine and the 2nd Annual Meeting of Japanese Orthopaedic Society of Knee, Arthroscopy and Sports Medicine (pp. 45), Okinawa, Japan. [Jul 2, 2010].

12. **Lam MH**, Fong DTP, Yung PSH, Ho EPY, Fung KY, Chan KM (2010).

Excessive tibial rotation is restored after anatomical double bundle anterior cruciate ligament reconstruction. In Proceedings of XXVIII International Symposium on Biomechanics in Sports (pp. 439), Marquette, USA.

13. **林默涵**、方迪培、容樹恆和陳啓明 (2010)。對雙束前交叉韌帶修復手術後回復多餘的脛骨轉動的研究。第十四屆全國運動生物力學學術交流大會 (pp. 277), 中國濟南. [2010 年 9 月 13 日]
14. **Lam MH**, Yung PSH, Fong DTP, Law BKY, Chan WY, Liao WH, Chan KM (2010). A knee rotational laxity meter to evaluate knee rotational instability. In Proceedings of SMART – Sports Medicine And Rehabilitation Therapy 2010 Convention (pp. 8-9), Hong Kong, China. [Oct 9, 2010].
15. Yung PSH, **Lam MH**, Fong DTP, Chan KM (2010). Knee kinematics before and after anatomical double bundle anterior cruciate ligament reconstruction. In Proceedings of the 30th Annual Congress of The Hong Kong Orthopaedic Association (pp. 97), Hong Kong, China. [Nov 27-28, 2010].

List of research grants

1. Fong DTP, Chan KM, Yung PSH, **Lam MH**. Anticipation effect on knee rotational stability during planned and un-planned movement tests in laboratory. The Chinese University of Hong Kong, Direct Grant for Research, 2008.2.020, HKD34,000

2. Yung PSH, Fong DTP, **Lam MH**, Law BKY, Chan WY, Liao WH, Cheng CK, Chan KM. A knee rotational laxity meter to evaluate knee rotational stability. Innovation Technology Fund, 2009-2010, HKSAR Innovation and Technology Commission, ITS/039/09, HKD999,824; plus Internship Programme, InP/277/09 (HKD226,380), InP/313/09 (HKD214,200)

List of research awards

1. Best Presentation Award, Hong Kong Association of Sports Medicine and Sports Science 2nd Student Conference on Sport Medicine, Rehabilitation and Exercise Science, 2008
2. 1st Runner-up, Vice-Chancellor's Cup of Student Innovation (Postgraduate Individual), The Chinese University of Hong Kong, 2009
3. Scholarship Award, 27th International Conference on Biomechanics in Sport, Ireland, 2009
4. Postgraduate Student Award for Overseas Academic Activities, Graduate School, The Chinese University of Hong Kong, 2009
5. Best Paper Award, Sports Medicine Chapter, The 29th Annual Congress of the Hong Kong Orthopaedic Association, 2009
6. Postgraduate Student Award for Overseas Academic Activities, Graduate School, The Chinese University of Hong Kong, 2010

Appendix A

Comparison of 2 Surgical Techniques for Reconstructing Posterolateral Corner of the Knee: A Cadaveric Study Evaluated by Navigation System

Eric Po-Yan Ho, M.B.Ch.B., M.R.C.S.(Edin), F.R.C.S.(Orth, Edin), F.H.K.A.M., F.H.K.C.O.S., Mak-Ham Lam, B.Ed., Mandy Man-Ling Chung, B.Eng., M.Sc., Daniel Tik-Pui Fong, B.Sc., M.Sc., Ph.D., F.I.S.B.S., Billy Kan-Yip Law, M.B.Ch.B., M.Sc.S.M.H.S.(CUHK), M.R.C.S.(Edin), F.R.C.S.(Orth, Edin), F.H.K.C.O.S., F.H.K.A.M., Patrick Shu-Hang Yung, M.B.Ch.B., F.C.S.H.K., F.R.C.S.(Edin), F.H.K.C.O.S., F.R.C.S.(Orth, Edin), F.H.K.A.M., Wood-Yee Chan, B.Sc., M.Phil., Ph.D., C.Biol., M.I.Biol., and Kai-Ming Chan, M.B.B.S., F.R.C.S.(Edin), F.R.C.P.S.(Glasg), M.Ch.Orth., F.R.C.S.(Orth, Edin), F.A.C.S., F.H.K.A.M., F.H.K.C.O.S., F.C.S.H.K.

Purpose: This study aimed to evaluate the immediate effect on knee kinematics by 2 different techniques of posterolateral corner (PLC) reconstruction. **Methods:** Five intact formalin-preserved cadaveric knees were used in this study. A navigation system was used to measure knee kinematics (posterior translation, varus angulation, and external rotation) after application of a constant force and torque to the tibia. Four different conditions of the knee were evaluated during the biomechanical test: intact knee and PLC-sectioned knee and PLC-reconstructed knee by the double femoral tunnel technique and single femoral tunnel technique. **Results:** Sectioning of the PLC structures resulted in significant increases in external rotation at 30° of flexion from 11.2° (SD, 2.6) to 24.6° (SD, 6.2), posterior translation at 30° of flexion from 3.4 mm (SD, 3.5) to 7.4 mm (SD, 3.8), and varus angulation at 0° of flexion from 2.3° (SD, 2.1) to 7.9° (SD, 4.1). Both reconstruction techniques significantly restored the varus stability. The external rotation and posterior translation at 30° of flexion after reconstruction with the double femoral tunnel technique were 10.2° (SD, 1.3) and 3.4 (SD, 2.7), respectively, which were significantly better than those of the single femoral tunnel technique. **Conclusions:** Both techniques of reconstruction showed improved stability compared with PLC-sectioned knees. The double femoral tunnel technique in PLC reconstruction showed better rotational stability and resistance to posterior translation than the single femoral tunnel technique without compromising varus stability. **Clinical Relevance:** PLC reconstruction by a double femoral tunnel technique achieves better rotational control and resistance to posterior translation.

Posterolateral instability is reported to be a significant disabling condition.[1-3] Failure to recognize posterolateral corner (PLC) injury will lead to failure in reconstructing the anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL).[4-6] Our understanding of the anatomy and biomechanics of the PLC has improved

From the Department of Orthopaedics and Traumatology, Prince of Wales Hospital (E.P-Y.H., M-H.L., M.M-L.C., D.T-P.F., B.K-Y.L., P.S-H.Y., K-M.C.); The Hong Kong Jockey Club Sports Medicine and Health Sciences Centre (E.P-Y.H., M-H.L., M.M-L.C., D.T-P.F., B.K-Y.L., P.S-H.Y., K-M.C.); and School of Biomedical Sciences (W-Y.C.), Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China.
Supported by a grant from The Hong Kong Jockey Club Charities Trust. The authors report no conflict of interest.
Received September 29, 2009; accepted June 4, 2010.
Address correspondence and reprint requests to Daniel Tik-Pui Fong, Department of Orthopaedics and Traumatology, Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, SAR, China. E-mail: dfong@ort.cuhk.edu.hk

0749-8063/09582/$36.00
doi:10.1016/j.arthro.2010.06.006

in the past 2 decades, but the best technique to reconstruct the PLC has not been well established.[illegible]

The anatomy of the PLC is complex, and it is composed of both static and dynamic stabilizers. Previous studies reported that there were 3 primary stabilizers of PLC, including the lateral collateral ligament (LCL), popliteus muscle-tendon unit, and popliteofibular ligament (PFL), which served as the primary restrainers of tibial external rotation maximally at 30° of flexion.[illegible] The LCL was suggested to act as a primary restraint to varus angulation, whereas the PFL and the popliteus were suggested to act as secondary stabilizers to varus angulation. Because most reconstructive methods in the literature aimed to reconstruct the 3 primary stabilizers (LCL, PFL, and popliteus muscle-tendon unit),[6-17] other structures of the PLC were removed to avoid their effect.

Larson et al.[4] described a technique for reconstruction in 1996 that involved the utilization of a free semitendinosus graft as a figure of 8 through a transfibular tunnel and fixation at an isometric point of the LCL and PFL using a screw and washer in the lateral femoral condyle. In previous decades various modifications of the reconstruction technique and development of anatomic reconstruction of PLC were reported.[illegible] Kumar et al.[10] described a technique in 1999 in which a tunnel was drilled in the fibular head and the lateral femoral epicondyle. The PLC structure was reconstructed by use of autogenous tendon graft passing through the tunnels and secured with an interference screw in the lateral epicondyle tunnel. However, residual laxity was reported after PLC reconstruction with this technique.[8] It was suggested that the single isometric femoral tunnel did not address the different insertion sites of the popliteus tendon and LCL. In 2005 Arciero[8] suggested another technique that aimed to provide a more anatomic reconstruction of the PLC by re-creating the insertion sites of the LCL and the popliteus on the femur using a dual femoral socket technique.

The purpose of this study was to compare the immediate effect of the double femoral tunnel technique and single femoral tunnel technique for PLC reconstruction on knee kinematics, by use of an isolated cadaveric injury model. It was hypothesized that the knee kinematics was better restored by the double-femoral tunnel technique.

METHODS

Specimen Preparation

Six intact human cadaveric formalin-preserved knees were used in this study. The specimens were checked by inspection, palpation, and physical examination including the Lachman test and varus/valgus stress test to detect any obvious bony deformity, previous fracture, and ligamentous laxity. One knee was found to have severe degeneration after dissection that was not suitable for the study. Five cadaveric knees were finally used in the experimental test.

For all cadaveric specimens, the femur was sawed at 15 cm above the joint line and the ankle was disarticulated, with the distal tibiofibular joint being kept intact. The skin and muscle 10 cm above and below the joint line were removed, with the interosseous membrane being kept intact. The soft tissue was carefully dissected by a single surgeon while keeping the following structures intact: medial collateral ligament, posteromedial complex, ACL, PCL, popliteus muscle-tendon unit, LCL, PFL, and menisci. Apart from these structures, all other soft tissues were removed including the capsule, patellar tendon, iliotibial band, biceps tendon, and hamstring tendons. The described procedures aimed to minimize the effects of the muscle tone, as well as restraint caused by the capsule, so that the 2 reconstruction techniques were compared in a well-controlled condition.

The dissected knees were put on a custom-made testing apparatus in which the distal femur was rigidly held and that allowed free movement of the tibia and fibula for conducting biomechanical testing. A custom-made 8-mm-diameter intramedullary nail with an adapter over the distal end was inserted from the distal tibia to the shaft of the tibia. Two 4.5-mm shanz screws were inserted to the tibia through 2 locking holes of the intramedullary nail for anchoring the trackers of the navigation system (Fig 1). A torque sensor (Futek Advanced Sensor Technology, Irvine, CA) with accuracy to less than 0.02 Nm was attached to the distal end of the intramedullary nail for application of external rotation torque during the test. Another 2 parallel 4.5-mm shanz screws were inserted over the distal shaft of the femur for anchoring of the trackers of the navigation system.

Testing Protocol

An intraoperative navigation system (BrainLab, Feldkirchen, Germany) was used for measurement of the testing parameters. The BrainLab ACL Reconstruction System, version 2.0, was used to measure the degrees of external rotation and posterior translation, and the BrainLab Total Knee Replacement System, version 2.1, was used to measure varus angulation. For the biomechanical test, constant force and torque

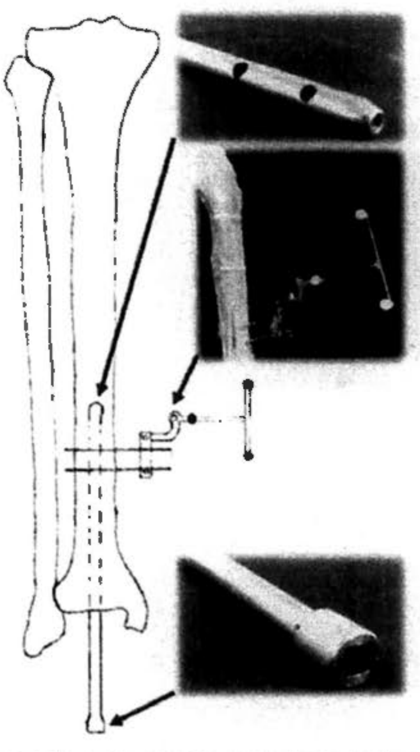


FIGURE 1. Anterior view of line diagram showing that the intramedullary nail was fixed inside the distal tibia by 2 Schanz screws connected with navigation trackers. The distal end of the intramedullary nail was connected to the torque sensor for application of constant torque.

were first applied to the tibia of the intact knee. Testing included anterior and posterior pulling forces of 133 N[17] for measuring anterior-posterior laxity at 30°/90° of flexion and rotational torques of 5 Nm[17] for measuring internal/external rotational laxity and varus/valgus laxity at 30°/90° and 0°/30° of flexion, respectively. The range of motion was guided by the navigation system, which was measured according to the guide pins and trackers inserted.

The popliteus, PFL, and LCL structures of the knee were then sectioned through their midsubstance. The same testing procedures were repeated to document the laxity of the sectioned knee. Two different techniques of PLC reconstruction were performed. In both techniques a formalin-fixed tibialis anterior tendon allograft was harvested from the same leg, and both ends of the tendon were whip-stitched with Ethibond No. 5 suture (Ethicon, Somerville, NJ) for 1.5 cm. The diameter of the 5 tibialis anterior tendon allografts measured 7 mm; thus none of the grafts could pass through the 6-mm graft sizer. During the technique B reconstruction, the 2 whip-stitched ends of the graft measured 9 mm in diameter, which was larger in the middle part of the graft. During graft preparation, only a 9-mm graft sizer would accommodate the passage of both ends together in all specimens. The details of both reconstruction techniques are described in the following section. The same testing procedures were used after each reconstruction.

Surgical Technique

Technique A: Technique A aimed to reconstruct the LCL and PFL in a more anatomic way by creating 2 femoral tunnels according to the footprint of the

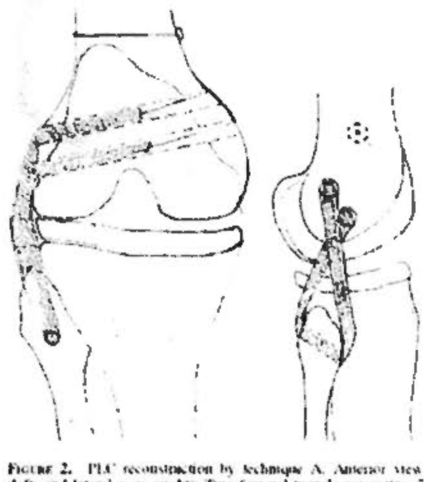


FIGURE 2. PLC reconstruction by technique A. Anterior view (left) and lateral view (right). Two femoral tunnels measuring 7 mm in diameter were created according to the footprint of the LCL and popliteus tendon. The tendon graft was passed through the 7 mm transfibular tunnel, the posterior limb was passed to the popliteofibular tunnel, and the anterior limb was passed over the posterior limb and then through the LCL tunnel toward the medial cortex. It was then fixed by sutures tied around a post created by a 4.5 mm cortical screw with a washer.

LCL and the popliteus tendon as described by Arciero[8] (Fig 2). A 2.4-mm guide pin was inserted anterior and inferior to the fibular insertion of the LCL. It then exited posteromedially to the posterior aspect of the fibular head at the level of the proximal tibiofibular joint. A 7-mm-diameter transfibular tunnel was created by the cannulated reamer. A 2.4-mm guide pin was inserted into the center of the footprint of the LCL over the lateral epicondyle of the femur toward the medial cortex. A 7-mm femoral tunnel was created by use of a cannulated reamer for the reconstruction of the LCL. A popliteofibular tunnel was created after establishment of the tunnel for the LCL by insertion of a 2.4-mm guide pin into the center of the footprint of the popliteus tendon. A 7-mm popliteofibular tunnel was created by the cannulated reamer. The tendon graft was passed through the transfibular tunnel. The posterior limb was passed along the posterior aspect of the proximal tibiofibular joint, through the popliteus hiatus, and then through the popliteofibular tunnel toward the medial cortex. The anterior limb was passed over the posterior limb and then through the LCL tunnel toward the medial cortex. The graft was tensioned at 30° of flexion, internal rotation, and slight valgus. It was then fixed by sutures tied around a post created by a 4.5-mm cortical screw with a washer.

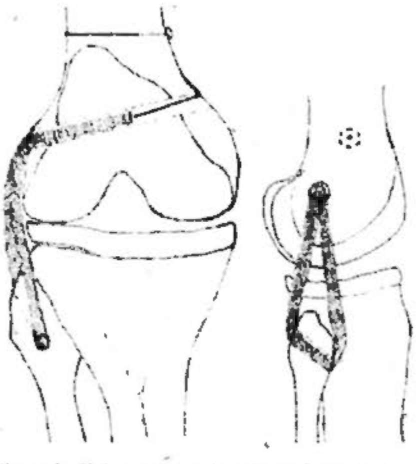


FIGURE 3. PLC reconstruction by technique B. Anterior view (left) and lateral view (right). A single femoral tunnel measuring 9 mm in diameter was created over the lateral epicondyle for the passage of both anterior and posterior limbs of the graft. The graft was fixed by sutures tied around a post.

Technique B: Technique B was the modified Larson technique[17] described by Kumar et al.,[19] which involved the use of a single femoral tunnel for the fixation of both anterior and posterior limbs of the graft (Fig 3). The transfibular tunnel created in technique A was reused. The femoral tunnel over the femoral insertion of the LCL created in technique A was used with the tunnel enlarged to 9 mm in diameter. Graft was passed through the transfibular tunnel, and both anterior and posterior limbs were passed through the femoral tunnel with a whipping suture. The graft was tensioned at a position of 30° of flexion, internal rotation, and slight valgus. The grafts were fixed by sutures tied around a post created by a 4.5-mm cortical screw.

Statistical Analysis

One-way multivariate analysis of variance (ANOVA) with repeated measures was used to examine the difference in all dependent variables. One-way ANOVA with repeated measures was used on each parameter to examine any significant differences between all testing conditions, which included intact knee, sectioned knee, and reconstructed knees. Least-square difference post hoc pairwise comparisons were used between the different conditions. All statistical tests were calculated by statistical analysis software (SPSS software, version 16.0; SPSS, Chicago, IL). The level of significance was set at $P < .05$. Results are presented as mean (SD).

RESULTS

Multivariate ANOVA showed that knee kinematics was significantly affected by the 4 different conditions of the knee ($P < .05$). ANOVA also showed that all dependent variables except posterior translation at 90° of flexion were significantly affected by the 4 conditions of the knee ($P < .05$). The results of the post hoc pairwise comparisons in different conditions of posterior translation, external rotation, and varus angulation are summarized in Table 1.

Posterior Translation

After sectioning of the structures of the PLC, there was a significant increase in posterior translation at 30° of flexion (from 3.4 mm (SD, 1.5) to 7.4 mm (SD, 3.8) after application of a posterior pulling force (Fig 4). After reconstruction of the PLC by

Table 1. *Statistical Results of Different Parameters Comparing 4 Testing Conditions (Intact, Sectioned, Technique A, and Technique B)*

Knee Specimen	I	S	A	B	Statistical Test (ANOVA*/Post Hoc†)
External rotation (°) at 30° of flexion					
1	7.0	17.0	12.0	15.0	
2	12.0	19.0	11.0	12.0	
3	12.0	29.0	10.0	15.0	
4	14.0	27.0	9.0	14.0	
5	11.0	31.0	9.0	16.0	
Mean (SD)	11.2 (2.6)	24.6 (6.2)	10.2 (1.3)	14.4 (1.5)	P < .01 for I v S,‡ S v A,‡ S v B‡ and A v B‡
External rotation (°) at 90° of flexion					
1	6.0	16.0	15.0	16.0	
2	15.0	26.0	20.0	17.0	
3	20.0	36.0	27.0	25.0	
4	17.0	25.0	13.0	20.0	
5	17.0	30.0	19.0	23.0	
Mean (SD)	15.0 (5.3)	26.6 (7.5)	18.8 (5.4)	20.2 (3.8)	P < .01 for I v S,‡ S v A,‡ S v B,‡ and I v B‡
Posterior translation (mm) at 30° of flexion					
1	2.0	4.0	3.0	4.0	
2	3.0	6.0	2.0	5.0	
3	6.0	14.0	8.0	9.0	
4	3.0	6.0	1.0	3.0	
5	3.0	7.0	3.0	4.0	
Mean (SD)	3.4 (1.5)	7.4 (3.8)	3.4 (2.7)	5.0 (2.3)	P < .01 for I v S,‡ S v A,‡ A v B,‡ and I v B‡
Posterior translation (mm) at 90° of flexion					
1	1.0	2.0	3.0	4.0	
2	3.0	5.0	3.0	3.0	
3	9.0	13.0	4.0	4.0	
4	2.0	1.0	0.0	1.0	
5	2.0	4.0	3.0	3.0	
Mean (SD)	3.4 (3.2)	5.0 (4.7)	2.6 (1.5)	3.0 (1.2)	No significant difference
Varus angulation (°) at 0° of flexion					
1	0.0	1.5	1.5	1.5	
2	1.0	4.5	1.5	0.5	
3	2.5	13.0	3.5	1.5	
4	2.5	7.5	0.0	0.5	
5	5.5	13.0	3.5	1.0	
Mean (SD)	2.3 (2.1)	7.9 (5.1)	2.0 (1.5)	1.0 (0.5)	P < .01 for I v S,‡ S v A,‡ and S v B‡
Varus angulation (°) of 30° of flexion					
1	0.5	6.5	4.5	4.0	
2	4.0	9.0	4.0	9.5	
3	5.5	19.5	5.0	6.0	
4	1.0	11.5	1.5	4.5	
5	9.0	17.5	9.5	8.0	
Mean (SD)	4.0 (3.5)	12.8 (5.5)	4.9 (2.9)	6.4 (2.3)	P < .01 for I v S‡ and S v A‡

Abbreviations: I, intact; S, sectioned; A, technique A; B, technique B.
*P value of ANOVA for the 4 conditions.
†Results of least square difference post hoc pairwise comparison.
‡Statistically significant difference.

technique A, there was an improvement at 30° of flexion to 3.4 mm (2.7), which showed a significance difference compared with the sectioned knee (P < .05). There was no significant difference compared with the intact knee (P > .05). Reconstruction of the PLC by technique B decreased posterior translation from 7.4 mm (3.8) to 5.0 mm (2.3) compared with the sectioned knee, which was not significant (P > .05). Moreover, reconstruction by technique B showed an inferior result in resisting

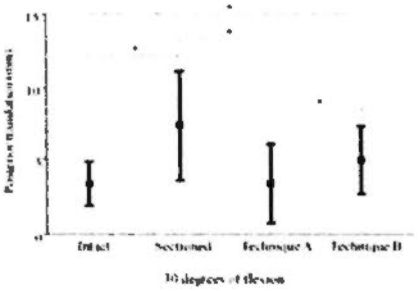


FIGURE 4. Posterior translation (in millimeters) for each tested knee state (intact, sectioned, technique A [double femoral tunnel technique], and technique B [single femoral tunnel technique]) at 30° of flexion. Asterisks indicate a significant difference ($P < .05$).

posterior translation when compared with technique A ($P < .05$).

External Rotation

External rotation of the intact knee was 11.2° (SD, 2.6) and 15.0° (SD, 5.3) at 30° and 90° of flexion, respectively (Fig 5). There was a significant increase in external rotation after sectioning of the PLC structures, which measured 24.6° (SD, 6.2) at 30° of flexion ($P < .05$) and 26.6° (SD, 7.3) at 90° of flexion ($P < .05$). Both PLC reconstruction techniques improved the rotational laxity when compared with the sectioned knee ($P < .05$). Reconstruction by technique A improved external rotation at 30° of flexion from 24.6° (SD, 6.2) to 10.2° (SD, 1.3), which was comparable to the intact knee ($P > .05$). Reconstruction with technique A showed a better result than that of technique B, which measured 14.4° (SD, 1.5) ($P < .05$). There was no significant difference in external rotation at 90° of flexion between technique A and technique B ($P > .05$).

Varus Angulation

At 0° of flexion, varus angulation significantly increased from 2.3° (2.1) to 7.9° (5.1) after sectioning of the structures of the PLC ($P < .05$). Both reconstruction techniques restored varus laxity to 2.0° (1.5) in technique A and 1.0° (0.5) in technique B, with no significant difference between the reconstructed knees and the intact knee ($P > .05$). There was also no significant difference between the 2 reconstruction techniques ($P > .05$). At 30° of flexion, the varus angulation significantly increased from 4.0° (3.5) to 12.8° (5.5) ($P < .01$). After reconstruction by technique A, varus laxity significantly decreased from 12.8° (5.5) to 4.9° (2.9) ($P < .05$). There was no significant difference between the sectioned knee and the reconstructed knees with technique B or between the reconstructed knees with both techniques.

DISCUSSION

Numerous surgical techniques have been proposed in the literature for restoring posterolateral instability, including acute repair, augmentation by the surrounding structures, and reconstruction by use of allograft or autograft. In the 1980s Hughston and Jacobson[illegible] used a lateral gastrocnemius, capsular, LCL, and popliteus advancement procedure that relied on the integrity of the posterolateral structures. However, the result was not satisfactory. Clancy et al.[3] diverted the biceps tendon and fixed it to the lateral femoral condyle by a screw and washer that aimed to reduce the external rotation of the knee, but the PLC function could not be completely restored. Muller[illegible] used a strip of the iliotibial band along the line of the popliteus tendon for a popliteal bypass procedure. The clinical outcomes and the degrees of residual laxity of this technique were not clearly reported.

In the 1990s Larson et al.[illegible] advocated a technique using a free semitendinosus graft as a figure of 8 through a fibular tunnel and around a screw and washer in the lateral femoral condyle to reconstruct the LCL and the PFL. The tunnel technique was

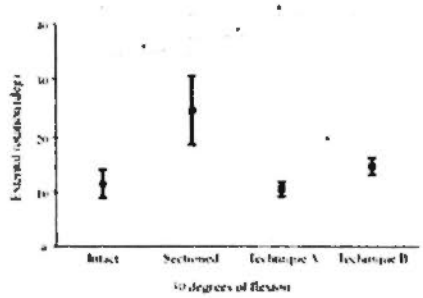


FIGURE 5. External rotation (in degrees) for each tested knee state (intact, sectioned, technique A [double femoral tunnel technique], and technique B [single femoral tunnel technique]) at 30° of flexion. Asterisks indicate a significant difference ($P < .05$).

similar to the technique proposed by Kumar et al., but it was simplified so that the semitendinosus loop formed a triangle and was secured in the lateral epicondyle by use of an interference screw. In 2004 LaPrade et al. described a 2-tail technique that offered a more anatomic reconstruction by adding a tibial tunnel to reconstruct the popliteus, which stressed the reconstruction of the 3 primary stabilizers (popliteus, PFL, and LCL). Nau et al. in 2005 compared the 2-tail technique and the 2-tunnel technique, which was similar to technique A used in our study. It was criticized that the reconstruction by the 2-tunnel technique only stressed the reconstruction of the static stabilizing structures of the PLC. However, both techniques restored the external rotation laxity at 30° and 90° of flexion and varus laxity at 0° and 30° of flexion, which showed no significant difference between the 2 techniques of reconstruction.

The anatomy over the lateral side of the knee was first described in 1982 and was divided into 3 layers from superficial to deep. The biomechanics of the PLC was then studied by sequential sectioning of the various structures in cadavers. From these studies, the LCL was found to be the primary restraint to varus movement. The PFL and popliteus tendon were reported to resist external rotation of the knee. Both the ACL and PCL served as secondary restraints to varus angulation and external rotation. Moreover, the structures of the PLC were considered secondary restraints to posterior translation; our study showed increased posterior translation after sectioning of the PLC structures.

Brinkman et al. quantitatively documented the insertion geometry of the LCL and popliteus tendon and found that the popliteus tendon inserted around 11 mm distally and 0.84 mm either anterior or posterior to the LCL. Therefore it was concluded that the single femoral tunnel technique could not restore the normal anatomy. Our study showed that the single femoral tunnel technique did not completely restore the rotational laxity in the sectioned knee and it was inferior to the double femoral tunnel technique as well. There was no significance difference in external rotation and varus angulation between the intact knee and the reconstructed knee with the double-femoral tunnel technique. The reconstruction with the double-femoral tunnel technique included 2 femoral tunnels with 2 separate limbs of soft-tissue graft to simulate the function of the LCL and PFL, which explained the experimental results of better rotational control. Apart from using tendon graft from the tibialis anterior for reconstruction, the literature has suggested using Achilles tendon allograft or split Achilles tendon allograft for reconstruction of the PLC with the double femoral tunnel technique.

The navigation system developed for ACL reconstruction would assist the surgeon in evaluating anteroposterior translation and rotation displacement at 30° and 90° of flexion. Given the accurate measurements provided by the system, it was used in our study to measure knee kinematics. Another software program in the navigation system (BrainLab Total Knee Replacement System, version 2.1) was used to evaluate the treatment's effect on varus angulation. The real-time changes in knee kinematics presented by the system provided valuable information for the surgeon to examine the intact, sectioned, and reconstructed knees with patients under anesthesia. Therefore the navigation system may be useful in the clinical setting, and this should be further studied.

The cadaveric knees in this study were fixed by formalin, which caused a limitation in the range of motion and the degree of ligament laxity. However, this negative effect was avoided by each specimen serving as its own control. The measurements were conducted in the same knee for 4 conditions including intact knee, sectioned knee, and reconstructed knee with both techniques. Although allograft with the same diameter was used in this study, we would suggest that artificial materials should be used in future studies to control thickness, preservation, and elasticity. Another limitation of this study is that the biomechanical test was not able to fully simulate in vivo conditions. Moreover, the function of the dynamic stabilizers was not addressed in this study. During PLC reconstruction in humans, the anterior limb of the graft is tunneled deep to the biceps femoris tendon insertion and adjacent to the native LCL, but this procedure could not be repeated in this study because the muscle tone of the biceps was absent. Lastly, graft healing and maturation, which are the most important clinical issues, were not investigated. In this study the real physiologic condition could not be simulated, but the tested conditions could be isolated clearly. Therefore the results were reproducible, which facilitated the experiment to determine the differences between the 2 reconstruction techniques.

CONCLUSIONS

Both techniques of PLC reconstruction in this study showed improved stability compared with the PLC-sectioned knee. PLC reconstruction with the double-femoral tunnel technique showed better rotational stability and resistance to posterior translation than the single femoral tunnel technique without compromising varus stability.

Acknowledgment: This research project was made possible by equipment/resources donated by The Hong Kong Jockey Club Charities Trust.

REFERENCES

1. Clancy WG Jr, Shepard MF, Cain EL Jr. Posterior lateral corner reconstruction. *Am J Orthop (Belle Mead NJ)* 2003;32:171-176.
2. LaPrade RF, Wentorf F. Diagnosis and treatment of posterolateral knee injuries. *Clin Orthop Relat Res* 2002:110-121.
3. Covey DC. Injuries of the posterolateral corner of the knee. *J Bone Joint Surg Am* 2001;83:106-118.
4. Gollehon DL, Torzilli PA, Warren RF. The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study. *J Bone Joint Surg Am* 1987;69:233-242.
5. LaPrade R, Konowalchuk B, Wentorf F. Posterolateral corner injuries. In: *Monograph series: Multiple ligamentous injuries of the knee in the athlete*. Rosemont, IL: American Academy of Orthopaedic Surgeons; 2002:53-71.
6. LaPrade RF, Muench C, Wentorf F, Lewis JL. The effect of injury to the posterolateral structures of the knee on force in a posterior cruciate ligament graft: A biomechanical study. *Am J Sports Med* 2002;30:233-238.
7. Seebacher JR, Inglis AE, Marshall JL, Warren RF. The structure of the posterolateral aspect of the knee. *J Bone Joint Surg Am* 1982;64:536-541.
8. Arciero RA. Anatomic posterolateral corner knee reconstruction. *Arthroscopy* 2005;21:1147.
9. Schechinger SJ, Levy BA, Dajani KA, Shah JP, Herrera DA, Marx RG. Achilles tendon allograft reconstruction of the fibular collateral ligament and posterolateral corner. *Arthroscopy* 2009;25:232-242.
10. Veltri DM, Warren RF. Operative treatment of posterolateral instability of the knee. *Clin Sports Med* 1994;13:615-627.
11. Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee. Effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am* 1988;70:88-97.
12. Nielsen S, Helmig P. The static stabilizing function of the popliteal tendon in the knee. An experimental study. *Arch Orthop Trauma Surg* 1986;104:357-362.
13. Nielsen S, Ovesen J, Rasmussen O. The posterior cruciate ligament and rotatory knee instability. An experimental study. *Arch Orthop Trauma Surg* 1985;104:53-56.
14. Nielsen S, Rasmussen O, Ovesen J, Andersen K. Rotatory instability of cadaver knees after transection of collateral ligaments and capsule. *Arch Orthop Trauma Surg* 1984;103:165-169.
15. Shahane SA, Ibbotson C, Strachan R, Bickerstaff DR. The popliteofibular ligament. An anatomical study of the posterolateral corner of the knee. *J Bone Joint Surg Br* 1999;81:636-642.
16. Nau T, Chevalier Y, Hagemeister N, Deguise JA, Duval N. Comparison of 2 surgical techniques of posterolateral corner reconstruction of the knee. *Am J Sports Med* 2005;33:1838-1845.
17. Larson R, Sidles J, Beals T. Isometry of the lateral collateral and popliteofibular ligaments and a technique for reconstruction. In: *University of Washington orthopedic research report*. Seattle, WA: University of Washington, 1996:42-44.
18. LaPrade RF, Johansen S, Wentorf FA, Engebretsen L, Esterberg JL, Tso A. An analysis of an anatomical posterolateral knee reconstruction: An in vitro biomechanical study and development of a surgical technique. *Am J Sports Med* 2004;32:1405-1414.
19. Kumar A, Jones S, Bickerstaff DR. Posterolateral reconstruction of the knee: A tunnel technique for proximal fixation. *Knee* 1999;6:257-260.
20. Fanelli GC, Giannotti BF, Edson CJ. Arthroscopically assisted combined posterior cruciate ligament/posterior lateral complex reconstruction. *Arthroscopy* 1996;12:521-530.
21. Stannard JP, Brown SL, Robinson JT, McGwin G Jr, Volgas DA. Reconstruction of the posterolateral corner of the knee. *Arthroscopy* 2005;21:1051-1059.
22. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. *J Orthop Res* 2004;22:85-89.
23. Hughston JC, Jacobson KE. Chronic posterolateral rotatory instability of the knee. *J Bone Joint Surg Am* 1985;67:351-359.
24. Muller W. *Form, function, and ligament reconstruction. The knee*. Berlin: Springer, 1983.
25. Brinkman JM, Schwering PJ, Blankevoort L, Koolos JG, Luites J, Wymenga AB. The insertion geometry of the posterolateral corner of the knee [published erratum appears in *J Bone Joint Surg Br* 2006;88:847]. *J Bone Joint Surg Br* 2005;87:1364-1368.
26. Sekiya JK, Kurtz CA. Posterolateral corner reconstruction of the knee: Surgical technique utilizing a bifid Achilles tendon allograft and a double femoral tunnel. *Arthroscopy* 2005;21:1400.

Appendix B

Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology

BioMed

Review

Open Access

Knee stability assessment on anterior cruciate ligament injury: Clinical and biomechanical approaches

Mak-Ham Lam[1], Daniel TP Fong*[1,2], Patrick SH Yung[1,2], Eric PY Ho[1], Wood-Yee Chan[3] and Kai-Ming Chan[1,2]

Address: [1]Department of Orthopaedics and Traumatology, Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, PR China, [2]The Hong Kong Jockey Club Sports Medicine and Health Sciences Centre, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, PR China and [3]School of Biomedical Sciences, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, PR China

Email: Mak-Ham Lam - makham_lam@ort.cuhk.edu.hk; Daniel TP Fong* - dtfong@ort.cuhk.edu.hk;
Patrick SH Yung - patrick@ort.cuhk.edu.hk; Eric PY Ho - pyho@ort.cuhk.edu.hk; Wood-Yee Chan - wy.chan@cuhk.edu.hk;
Kai-Ming Chan - kaimingchan@cuhk.edu.hk

* Corresponding author

Published: 27 August 2009

Received: 23 September 2008

Accepted: 27 August 2009

Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology 2009, 1:20 doi:10.1186/1758-2555-1-20

This article is available from: http://www.smarttjournal.com/content/1/1/20

Abstract

Anterior cruciate ligament (ACL) injury is common in knee joint accounting for 40% of sports injury. ACL injury leads to knee instability, therefore, understanding knee stability assessments would be useful for diagnosis of ACL injury, comparison between operation treatments and establishing return-to-sport standard. This article firstly introduces a management model for ACL injury and the contribution of knee stability assessment to the corresponding stages of the model. Secondly, standard clinical examination, intra-operative stability measurement and motion analysis for functional assessment are reviewed. Orthopaedic surgeons and scientists with related background are encouraged to understand knee biomechanics and stability assessment for ACL injury patients.

Introduction

Sports injury is common, ranking the second highest (21%) in terms of cause of injury [1] and leading to long-term disabilities and handicaps especially in patients with knee injuries [2]. Among all sport-related knee injuries, one-fifth (20%) involves the anterior cruciate ligament (ACL) – the most commonly traumatized structure [3]. ACL rupture results in knee instability [4], prohibits the athletes back to sports, and results in early retirement [5]. Conservative treatments can somewhat enhance the sense of stability and rehabilitation, but not in objective outcome assessment [6] and rate of returning to sports [7]. Therefore, operative treatments are often prescribed to reconstruct the ACL in order to restore the knee stability and return the athletes to sports and active lifestyle [8].

Numerous anatomy studies showed that the intact human ACL consists of an anteromedial (AM) bundle, and a posterolateral (PL) bundle [9], while some studies even reported an intermediate bundle in between [10]. Biomechanics studies showed that AM and PL bundles mainly contribute to anterior-posterior and rotational stability of the knee respectively [11,12]. Traditional surgical methods employ a single bundle bone-patellar-tendon-bone or hamstrings autograph, however, the methods provide good resistance to anterior tibial loads but not to rotational loads [13]. Therefore, the unique anatomical and biomechanics characteristics of the two bundles provide a rationale to the recent emerge of anatomical double bundle ACL reconstruction approach [14,15] to better mimic and restore the anatomy and biomechanics of the intact ACL in the reconstructed knee [12]. However, this advantage of rotational stability has not been widely proved on living human

Returning to high level athletic activity is an ultimate goal for patient who undergoes ACL reconstruction. However, standardized and objective criteria to assess athletes' safe return-to-sports are limited. Functional knee stability is proposed to be one of the key factors influencing safe return-to-sports [16]. Before recommending reconstructed patients to return to activity with pre-injury level, good knee stability should be attained when performing similar on-field movements such as stop-jumping and cutting in the laboratory setting. Therefore, functional knee stability evaluated by kinematics assessment definitely provides valuable information on standardization for safe return-to-sports. This article reviews the knee stability assessments for injury diagnosis, treatment evaluation and long term standard for safe return-to-sports for ACL deficient knee. It aims to provide the basic introduction in knee biomechanics and the importance of stability assessments for orthopaedic surgeons, physiotherapists and scientists with related background.

The knee and its movement

The lower extremity is composed of three major joints: the hip joint, the knee joint and the ankle joint. Located in between hip and ankle joint, knee provides balance and transformation of load of body even when we perform a rapid change of speed and direction. Study has shown that unanticipated cutting maneuvers would increase the risk of non-contact knee ligament injury due to the increased external varus/valgus and internal/external rotation moments applied to the knee [17]. Even in straight running, the ground reaction force can be up to three times the body weight [18]. Therefore, being with the function of supporting the entire body weight during stance phase, knee is one of the most vulnerable joints suffering acute injury [19] and long term development of osteoarthritis [20,21].

Anterior cruciate ligament

The anterior cruciate ligament is a band of dense connective tissue which courses from the femur to the tibia [22]. It is a major knee ligament to stabilize the joint movement against anterior tibial translation [23] and rotational loads [24]. While Norwood and Cross [12] in 1979 suggested ACL to have three separate bundles, most anatomical studies [25,26] agreed that AM bundle and PL bundle

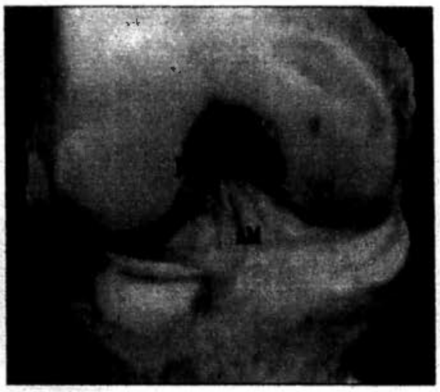


Figure 1
An anterior view of the right knee, showing anterior cruciate ligament with anteromedial (AM) and posterolateral (PL) bundles.

are the only two components of ACL (Figure 1). The AM and PL bundles behave differently in length [27] and in situ force [11] during passive flexion. Due to the different bony orientation attachment [27] of the two bundles, AM and PL bundles are responsible for resisting anterior tibial load and rotational load respectively. Biomechanical study [28] revealed the ultimate load of ACL to failure can be as high as three times of the body weight. Video analysis [29] reported that ACL rupture occurs within 100 ms, indicating a huge explosive force acting to the knee joint during ACL injury.

Biomechanical presentation of knee motion

The knee joint motion is the relative movement between the femur and the tibia. Theoretically, it is capable to a six degree-of-freedom movement: both translation and rotation in three body planes. Clinically, excessive motion in specific direction (anterior-posterior direction) during physical examination may be an indication of knee ligament injury [30]. The result of these assessments is often determined by the subjective feeling and experience of the examiners. Biomechanical presentation of the knee motion, instead, provides precise information for comparison between intact and deficient knee when assessing knee stability. To describe the geometric representation, Grood and Suntay [31] proposed a joint coordinate system for measuring three dimensional translation and rotation motions of the knee joint. This is essential for studying ligament injury as knee ligaments govern the motion of the knee. For example, ACL rupture would lead to excessive motion in AP translation and tibial rotation [22]. In cadaveric study, it is also suggested that an isolated excision of ACL would increase anterior drawer and tibial rotation in both flexion and extension [26]. Therefore, a well understanding of knee kinematics assessments is crucial for the said purpose of this study.

Contribution of knee stability assessment at different stages of ACL injury

Figure 2 shows a management model for ACL injury, starting from sport participation. Most of the ACL injury (approximately 70%) occurs in sport situation [32]. It often appears to occur in competitive sports such as soccer and handball, which involves landing, deceleration and rapid change of direction movements [33]. When injury occurs during sport activity, athlete with ACL rupture is confirmed after an adequate diagnosis by orthopaedic specialist. Either operative or non-operative treatments [34] followed by a rehabilitation program [35] are advised to the injured patients before they can safely return-to-sports [16].

Knee stability assessments contribute three main roles in the management model for ACL injury – (i) clinical assessment provides a quick and reliable way for the diagnosis of ACL injury. (ii) Intra-operative assessment evaluates immediate effect of operative treatment and compares different reconstruction techniques. (iii) functional assessment acts as long-term guidelines during or after rehabilitation program, indicating if the athlete is fully recovered in terms of stability to pre injury activity level. These three main roles are then elaborated in the following sections.

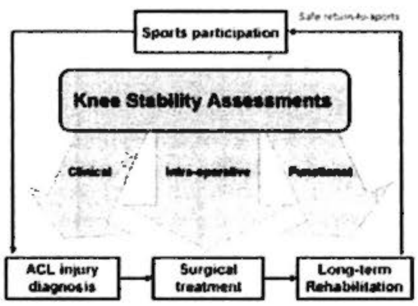


Figure 2
A management model for ACL injury and contribution of knee stability assessment before safe return to sports.

Diagnosis of anterior cruciate ligament injury – clinical assessment

Accurate diagnosis of ACL injury relies on injury history [36], clinical assessment [37] as well as advanced imaging technique [38]. Being different from others, clinical assessment provides a stability evaluation of the injured knee to test if excessive motion exists. It varies considerably within the normal population and a greater motion would be found in hyper-laxity group [39]. It is always recommended to compare the motion of the injured side to the normal side [40] if the patients have unilateral knee injury. The potential limitations should be kept in mind, including the uncontrolled force applied and the reflex resistance of the patient because of anxiety and pain. The first clinical examination after an acute knee trauma is suggested to have a low diagnostic value [41]. Therefore, clinical assessments should be performed by skillful and experienced examiner. Several typical assessments for diagnosing ACL injury are demonstrated below.

Lachman test

Lachman test has a high accuracy for diagnosing ACL injury [42]. Before the test, the examiner should ensure that the tibia is not subluxated posteriorly to avoid false-positive result in a posterior cruciate ligament deficient knee. The patient is asked to lie supine and the knee flexes around 30°. The examiner stabilizes the femur and applies an anterior force on tibia without restraining axial rotation (Figure 3). A positive result of an ACL deficient knee will be presented with proprioceptive or visible anterior translation of the tibia [43]. The anterior translation of 1 mm to 5 mm is defined as grade I laxity, 6 mm to 10 mm as grade II, and greater than 10 mm or without a displacement limit (end point) as grade III [40]. End point is further graded as firm, marginal or soft.

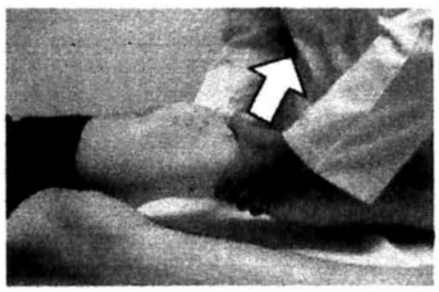


Figure 3
Lachman test.

Pivot shift test

Pivot shift test is relatively complex since it is a combination of internal rotation torque and valgus torque [44]. This test is highly dependent to the technique and experience of the examiner as the result is graded subjectively according to the knee laxity. However, a positive result for the pivot shift test is the best for ruling in an ACL rupture [37]. To perform the test, the basic principle is to apply valgus torque and internal rotation to the leg. The test starts with the knee in full extension and then gently flexed to about 40° (Figure 4). A positive pivot shift test is defined as a forward subluxation of tibia during sudden change in direction. It is a reproduction of event that occurs when the knee gives way because of the loss of ACL.

KT-1000

This is an instrument that has been developed for an objective measurement for knee anterior-posterior laxity on sagittal plane. The patient lies in a supine position with knee flexion of about 20° to 30°, supporting with a firm platform placed proximal to the popliteal space. The patient is told to relax in this position. The KT-1000 arthrometer is then placed above the tibia and attached firmly by two bands. After the zero adjustment, the arthrometer is pulled anteriorly to the tibia in order to provide an anterior force (Figure 5). An audible indication will be noticed at 15, 20 and 30 pounds of force. The anterior displacement is measured in millimeter while the laxity is often presented in side-to-side difference.

Operation treatment evaluation – intra-operative assessment of ACL reconstruction

Computer assisted navigation system

Computer-assisted surgery has gone through lots of evolutions in recent 15 years. One of the technologies for orthopaedic surgery is the navigation system, which has been applied in spine surgery [45] and total joint surgery [46]. It has two basic components for ACL reconstruction:

• A set of optical camera to locate the surgical joint and limb, and to create a picture or image of the operation site

• Computer programs which integrate these images with surgical information and assist the surgeon during the operation.

Navigation systems improve the accuracy of surgical procedures [47]. The computer provides information of the real time relative positions between the instruments and the bone to assist surgeon during surgical procedures. Moreover, by locating joint centre between two relative bodies, it accurately measures the kinematics data in sagittal, coronal or transverse plane (Figure 6). This technique has been utilized in the total knee replacement surgery to guide the balancing of ligaments [46]. In the same way, computer assisted navigation system is employed to collect intra-operative details on the laxity of knee in different planes both before and after the ACL reconstruction [48]. Therefore, it would be a good way to assess immediate effect of ACL reconstruction, especially to compare single-bundle technique and anatomical double-bundle technique in terms of anterior translation and tibial rotation.

Navigation details and measurement

Fluoroscopic navigation system [47,49] is based on the pre imaging data (both AP and lateral views), such as computer tomography or C-arm shots, for the model formation to be displaced in the computer software. A pointer containing integrated reflective markers discs is also attached to the C-arm image. By holding the pointer to the known anatomical landmarks, the surgeon reviews the accuracy of the images when acquiring the AP and lateral images. To accurately locate the navigated tools in relationship to the selected anatomic landmarks, surgical instrument with passive marker spheres must be fixed securely to the patient's femur and tibia (Figure 7). Optoelectronic camera system with infrared light-emitting diodes tracks all passive markers throughout the surgical procedure. The line of sight must be guaranteed once after the navigated procedure starts.

Figure 4
Pivot shift test.

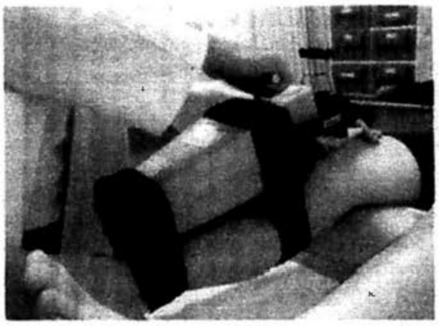


Figure 5
KT 1000 to measure anterior-posterior laxity of the knee.

Image free navigation [50] has been widely established recently. Based on the intra-operative knee alignment measurement such as knee axis and joint lines, the system provides virtual illustration of the anatomical structures. With the information after digitizing the cartilage surface of the femur and the tibia, this method combines the existing model and patient's knee as defined by surface matching.

For both fluoroscopic and image free navigations, since one reference base is fixed each to the femur and the tibia the relative motion in space can be measured precisely. A few studies have reported the validity and reliability of the navigation system. Tsuda et al. [50] validated the navigation system for femoral tunnel placement in double bundle ACL reconstruction with motion analysis system (digital camera). The average differences between the two measurement systems were less than 3% for both AM and PL tunnels. Another studies conducted by Martelli et al. [51], Pearle et al. [52] and Colombet et al. [53] reported that navigation system is reliable to quantify knee kinematics during stability examinations, particularly in the setting of complex rotatory patterns such as pivot shift test. This suggests an accurate and precise evaluation of different techniques of ACL reconstruction.

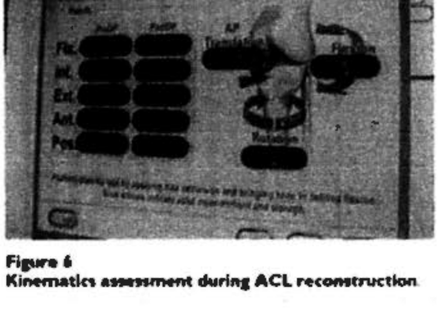


Figure 6
Kinematics assessment during ACL reconstruction.

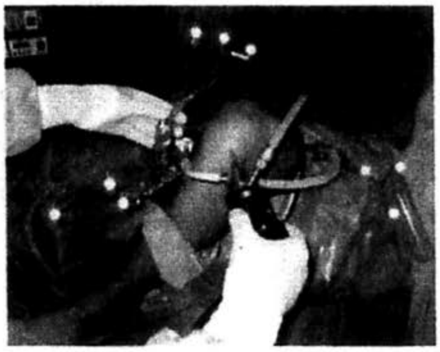


Figure 7
Femoral and tibial transmitters are inserted into bone during navigation process.

Long term evolution during and after rehabilitation – functional assessment

Passive and active motion

By applying a certain force on specific direction to the relaxed knee, ligament injury would be identified if laxity is found when comparing to the other side. This is a usual clinical examination for suspected knee injury without any patients' active movement. However, it may not be the best assessment when it comes to the rehabilitation stage after operative treatment as clinical examinations do not produce sufficient force to stimulate physical activity [40]. The ultimate goal for clinical treatment in sports medicine is to allow patients' safe return-to-sports. It was also suggested that functional knee stability should be one of the criteria that determine a safe return-to-sports [16]. Being different from static knee stability test such as KT 1000, dynamic functional test, which mimics real game situation during sports, involves patients' muscle strength and neuromuscular perception, demand of specific movement and confidence for performing. To monitor the knee stability during this specific dynamic movement, motion analysis is a good way to achieve.

Optical motion analysis with reflective skin marker

Patients with ACL injury can be assessed using motion analysis before and after ACL reconstruction. The functional assessment is conducted in a gait laboratory (Figure 8), which is equipped of more than three high speed cameras and data processing software, providing 10 × 5 m2 captured volume. The three dimensional coordinates of nine millimeter reflective markers can be recognized in the captured volume by means of infra-red light emitting cameras. In the centre of the captured volume, force plates are placed on floor level in order to collect ground reaction force during the movement.

Marker model is essential for motion analysis. It consists of several reflective skin markers that depend on outcome parameters. Ristanis et al [54] adopt the method described by Vaughan [55] for measuring knee joint kinematics. Fifteen markers are stuck on anatomical landmarks of lower extremities including anterior superior iliac spine (ASIS), greater trochanter, lateral femoral epicondyle, tibial tubercle, lateral malleolus, heel, metatarsal head V on both sides and sacrum (Figure 9). Before capturing the dynamic movement, anthropometric data which include weight, ASIS breadth and thigh length, midthigh circumference, calf length, calf circumference, knee diameter, foot length, malleolus height, malleolus diameter, foot breadth on both sides, are collected.

After data collection, the evaluation period should be well defined and trimmed. In clinical practice, stance phase is chosen for evaluation due to the landing risk factor of noncontact ACL injury. A standing trial with anatomical position is needed to define the offset degree for all segmental movements in all planes. Kinematics of knee joint

Figure 8
Gait Laboratory

Figure 9
Marker set of motion analysis assessment (Left to right: anterior view, posterior view and lateral view)

such as flexion angle, tibial rotation and valgus angle are calculated using programming software. Anthropometric measurements combined with three dimensional coordinates from standing trial provide joint centre position and axes of joint rotations. Joint kinematics is then calculated from the position of reflective markers during the movements.

The dynamic movement

Dynamic movement should be clinically based and specific to the research objective. ACL injury would lead translational and rotational instability. The movement that performed by the ACL deficient and reconstructed patients should be high demanding, giving a rotational and valgus stress to the knee. Ristanis et al [54] employ a combined movement in assessing ACL deficient and reconstructed patients. The movement involves jumping, landing, pivoting and running. The patient is required to jump forward from a 40 cm high platform, land with both feet, pivot to the right or left at 90° and run away with their maximum speed. It is treated as a high demand of activity in which the movement has to resist a high rotational stress to the knee during pivoting.

The injury mechanism can be an implication of how we assess ACL injury patients. It is reported that over 70% of ACL injury occur in non-contact situation (Figure 10), which involves landing, decelerating and changing direction [33]. If the patient has good stability during these

Figure 10
Non-contact anterior cruciate ligament injury

'high risk' movements, it would be an important indication for safe return-to-sports. Therefore, movements such as 3-way cutting [56] and 4-way jumping [57] maneuvers are useful to assess the knee stability. In the cutting task, patients are required to run and cut with single leg in three directions: 90° cut, 45° cut and crossover cut. The 4-way jumping task consists of straight run and a two-footed landing followed by a two-footed takeoff maximum jumping in four directions: vertical, anterior, right and left. After data collection, stance phase is trimmed for further evaluation. Kinematics and kinetics data will be measured from the motion analysis system and the force-plate. Both injury (deficient or reconstructed) and intact knee should be assessed since comparison is important when investigating knee laxity.

In most situations during sports, movements such as landing and sudden change of direction are often unexpected. Planned laboratory experiments and actual athletic competition would result different biomechanics performances [17]. Biomechanics study has also shown that unplanned cutting is identified as a risk factor of non-contact ACL injury [58]. In order to investigate this unanticipated effect, a device containing photo cell receiver with light source is instrumented across the runway. When the patient passes through the device, a randomized signal will be generated from the computer connecting to the device. It will then create a visual cue for the cutting and jumping direction through a monitor placing in front of the patient This laboratory setting would only allow subjects' short time decision so that a game-like situation is reproduced in the laboratory.

Discussion

Standard clinical tests, such as Anterior Drawer test and Lachman test, are commonly used to assess AP stability before and after reconstructing the graft. With the help of validated navigation system, knee kinematics stability test can be assessed during operation procedure, enabling the evaluation of immediate effect of ACL reconstruction. The clinical result in terms of laxity is more reliable using navigation system when compared to conventional procedure [59]. To investigate if ACL reconstruction with anatomical double-bundle technique better improve rotational stability, Robinson et al [60] suggested that PL bundle was important than AM bundle in controlling rotational component during Pivot Shift test. In another intra-operative study [61] in which the surgeon applied manual maximum force to test anterior-posterior and rotational stability, however, found no significant different between single-bundle technique and double-bundle technique in restoring knee kinematics. It is still a controversial issue for double-bundle technique before it comes to a consensus from different research groups.

Patients with ACL deficiency report that they feel giving way rather than anterior-posterior instability during cutting movement in sports. Pivot Shift test is a dynamic test containing multiple directional motion to assess abnormal joint excursion [53]. Using navigation system, stability in terms of rotational displacement and anterior translation can be objectively monitored during Pivot Shift test. However, the manual force applied by the surgeon remains one of major limitations in these intra-operative studies [53,60,61]. Robotic testing systems have been employed in cadaveric experiments to simulate Pivot Shift test to a combined valgus and internal rotatory loads [44,62]. This kind of equipments with controlled manual force should be implemented to the operation theatre for future study which aims at a more scientific proof for having double-bundle technique on ACL injury patients.

For the dynamic pivoting movement, the evaluation period is identified during the stance phase of the pivoting knee, from the first contact of landing to the take-off after pivoting. Knee joint kinematics should be focused during the pivoting movement as it gives a high rotational stress on the knee. When it starts to pivot, the upper body with the femur will externally rotate. Meanwhile, the fore foot of the pivoting leg is sticking on the ground, the tibia then internally rotates relatively to a maximum point as a result (Figure 11).

In the study conducted by Ristanis et al [54], the range of internal rotation was reported to be significantly higher in deficient knees than that in intact knees. The authors,

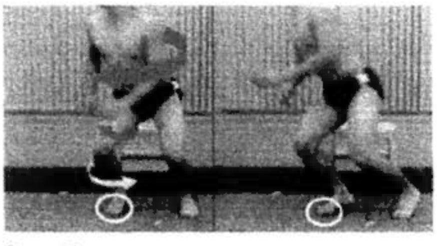


Figure 11
Rotation mechanism during pivoting movement: The upper body and femur externally rotate during the start of pivoting. While the fore foot is sticking on the ground, the tibia internally rotates as a result.

however, did not mention about the other knee kinematics data such as valgus angle during the landing phase, which might be an important implication of instability of ACL deficient patients. This kinematics study maneuver, which demonstrates a similar clinical result [63], not only further confirms the rotational laxity in ACL deficient patients, but also provides an adequate assessment for the long term evaluation of anatomical double-bundle ACL reconstruction.

Conclusion

The knee stability assessments in different stages of management model for ACL injury are important in sports medicine. Related researches on clinical examination, intra-operative navigation ACL reconstruction and functional evaluation with motion analysis system are highlighted for better understanding of how these assessments contribute to the diagnosis of ACL injury, the immediate evaluation of operation treatments and the establishment of safe return-to-sports criteria respectively. The clinical relevance is for orthopaedic surgeons, physiotherapists and scientists with related background to apply appropriate assessments for ACL injury patients.

Competing interests

There are no sources of funding used to assist in the preparation of this manuscript.

There are no potential conflicts of interest the authors may have that are relevant to the contents of this manuscript.

Authors' contributions

MHL drafted the manuscript, PSHY participated in study design and manuscript structure, EPYH advised clinical opinions for assessing stability, DTPF advised on biomechanical assessment and drafted the manuscript. WYC provided pictures of cadaver specimens and advised on anatomical knowledge. KMC provided equipments and clinical setting. All authors read and approved the final manuscript.

References

1. Dekker R, Kingma J, Groothoff JW, Eisma WH, Ten Duis HJ: **Measurement of severity of sports injuries: an epidemiological study.** *Clin Rehabil* 2000, 14:651-656.
2. Dekker R, Groothoff J, Sluis C Van der, Eisma W, Ten Duis H: **Long-term disabilities and handicaps following sports injuries: outcome after outpatient treatment.** *Disabil Rehabil* 2003, 25:1153-1157.
3. Majewski M, Susanne H, Klaus S: **Epidemiology of athletic knee injuries: A 10-year study.** *Knee Surg Sport Tr A* 2006, 13:184-188.
4. Vakri DM, Deng XH, Torzilli PA, Warren RF, Maynard MJ: **The role of the cruciate and posterolateral ligaments in stability of the knee. A biomechanical study.** *Am J Sports Med* 1995, 23:436-443.
5. Myklebust G, Bahr R: **Return to play guidelines after anterior cruciate ligament surgery.** *Brit J Sport Med* 2005, 39:127-131.
6. Swirtun LR, Jansson A, Renstrom P: **The effects of a functional knee brace during early treatment of patients with a nonoperated acute anterior cruciate ligament tear: a prospective randomized study.** *Clin J Sport Med* 2005, 15:299-304.
7. Fink C, Hoser C, Hackl W, Navarro RA, Benedetto KP: **Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture – is sports activity a determining variable?** *Int J Sports Med* 2001, 22:304-309.
8. Gotlin RS, Huie G: **Anterior cruciate ligament injuries. Operative and rehabilitative options.** *Phys Med Rehabil Clin N Am* 2000, 11:895-928.
9. Petersen W, Zantop T: **Anatomy of the anterior cruciate ligament with regard to its two bundles.** *Clin Orthop Relat R* 2007, 454:35-47.
10. Zaricznyj B: **Reconstruction of the anterior cruciate ligament of the knee using a doubled tendon graft.** *Clin Orthop Relat R* 1987, 220:162-175.
11. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE: **Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads.** *J Orthopaed Res* 2004, 22:85-89.
12. Norwood LA, Cross MJ: **Anterior cruciate ligament: functional anatomy of its bundles in rotatory instabilities.** *Am J Sport Med* 1979, 7:23-26.
13. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH: **The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon. A cadaveric study comparing anterior tibial and rotational loads.** *J Bone Joint Surg Am* 2002, 84:907-914.
14. Hara K, Kubo T, Suginoshita T, Shimizu C, Hirasawa Y: **Reconstruction of the anterior cruciate ligament using a double bundle.** *Arthroscopy* 2000, 16:860-4.
15. Yagi M, Kuroda R, Nagamune K, Yoshiya S, Kurosaka M: **Double-bundle ACL reconstruction can improve rotational stability.** *Clin Orthop Relat R* 2007, 454:100-107.
16. Kvist J: **Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation.** *Sports Med* 2004, 34:269-280.
17. Besier T, Lloyd D, Ackland T, Timothy R, Cochrane J: **Anticipatory effects on knee joint loading during running and cutting manouvers.** *Med Sci Sport Exer* 2001, 33:1176-1181.
18. Cavanagh P, Lafortune M: **Ground reaction forces in distance running.** *J Biomech* 1980, 13:397-406.
19. Adirim TA, Cheng TL: **Overview of injuries in the young athlete.** *Sports Med* 2003, 33:75-81.
20. Drawer S, Fuller CW: **Propensity for osteoarthritis and lower limb joint pain in retired professional soccer players.** *Brit J Sport Med* 2001, 35:402-408.
21. DelIaven KE, Cosgarea AJ, Sebastianelli WJ: **Arthrofibrosis of the knee following ligament surgery.** *Instr Course Lect* 2003, 52:369-381.
22. Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Menetrey J: **Anatomy of the anterior cruciate ligament.** *Knee Surg Sport Tr A* 2006, 14:204-213.

23. Furman W, Marshall JL, Girgis FG: The anterior cruciate ligament – A functional analysis based on postmortem studies. J Bone Joint Surg Am 1976, 58:179-185.
24. Fu FH, Zelle BA: Rotational instability of the knee: editorial comment. Clin Orthop Relat R 2007, 454:3-4.
25. Lam SJ: Reconstruction of the anterior cruciate ligament using the Jones Procedure and its Guy's Hospital Modification. J Bone Joint Surg Am 1968, 50:1213-1224.
26. Girgis FG, Marshall JL, Monajem A: The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat R 1975:216-231.
27. Hollis JM, Takai S, Adams DJ, Horibe S, Woo SL: The effects of knee motion and external loading on the length of the anterior cruciate ligament (ACL): a kinematic study. J Biomed Eng 1991, 113:208-214.
28. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S: Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. Am J Sports Med 1991, 19:217-225.
29. Krosshaug T, Slauterbeck JR, Engebretsen L, Bahr R: Biomechanical analysis of anterior cruciate ligament injury mechanisms: three-dimensional motion reconstruction from video sequences. Scand J Med Sci Spor 2007, 17:508-519.
30. Woo S, Debski R, Withrow J, Janaushek M: Biomechanics of knee ligaments. Am J Sport Med 1999, 27:533-543.
31. Grood E, Suntay W: A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomed Eng 1983, 105:136-144.
32. Smith BA, Livesay GA, Woo SL: Biology and biomechanics of the anterior cruciate ligament. Clin Sport Med 1993, 12:637-670.
33. Hughes G, Watkins J: A risk-factor model for anterior cruciate ligament injury. Sports Med 2006, 36:411-428.
34. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE: Treatment of anterior cruciate ligament injuries, part I. Am J Sport Med 2005, 33:1579-1602.
35. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE: Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. J Orthop Sport Phys 2006, 36:385-402.
36. Krosshaug T, Andersen TE, Olsen OE, Myklebust G, Bahr R: Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities. Brit J Sport Med 2005, 39:330-339.
37. Ostrowski JA: Accuracy of 3 diagnostic tests for anterior cruciate ligament tears. J Athl Training 2006, 41:120-121.
38. Klass D, Toms AP, Greenwood R, Hopgood P: MR imaging of acute anterior cruciate ligament injuries. Knee 2007, 14:339-347.
39. Renstrom P, Ljungqvist A, Arendt E, Beynnon B, Fukubayashi T, Garrett W, Georgoulis T, Hewett TE, Johnson R, Krosshaug T, Mandelbaum B, Micheli L, Myklebust G, Roos E, Roos H, Schamasch P, Shultz S, Werner S, Wojtys E, Engebretsen L: Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 2008, 42:394-412.
40. Lubowitz JH, Bernardini BJ, Reid JB 3rd: Current concepts review: comprehensive physical examination for instability of the knee. Am J Sport Med 2008, 36:577-594.
41. Frobell RB, Lohmander LS, Roos HP: Acute rotational trauma to the knee: poor agreement between clinical assessment and magnetic resonance imaging findings. Scand J Med Sci Spor 2007, 17:109-114.
42. Jonsson T, Althoff B, Peterson L, Renstrom P: Clinical diagnosis of ruptures of the anterior cruciate ligament: a comparative study of the Lachman test and the anterior drawer sign. Am J Sports Med 1982, 10:100-102.
43. Torg JS, Conrad W, Kalen V: Clinical diagnosis of anterior cruciate ligament instability in the athlete. Am J Sports Med 1976, 4:84-93.
44. Kanamori A, Zeminski J, Rudy TW, Li G, Fu FH, Woo SL: The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. Arthroscopy 2002, 18:394-398.
45. Holly L, Foley K: Intraoperative spinal navigation. Spine 2003, 28(Suppl 15):S54-S61.
46. Laskin R, Beksac B: Computer-assisted navigation in TKA: where we are and where we are going. Clin Orthop Relat R 2006, 452:127-131.
47. Hufner T, Meller R, Kendoff D, Zeichen J, Zelle BA, Fu FH, Krettek C: The role of navigation in knee surgery and evaluation of three-dimensional knee kinematics. Oper Techn Orthopaedics 2005, 15:64-69.
48. Koh J: Computer-assisted navigation and anterior cruciate ligament reconstruction: accuracy and outcomes. Orthopedics 2005, 28(Suppl 10):S1283-S1287.
49. Shafizadeh S, Hurer HJ, Grote S, Hoeher J, Paffrath T, Tiling T, Bouillon B: Principles of fluoroscopic-based navigation in anterior cruciate ligament reconstruction. Oper Techn Orthopaedics 2005, 15:70-75.
50. Tsuda E, Ishibashi Y, Fukuda A, Tsukada H, Toh S: Validation of computer-assisted double-bundle anterior cruciate ligament reconstruction. Orthopedics 2007, 30(Suppl 10):S136-S140.
51. Martelli S, Zaffagnini S, Bignozzi S, Bontempi M, Marcacci M: Validation of a new protocol for computer-assisted evaluation of kinematics of double-bundle ACL reconstruction. Clin Biomech 2006, 21:279-287.
52. Pearle AD, Solomon DJ, Wanich T, Moreau-Gaudry A, Granchi CC, Wickiewicz TL, Warren RF: Reliability of navigated knee stability examination: a cadaveric evaluation. Am J Sport Med 2007, 35:1315-1320.
53. Colombet P, Robinson J, Christel P, Franceschi JP, Djian P: Using navigation to measure rotation kinematics during ACL reconstruction. Clin Orthop Relat R 2007, 454:59-65.
54. Ristanis S, Giakas G, Papageorgiou CD, Moraiti T, Stergiou N, Georgoulis AD: The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs. Knee Surg Sport Tr A 2003, 11:360-365.
55. Vaughan C, Davis B, O'Connor J: Dynamics of Human Gait Cape Town. Human Kinetics Publishers Champaign; 1992.
56. Waite JC, Beard DJ, Dodd CA, Murray DW, Gill HS: In vivo kinematics of the ACL-deficient limb during running and cutting. Knee Surg Sport Tr A 2005, 13:377-384.
57. Sell TC, Ferris CM, Abt JP, Tsai YS, Myers JB, Fu FH, Lephart SM: The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. Am J Sport Med 2006, 34:43-54.
58. Landry S, McKean K, Hubley-Kozey C: Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. Am J Sport Med 2007, 35:1888-1900.
59. Plaweski S, Cazal J, Rosell P, Merloz P: Anterior cruciate ligament reconstruction using navigation – A comparative study on 60 patients. Am J Sport Med 2006, 34:542-552.
60. Robinson J, Carrat L, Granchi C, Colombet P: Influence of anterior cruciate ligament bundles on knee kinematics: clinical assessment using computer-assisted navigation. Am J Sport Med 2007, 35:2006-2013.
61. Ferretti A, Monaco E, Labianca L, Conteduca F, De Carli A: Double-bundle anterior cruciate ligament reconstruction: a computer-assisted orthopaedic surgery study [see comment]. Am J Sport Med 2008, 36:760-766.
62. Bull AM, Andersen HN, Basso O, Targett J, Amis AA: Incidence and mechanism of the pivot shift. An in vitro study. Clin Orthop Relat R 1999:219-231.
63. Siebold R, Dehler C, Ellert T: Prospective randomized comparison of double-bundle versus single-bundle anterior cruciate ligament reconstruction. Arthroscopy 2008, 24:137-145.

AJSM PreView, published on February 18, 2011 as doi:10.1177/0363546510394430

Knee Rotational Stability During Pivoting Movement Is Restored After Anatomic Double-Bundle Anterior Cruciate Ligament Reconstruction

Mak-Ham Lam,*† BEd, Daniel Tik-Pui Fong,*†‡ PhD,
Patrick Shu-Hang Yung,*† FRCS Ed (Orth), Eric Po-Yan Ho,*† FRCS Ed (Orth),
Kwai-Yau Fung,§ FRACS (Orth), and Kai-Ming Chan,*† FRCS Ed (Orth)
Investigation performed at The Chinese University of Hong Kong, Hong Kong, China

Background: The restoration of knee rotational stability after anatomic double-bundle anterior cruciate ligament (ACL) reconstruction has been demonstrated in the cadaveric model and with passive stress tests on humans but not yet with dynamic functional biomechanical tests performed by human participants.

Purpose: To prospectively investigate the range of tibial rotation of ACL-deficient and ACL-reconstructed knees during a pivoting task. The authors hypothesized that there would be a significant increase in tibial internal rotation in the ACL-deficient knee compared with the contralateral knee and that the increased rotation would return to normal after anatomic double-bundle ACL reconstruction.

Study Design: Case series; Level of evidence, 4.

Methods: Ten men with unilateral ACL injury performed a high-demand jump-landing and pivoting task before and after ACL reconstruction with mean follow-up of 11 months. The range of tibial rotation of the injured, reconstructed, and intact knees during the pivoting movement was measured by an optical motion analysis system. Paired *t* tests were performed to investigate any significant difference between the 2 limbs preoperatively and postoperatively and within the injured limb before and after the surgical treatment. Statistical significance was set at *P* .05.

Results: The range of tibial rotation was higher in the ACL-deficient knee (12.6 4.5) than in the intact knee (7.9 3.1) preoperatively (*P* .05). The increased rotation was reduced in the reconstructed knee (8.9 3.0) after ACL reconstruction versus the intact knee postoperatively (8.2 2.6) (*P* .05). There was no significant difference in the tibial rotation between the intact knee and the reconstructed knee postoperatively (*P* .05).

Conclusion: As assessed with a dynamic functional pivoting movement, the anatomic double-bundle ACL reconstruction successfully restores knee rotational stability from an impaired level.

Keywords: kinematics; rotational instability; rotation; anterior cruciate ligament; double bundle

Anterior cruciate ligament (ACL) injury leads to knee instability, mainly in anterior-posterior translation and axial internal-external rotation. It has been well documented in cadaver models that excessive tibial rotation follows an ACL excision. Clinically, knee instability before and after ACL reconstruction is often examined subjectively by the pivot-shift test, in which passive valgus and internal rotation stresses are applied to the knee. Mechanical devices were recently developed for objective and biomechanical assessment of knee rotational laxity. They provide an easy and noninvasive way of applying a controlled torque to the knee joint and documenting the knee rotational abnormality. However, these clinical and biomechanical tests measure passive knee joint laxity with relaxed muscles. When a patient performs a dynamic functional movement after returning to sport, it

[illegible]Address correspondence to Daniel Tik-Pui Fong, PhD, Department of Orthopaedics and Traumatology, Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China (e-mail: dfong@ort.cuhk.edu.hk).

[illegible]Department of Orthopaedics and Traumatology, Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China.

‡Hong Kong Jockey Club Sports Medicine and Health Sciences Centre, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China.

[illegible]Department of Orthopaedics and Traumatology, Alice Ho Miu Ling Nethersole Hospital, Hong Kong, China.

One or more authors has declared the following potential conflict of interest or source of funding: This research project was made possible by equipment/resources donated by the Hong Kong Jockey Club Charities Trust.

The American Journal of Sports Medicine, Vol. XX, No. X
DOI: [illegible]

1

is not only the ligaments but also the muscle contractions that provide joint stability. There is a need to conduct functional performance tests to evaluate dynamic joint stability during high-demand tasks.

The movement of a functional test should be specific to the purpose of study. Several kinematics studies have employed different dynamic movements to investigate patients with unilateral ACL injury. Andriacchi and Dyrby reported that external rotation and anterior translation were different between ACL-deficient and intact knees during the swing phase of walking. On treadmill running, tibial rotation increased with speed in injured and normal knees. The differences between the knees, however, were not significant. Waite and coworkers suggested that low-demand activities such as walking and running did not produce sufficient stress to initiate knee instability in the ACL-deficient knee. In a study assessing functional stability with a high-demand movement, tibial rotation was found not to be restored after single-bundle ACL reconstruction with hamstring or patellar tendon autograft. Therefore, in the current study, a pivoting task was used to evaluate the effect of anatomic double-bundle ACL reconstruction.

In vitro studies have shown that anatomic double-bundle ACL reconstruction using hamstring grafts restores anterior-posterior translation and axial rotation stability. With this current technique, clinical studies have reported good restoration of joint stability and patient-reported outcomes after a short-term follow-up. Moreover, a few studies compared double-bundle and single-bundle ACL reconstruction using subjective clinical tests and questionnaires for evaluation. However, among these studies, there is limited knowledge of rotational stability, as investigated by objective assessment after anatomic double-bundle ACL reconstruction. Yet, studies using dynamic functional activity reported that single-bundle ACL reconstruction could not restore rotational stability. Therefore, the purpose of the current study was to prospectively investigate the range of tibial rotation of ACL-deficient and ACL-reconstructed knees during a high-demand task. The contralateral intact knee was used as a control. It was hypothesized that there would be a significant increase in tibial rotation in the ACL-deficient knee and that it would be returned to normal after anatomic double-bundle ACL reconstruction.

MATERIALS AND METHODS

Participants

Ten men with unilateral ACL injury were recruited for the study (6 right knees and 4 left knees; age, 27.2 ± 4.7 years; height, 1.76 ± 0.1 m; body mass, 69.4 ± 9.2 kg). All participants were recruited in our sports clinic. When patients were confirmed with unilateral ACL rupture, they were screened with exclusion criteria. The ACL rupture was confirmed by arthroscopy, MRI, or clinical examination. Exclusion criteria included the presence of bone fractures, complex meniscal injury, other ligamentous injuries of the involved knee, and previous surgery on either knee. All participants reported knee joint instability during sports, and all were recommended to receive surgical treatment. All injuries were sports related, and all participants participated in these sports at least one time per week before the injury. Table 1 shows the preoperative and postoperative clinical data. The participants in our study were the first 10 patients invited to participate. The university ethics committee approved the study. Informed consent was obtained from each participant before the study.

Surgical Technique

In all participants, anatomic double-bundle ACL reconstructions were performed by 2 authors (P.Y. and K.H.) who have more than 10 years of experience performing ACL reconstructions. The injured knee was put on the operating table with a foot rest and with lateral thigh support at 90° of flexion. The operation was performed after inflating the tourniquet. The hamstring grafts (gracilis and semitendinosus tendons) were harvested through an incision over the ipsilateral tibia and braided with Ultrabraid 2 (Smith & Nephew Endoscopy, Andover, Massachusetts) to each tendon graft. A diagnostic arthroscopy was performed using the anterolateral and anteromedial (AM) portals. After confirming the rupture of AM and posterolateral (PL) bundles, the surgeon debrided the ACL stump and identified the footprints of the AM and PL bundles, which were marked by a radiofrequency probe. The footprint of the ACL was identified by locating the lateral intercondylar ridge and the lateral bifurcate ridge, as suggested by previous studies.

The AM femoral tunnel was prepared through the AM portal with the aid of a 6-mm offset guide; the guide pin was placed at the footprint of AM bundle and reamed to a diameter of 4.5 mm for the passage of the Endobutton (Smith & Nephew Endoscopy). The AM bundle was further reamed to a diameter of 6 or 7 mm, and the integrity of the outer cortex was preserved. The diameter and length of the tunnel depended on the graft size and the patient's anatomy. After the tunnel for the AM bundle was created, the knee was then flexed to 110°. An accessory AM portal was created according to the guidance of a spinal needle, which was used to aim the footprint of the PL bundle. A 2.4-mm guide pin was inserted according to the footprint of the PL bundle. The PL femoral tunnel, which varied from 5 to 6 mm in diameter, was then created through the accessory AM portal by the Endobutton reamer and the 5- or 6-mm reamer. The bone bridge between the 2 tunnels was at least 2 mm.

For the tibial tunnels of the AM and PL bundles, 45° and 55° tibial jigs (Smith & Nephew Endoscopy) were used, respectively. The ACL remnant was used as a guide to identify the footprint of the ACL. The tibial tunnel of the PL bundle was created by inserting a 2.4-mm guide pin through a 55° tibial jig. The guide pin was aimed to the footprint of the ACL, about 6 to 7 mm anterior to the posterior cruciate ligament. Another 2.4-mm guide pin was inserted through a 45° tibial jig, aimed about 9 mm away

TABLE 1
Preoperative and Postoperative Clinical Data of All Patients

No.	Injured Knee	Time, Months	IKDC	Lysholm	KT-1000, mm	Lachman	Anterior Drawer	Pivot Shift
				Preoperative Assessment				
1	L	11	47.1	90	[illegible]	[illegible]	2	2
2	R	1	71.7	85	4.5	[illegible]	1	2
3	L	5	71.7	8[illegible]	4.5		2	2
4	L	4	74.7	80	9.[illegible]	[illegible]	1	2
5	R	9	74.7	8[illegible]	8.5	[illegible]	2	[illegible]
6	R	3	79.3	84	[illegible]	[illegible]	2	2
7	L	5	69.0	80	4.5	[illegible]	2	3
8	R	1	75.0	80	4.5	1	3	2
9	R	2	73.6	[illegible]	7.[illegible]	1	1	[illegible]
10	R	1	66.7	8[illegible]	7.0	1	1	[illegible]
Mean ± SD		[illegible] ± 2.8	70.8 ± 3.0	82.9 ± 4.2	[illegible] ± 2.6			
		Time, Months[d]		Postoperative Assessment				
1	L		100.0	90	1.[illegible]	0	[illegible]	0
2	R	18	100.0	100	0.0	0	[illegible]	0
3	L	10	79.3	90	1.[illegible]	0	0	0
4	L	12	80.5	100	2.[illegible]	0	[illegible]	0
5	R	7	71.8	90	3.0	1	1	0
6	R	1[illegible]	100.0	98	1.0	0	0	0
7	L	[illegible]	100.0	100	1.0	0	1	1
8	R	12	93.1	98	1.5	0	0	0
9	R	7	100.0	100	1.0	0	0	0
10	R	8	93.1	90	0.0	1	1	1
Mean ± SD		10.3 ± 3.9	92.1 ± 10.1	97.1 ± 1.0	2.0 ± 1.6			

[a] Time from injury to preoperative assessment.
[b] International Knee Documentation Committee.
[c] Differences between both knees when assessed with 30 lb (13.61 kg) of anterior forces.
[d] Time from surgery to postoperative assessment.

anterior and medial) from the guide pin for the PL tunnel. According to the size of the graft, the PL and AM tibial tunnels were then further reamed to 5 or 6 mm and 6 or 7 mm in diameter, respectively. The tunnels were designed to create a bone bridge of about 2 mm between the 2 tibial tunnels.

Doubled gracilis and semitendinosus tendons were used for the PL and AM bundle reconstructions, respectively. Graft passage was completed for the PL bundle, followed by the AM bundle. On the femoral side, the PL bundle was fixed by 15-mm Endobutton loop (Smith & Nephew Endoscopy), whereas the AM bundle was fixed by 15- or 20-mm Endobutton loop. The PL bundle was tensioned at 15° of flexion and the AM bundle at 80° of flexion. On the tibial side, bioabsorbable interference screws were used to fix each bundle individually, and staples were used to fix both grafts over the medial surface of the tibia. Figure 1 shows the arthroscopic images and postoperative radiograph. After ACL reconstruction, all patients completed a standard rehabilitation program.[3]

Experimental Procedure

All participants were assessed before and after ACL reconstruction, with a follow-up of 10.3 ± 3.9 months. An optical motion analysis system with 8 cameras (Vicon 624, Vicon Motion Systems Ltd, Oxford, United Kingdom) was used to record the 3-dimensional rotation movements of lower extremities at a capturing frequency of 120 Hz. The system was calibrated on the same day of testing, and the mean residual was less than 1 mm. If it was not, the system was recalibrated. Synchronized force plate (model OR6-7, AMTI, Watertown, Massachusetts) data were collected at the center of the capture volume at 1080 Hz. A 15-marker model[7] was adopted to collect lower limb kinematics during movements. Skin reflective markers (diameter, 9 mm) were placed at anatomic landmarks including anterior superior iliac spine, sacrum, greater trochanter, femoral epicondyle, tibial tubercle, lateral malleolus, heel, and fifth metatarsal head on both limbs. Anthropometric data were measured for kinematics calculation, including body mass, anterior superior iliac spine breadth, thigh and calf length, midthigh and calf circumference, knee diameter, foot breadth and length, and malleolus height and diameter. The reliability of the overall procedure has been reported to be less than 2.4° for within-day measures.[11]

Experimental Task

Before the movement was performed, a trial of standing anatomic position was recorded. Every participant was

Figure 1. The arthroscopic images of the anatomic double-bundle ACL reconstruction, with postoperative radiograph: 1, ACL footprint of femoral side at 90° of knee flexion; 2, femoral tunnels at 110° of knee flexion, viewed from anteromedial portal; 3, tibial tunnels created by inserting 2 guide pins with tibial jig at 55° and 45° for posterolateral and anteromedial bundles, respectively; 4, graft passage viewed from anterolateral portal. The postoperative radiograph shows the position of both the anteromedial and posterolateral tunnels in the distal femur and proximal tibia, with Endobutton fixation on the femoral side and bioabsorbable screws and bone staples on the tibial side.

instructed by the same tester to stand with both feet at shoulder width and to align the shank and foot segment to a neutral position. This calibration file provided a definition of 0° for all segmental movements. Both limbs were tested individually. The participants were asked to jump off a platform, 40 cm in height and 10 cm behind the force plate, and to land with both feet on the ground, with only the testing foot on the force plate. After the foot contact, they were to pivot 90° to the lateral side of the testing leg, which acted as the core leg during pivoting. They were then instructed to run away with their maximum effort for 3 steps after completing the pivoting movement (Figure 2).

Data Collection and Reduction

The evaluation period was defined from the first foot contact to the takeoff of the testing leg on the ground. Foot contact was determined by the force plate when the vertical ground-reaction force exceeded 5% of the participant's body weight. Three-dimensional coordinates of every marker were exported from the VICON software. With the anthropometric measurements, knee joint kinematics was then calculated. All calculations were conducted using a self-compiled program (MathWorks, Natick, Massachusetts). The main dependent variable was range of tibial rotation during pivoting movement, defined as the difference between the lowest tibial internal rotation after landing and the highest tibial internal rotation within the foot contact period.

Data Analysis

Paired *t* tests were performed to investigate any significant difference between the 2 limbs preoperatively and postoperatively and within the injured limb before and after the anatomic double-bundle ACL reconstruction. Post hoc power analysis was conducted if there was no significant difference between the reconstructed knee and the intact knee after reconstruction. The level of significance and study power were set at .05 and .80, respectively.

RESULTS

During the pivoting phase, the tibia internally rotated to a maximum degree (Figure 3). For the range of tibial rotation, there was a significant (P = .005) increase in internal rotation of the deficient knee (12.6° ± 4.5°) when compared with the intact knee (7.9° ± 3.1°) preoperatively. This increased tibial rotation significantly (P = .035) decreased to 8.9° ± 3.0° in the reconstructed knee and did not differ from that of the intact knee (8.2° ± 2.6°) after ACL reconstruction (Figure 4).

Figure 2. The video sequence of the jump-landing and pivoting task, assessing the right knee of the patient. 1, initial position; 2, jumping; 3, landing; 4, pivoting; 5, push-off; 6, running.

Regarding overconstraining, we compared the reconstructed and intact knees after surgery and did not find any case demonstrating this problem. Because there was no significant difference between the reconstructed knee and the intact knee after reconstruction, power analysis was conducted (true difference, 2°; correlation, 27), and the statistical power was reported to be .81 between the 2 groups.

DISCUSSION

This study demonstrates the increased tibial rotational movement of the ACL-deficient knee and the restoration of this movement after ACL reconstruction. The difference between the intact and deficient knees supports the first hypothesis, whereas the decreased tibial rotation and adequate statistical power support the second hypothesis.

Our findings support previous studies showing knee rotational instability of the ACL-deficient knee and the ACL-reconstructed knee with the single-bundle technique.[illegible] In 2 studies with protocols similar to those of the present study,[illegible] the tibial rotation of the deficient knee was significantly higher than that of the intact knee. Whereas those patients were instructed to walk after the pivoting movement, ours were instructed to run. We believe that the task in our study provides a higher rotational stress to the knee. However, the increased tibial rotation found in the current study was not as high as that in either of the 2 previous studies, perhaps because of the difference in the time from injury to assessment. The cases in this study were based on acute injury, whereas those in the 2 studies were based on chronic injury. Our participants in this study might have performed cautiously in the preoperative assessment. Other studies employing different functional activities, such as downhill running[illegible] and single-legged hopping,[illegible] have shown abnormal rotational motion after ACL reconstruction. Regarding study design, all the participants in our study were assessed prospectively, before and after ACL reconstruction. The variations between the study group and the control group were minimized because the contralateral intact knee was used as a control.

Anatomic ACL reconstruction[illegible] aims to reconstruct the original ACL with normal kinematics in all six degrees of freedom, including mediolateral and anteroposterior translation as well as axial rotation. However, in vitro[illegible] and in vivo[illegible] studies have shown that tibial rotation is not restored by single-bundle ACL reconstruction. One of the suggested reasons is that only the AM bundle is replicated, thereby resulting in insufficient rotational control of the knee; another is that the single-bundle techniques tested may not have been completely anatomic. In the current study, all patients were treated with anatomic double-bundle ACL reconstruction, in which AM and PL bundles were both reconstructed to mimic the original ACL anatomy. In addition to the AM bundle, the PL bundle might provide a role in the stabilization of the knee against a combined rotatory load.[11] In evaluation of the double-bundle ACL reconstruction with a high-demand movement, the

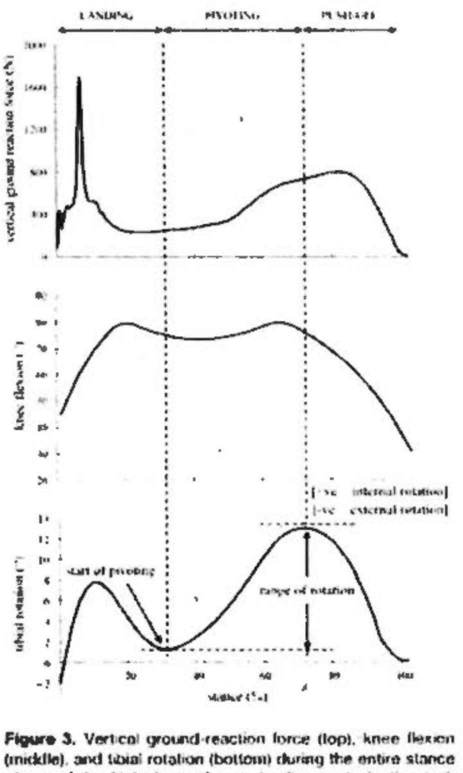


Figure 3. Vertical ground-reaction force (top), knee flexion (middle), and tibial rotation (bottom) during the entire stance phase of the high-demand jump-landing and pivoting task from a typical ACL-deficient knee.

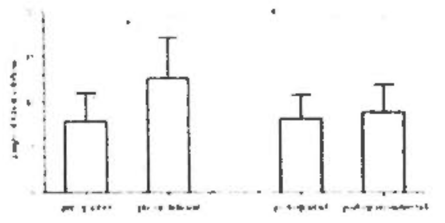


Figure 4. Range of tibial internal rotation during pivoting movement before and after ACL reconstruction. *Significant difference as suggested by the paired *t* test: $P = .005$ for preoperatively intact and preoperatively deficient; $P = .035$ for preoperatively deficient and postoperatively reconstructed.

significant decrease in range of tibial rotation of the reconstructed knee in this study suggests the effectiveness of rotational control of such an anatomic reconstruction. To better demonstrate the superiority of the double-bundle technique as well as the effect of the PL bundle, future studies are needed with large-scale randomized controlled trials comparing the effect of single-bundle and double-bundle ACL reconstruction on functional stability.

Functional testing should be the ultimate step for evaluating ACL reconstruction, given that it involves real-life loading to which human joints are exposed in daily activities or even sports motion. Although dynamic functional testing has been employed,[9] previous studies have mainly focused on functional performance. Muscle strength is a performance index during rehabilitation in which there is a positive association between thigh muscle strength and functional outcome of the knee.[25] Other functional tests have been used as assessment after ACL reconstruction, such as vertical jump, figure of 8, and stairs running.[29] All were expressed as strength and ability that a patient would achieve. Instead, joint functional stability should be investigated through function tests such as running[31] and jumping.[7] In the present study, a high-demand sports movement was used to investigate the effect of anatomic double-bundle ACL reconstruction on knee rotational stability. The stability was expressed as tibial rotation during a pivoting movement, and the result of excessive rotation before ACL reconstruction was in line with a previous study.[24] Functional testing with motion analysis would be a good tool to evaluate patients with knee instability, after knee ligamentous injury, for example.

The limitations of the present study include known drawbacks of motion analysis, including the movement of skin markers.[27] However, the marker model was validated[6] and employed by other researchers for similar movement.[29,34,38] During the procedure, the intertester error was minimized by having the same technician place the skin markers and measure all anthropometric data. A standing offset trial to define 0° for all segmental movements was collected to avoid subtle misalignment of the knee joint. Moreover, tibial rotation was reliably measured in a similar previous study,[34] and typical error values (<2.9°) were less than the usual group differences in rotational excursion as reported in the literature. Furthermore, to avoid variation among surgeons in the complicated surgical technique,[14] 2 experienced orthopaedic surgeons performed all reconstructions. Last, to avoid unnecessary subject variations, the current study employed a prospective design in which the same injured knee was compared before and after the reconstruction. The intact knee of the same individual was used as a control.

CONCLUSION

The ACL-deficient knee demonstrated increased tibial rotation. By using a dynamic functional biomechanical assessment, we demonstrated that the anatomic double-bundle ACL reconstruction successfully restores functional knee rotational stability during a pivoting movement.

REFERENCES

1. Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N. Comparison between single- and double-bundle anterior cruciate ligament reconstruction: a prospective, randomized, single-blinded clinical trial. *Am J Sports Med*. 2010;38:25-34.
2. Amis AA, Scammell BE. Biomechanics of intra-articular and extra-articular reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Br*. 1993;75:812-817.
3. Andriacchi TP, Dyrby CO. Interactions between kinematics and loading during walking for the normal and ACL deficient knee. *J Biomech*. 2005;38:293-298.
4. Colombet P, Robinson J, Christel P, Franceschi JP, Djian P. Using navigation to measure rotation kinematics during ACL reconstruction. *Clin Orthop Relat Res*. 2007;454:59-65.
5. Czerniecki JM, Lippert F, Olerud JE. A biomechanical evaluation of tibiofemoral rotation in anterior cruciate deficient knees during walking and running. *Am J Sports Med*. 1988;16:327-331.
6. Davis RB, Ounpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. *Hum Mov Sci*. 1991;10:575-587.
7. Deneweth JM, Bey MJ, McLean SG, Lock TR, Kolowich PA, Tashman S. Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee during a single-legged hop landing. *Am J Sports Med*. 2010;38:1820-1828.
8. Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Menetrey J. Anatomy of the anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc*. 2006;14:204-213.
9. Fitzgerald GK, Lephart SM, Hwang JH, Wainner RS. Hop tests as predictors of dynamic knee stability. *J Orthop Sports Phys Ther*. 2001;31:588-597.
10. Fu FH, Shen W, Starman JS, Okeke N, Irrgang JJ. Primary anatomic double-bundle anterior cruciate ligament reconstruction: a preliminary 2-year prospective study. *Am J Sports Med*. 2008;36:1263-1274.
11. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. *J Orthop Res*. 2004;22:85-89.
12. Georgoulis AD, Ristanis S, Chouliaras V, Moraiti C, Stergiou N. Tibial rotation is not restored after ACL reconstruction with a hamstring graft. *Clin Orthop Relat Res*. 2007;454:89-94.
13. Jarvela T. Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective, randomize clinical study. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:500-507.
14. Karlsson J. ACL injuries: unanswered questions. Are there any solutions? *Knee Surg Sports Traumatol Arthrosc*. 2010;18:275-276.
15. Karlsson J. "Anatomy is the key". *Knee Surg Sports Traumatol Arthrosc*. 2010;18:1.
16. Kondo E, Yasuda K, Azuma H, Tanabe Y, Yagi T. Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients. *Am J Sports Med*. 2008;36:1675-1687.
17. Kopf S, Musahl V, Tashman S, Szczodry M, Shen W, Fu FH. A systematic review of the femoral origin and tibial insertion morphology of the ACL. *Knee Surg Sports Traumatol Arthrosc*. 2009;17:213-219.
18. Lam MH, Fong DT, Yung P, Ho EP, Chan WY, Chan KM. Knee stability assessment on anterior cruciate ligament injury: clinical and biomechanical approaches. *Sports Med Arthrosc Rehabil Ther Technol*. 2009;1:20.
19. Li G, Papannagari R, DeFrate LE, Yoo JD, Park SE, Gill TJ. Comparison of the ACL and ACL graft forces before and after ACL reconstruction: an in-vitro robotic investigation. *Acta Orthop*. 2006;77:267-274.
20. Lipke JM, Janecki CJ, Nelson CL, et al. The role of incompetence of the anterior cruciate and lateral ligaments in anterolateral and anteromedial instability: a biomechanical study of cadaver knees. *J Bone Joint Surg Am*. 1981;63:954-960.
21. Lorbach O, Wilmes P, Maas S, Zerbe T, Busch L, Kohn D, Seil R. A non-invasive device to objectively measure tibial rotation: verification of the device. *Knee Surg Sports Traumatol Arthrosc*. 2009;17:756-762.
22. Lubowitz JH, Bernardini BJ, Reid JB 3rd. Current concepts review: comprehensive physical examination for instability of the knee. *Am J Sports Med*. 2008;36:577-594.
23. Mae T, Shino K, Miyama T, et al. Single- versus two-femoral socket anterior cruciate ligament reconstruction technique: biomechanical analysis using a robotic simulator. *Arthroscopy*. 2001;17:708-716.
24. Martins CAQ, Kropf EJ, Shen W, van Eck CF, Fu FH. The concept of anatomic anterior cruciate ligament reconstruction. *Oper Tech Sports Med*. 2008;16:104-115.
25. Meisala AS, Jarvela T, Kannus P, Jarvinen M. Muscle strength evaluations after ACL reconstruction. *Int J Sports Med*. 2007;28:868-872.
26. Musahl V, Bell KM, Tsai AG, et al. Development of a simple device for measurement of rotational knee laxity. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:1009-1012.
27. Reinschmidt C, van den Bogert AJ, Nigg BM, Lundberg A, Murphy N. Effect of skin movement on the analysis of skeletal knee joint motion during running. *J Biomech*. 1997;30:729-732.
28. Risberg MA, Ekeland A. Assessment of functional tests after anterior cruciate ligament surgery. *J Orthop Sports Phys Ther*. 1994;19:212-217.
29. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21:1323-1329.
30. Shelbourne KD, Nitz P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. *Am J Sports Med*. 1990;18:292-299.
31. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2004;32:975-983.
32. Tsuda Y, Amano H, Kuwano M, et al. Outcome of double-bundle ACL reconstruction using hamstring tendons. *Knee Surg Sports Traumatol Arthrosc*. 2009;17:456-463.
33. Waite JC, Beard DJ, Dodd CA, Murray DW, Gill HS. In vivo kinematics of the ACL-deficient limb during running and cutting. *Knee Surg Sports Traumatol Arthrosc*. 2005;13:377-384.
34. Webster KE, McClelland JA, Wittwer JE, Tecklenburg K, Feller JA. Three dimensional motion analysis of within and between day repeatability of tibial rotation during pivoting. *Knee*. 2010;17(5):329-333.
35. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH. The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon: a cadaveric study comparing anterior tibial and rotational loads. *J Bone Joint Surg Am*. 2002;84:907-914.
36. Yagi M, Kuroda R, Nagamune K, Yoshiya S, Kurosaka M. Double-bundle ACL reconstruction can improve rotational stability. *Clin Orthop Relat Res*. 2007;454:100-107.
37. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL. Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med*. 2002;30:660-666.
38. Yu B, McClure SB, Onate JA, Guskiewicz KM, Kirkendall DT, Garrett WE. Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *Am J Sports Med*. 2005;33:1356-1364.

第八章

前交叉韧带损伤的膝关节运动学分析

一、研究膝关节运动学的重要性

人体下半身有三大主要关节：髋关节、膝关节及踝关节。膝关节位于髋关节和踝关节中间，提供身体平衡和应力转移，特别是在高速活动中。研究表明，非预期的急转向活动会增加膝关节内翻或外翻及内旋或外旋时的应力，继而增加非接触性膝关节韧带损伤的风险。即便在直线奔跑时，膝关节所受的地面作用力可高达身体重量的3倍。由于站立时支撑整个身体的重量，膝关节是全身关节中最容易出现急性损伤和长期性关节炎的关节。因此，研究动态运动的生物力学，如急转向或着陆等，可以了解受伤的机制，从而设计及建立特定的预防项目。此外，运动学分析对评估关节重建（如前交叉韧带重建）的即时和长期效果也非常重要。

二、膝关节及膝关节运动

（一）膝关节结构

膝关节由骨、韧带及软骨组成，是一个滑膜关节，连接股骨、腓骨、髌骨和胫骨。解剖学研究表明，膝关节可被分为两个独立的骨关节，即连接胫骨近端及股骨远端的胫股骨关节，以及连接髌骨和前股骨平台的髌股关节。这些关节造就了膝关节的独特运动。膝关节韧带限制了膝关节的过度活动。但当不平衡的作用力作用于膝关节，造成韧带断裂时，则膝关节出现活动异常。膝关节韧带主要包括交叉韧带、副韧带、髌韧带和腘韧带。半月板主要由纤维软骨组成，主要作用是保护骨端和减震。当膝关节被迫过度旋转及弯曲时，可能造成半月板撕裂。

（二）膝关节活动

在滑膜关节中，膝关节属于活动性较低的铰链关节。与髋、肩等球窝关节不同，膝关节只存在单一平面运动，它可以在行走、奔跑及着陆时在矢状面自由屈伸。横断面及冠状面的平移和旋转则受到膝关节结构的限制，只能在小范围内活动。例如，交叉韧带限制了横断面的前后平移活动，而副韧带则限制了冠状面的内旋或外旋（内翻或外翻）活动。

（三）膝关节运动的生物力学

膝关节运动是股骨与胫骨之间的相对运动。Grood设计了一套关节的坐标系统，用于测量3个方向的股骨与胫骨之间的旋转和平移运动。由于膝关节的韧带控制着膝关节运动，因此研究韧带损伤十分重要。例如，前交叉韧带断裂会导致前后过度平移及胫骨过度旋转。在尸体中，单侧前交叉韧带断裂会增加屈伸时的前后平移及胫骨旋转。临床检验中，这些特殊定向（前后向）的过度活动可作为前交叉韧带损伤的一个征兆。因此，有必要深入分析膝关节运动学，以比较正常膝关节及受损膝关节，有利于损伤诊断及评估治疗方案。

三、前交叉韧带损伤的临床检查

一般来说，膝关节损伤的诊断包括以下几个步骤：①损伤病史；②检查；③触诊；④活动范围；⑤神经肌肉功能。

X线检查可以帮助鉴定骨折。如果怀疑韧带及软骨损伤，应用磁共振做进一步检查。在此部分，我们不会对一般诊断方案做详细的描述，但对一些可用于确定急性前交叉韧带损伤的临床测试，我们会在以下部分做详细介绍。测试中，过度活动取决于

受力的大小和方向，在正常人群和关节韧带较松的人群中有显著差异。如患者单侧膝关节损伤时，建议比较患侧和正常侧的膝关节活动能力。

（一）Lachman测试

Lachman 测试诊断前交叉韧带损伤的准确度很高。测试中患者仰卧、屈膝约 30°，测试者扶稳股骨，胫骨向前用力并不限制中轴旋转。如膝关节前交叉韧带损伤，测试者会感受到胫骨前后移位，导致出现无移位限制（终点）。终点评估为稳固、中度稳固和不稳固。

（二）Pivot Shift测试

Pivot Shift 测试结合了内旋和外翻扭转，较为复杂。由于其结果要通过膝关节松弛度来决定，因此这项测试对测试者的技术和经验有较高要求。但是，轴移测试对前交叉韧带断裂的确定效果最好。测试中，主要是向腿施加外翻及内旋力。膝关节起先完全伸直，然后慢慢屈曲至 40°。Pivot Shift 测试呈阳性结果的患者屈膝时出现胫骨向前半脱位，这是因膝关节前交叉韧带受损而下陷的结果。

（三）KT 1000

这项设备是设计用于测量膝关节前后方向松弛度的。患者仰卧、屈膝 20° ~ 30°，由置于上端至腘窝中的牢固平台支撑。患者需要在此姿势下保持放松。然后在胫骨之间放置 KT 1000 关节测量仪，用两条束带固定。调零后，将关节测量仪往前方拉以制造垂直作用力（图 10-8-1）。当作用力为 15、20 和 30 磅（1 磅 =0.45kg）时，能听到响声提示。以毫米衡量前向移位，松弛度则由双侧差异衡量。

四、前交叉韧带重建的功能评估

（一）被动评估与主动评估

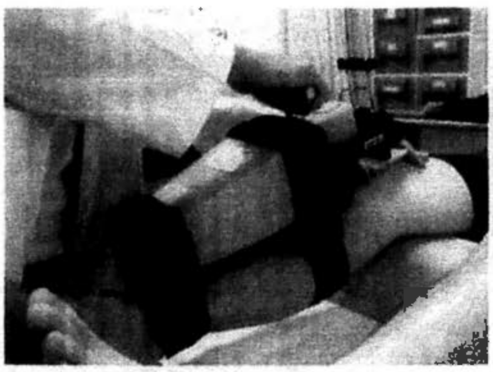


图 10-8-1 KT 1000 测量膝关节前后向松弛度

上一节中，我们回顾了一些诊断前交叉韧带损伤的临床测试。对于放松的膝关节施加特定方向和不同大小的力度，如果一侧膝关节比另一侧松弛，则说明有前交叉韧带损伤。这在临床上常用于确诊疑似膝关节损伤，且无需患者主动参与活动。但在手术后康复治疗期间，这不一定是最好的评估方法。运动医学的最终目的是令患者恢复运动水平；功能性膝关节稳定是恢复运动的一项必要条件。与 KT1000 等静态膝关节稳定的测试不同，动态功能测试涉及患者的肌力、神经肌肉感知以及患者对康复后的自信心等等。动态分析可以有效地测量特殊动态活动下膝关节的稳定性。

（二）光学动作分析

本节中，我们将探讨如何通过动作分析测试前交叉韧带重建手术前后前交叉韧带的损伤患者。功能测评在步态分析实验室（图 10-8-2）中进行，步态分析实验室中有 8 个高速摄影机和相关软件（VICON），可拍摄范围为 10m × 5m。在拍摄范围内，通过红外线摄影机可确认贴在皮肤上的 9mm 大小的反光球。在拍摄空间中心的地面上排放 6 块测力板，以收集运动中地面反应的受力数据（图 10-8-3）。

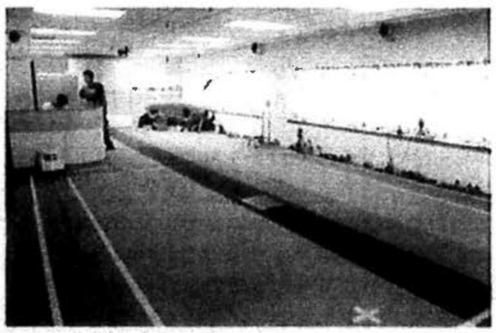


图 10-8-2 步态实验室

图 10-8-3 步态分析仪器

反光球的数目及位置对动作分析十分重要。我们采用Vaughan描述的方法测量膝关节运动学。用15个标记贴在下肢的解剖标志上，包括髂前上棘、大转子骨突、外侧股骨上髁、胫骨结节、外踝、足跟、第5跖骨头两侧和骶骨(图10-8-4)。在拍摄的动态运动中，需要先收集人体测量数据，包括体重、髂前上棘宽度，以及双侧下肢的大腿长、大腿中围、小腿长、小腿围、膝直径、足长、踝高、踝直径和足宽度。

图10-8-4 步态分析仪器的标记系统
左：正面视图；右：侧面视图

对于不同的动态运动在下一部分中将会详细讨论。在收集数据后，应明确定义需要分析的范围。由于着陆时存在非接触性前交叉韧带损伤的风险，我们选定的分析范围为足部与地面接触的时间。先收集站立姿态的数据，作为所有平面的所有关节间活动的参照。用软件(MATLAB)计算膝关节的屈曲角度、胫骨旋转度、外翻角度等动态数据。通过站立时的反光球坐标及人体测量数据，我们可以计算各关节中心的位置，再延伸至动态活动时的各种数据。

（三）动态运动

动态运动的测量应以临床诊断为基础，并且因研究的客观要求不同而各不相同。前交叉韧带损伤导致前后向及旋转不稳定，传统的手术方法是采用单束腘腱和自体腘绳肌腱，为前向胫骨载荷提供了良好的抵抗能力，但对旋转载荷无效。因此，双束腘腱和自体腘绳肌腱以其独特的解剖和生物力学，为近来出现的双束前交叉韧带重建术提供了理论支持，证明了该技术能令受损的前交叉韧带在术后实现或接近解剖及生物力学的正常化。因此，要测试前交叉韧带损伤和重建术后患者的动态动作要求，可使膝关节受到旋转和外翻的压力。

我们采用了一项混合动态动作，以测试患者的前交叉韧带损伤及重建。这套动作包括跳跃、着陆、中轴旋转及跑步。要求患者从一个40cm高的平台上向前跳，双脚着陆，向左或右中轴旋转90°并全速奔跑。由于运动令膝关节受到很大的旋转作用力，所以被视为高要求活动。

受伤原理是评估前交叉韧带损伤患者的依据之一。据报道，超过70%的前交叉韧带损伤发生在非接触状态，包括着陆、减速及转向。如果患者在做这些"高危"动作时仍表现出良好的稳定性，则说明该患者可以安全地重返运动场。因此，我们设计了3种急转向动作和4种跳跃动作来测试膝关节的稳定性。在急转环节中，要求患者奔跑并单脚急转向3个方面，即90°急转和左右两边的45°急转。跳跃环节包括向前跑、双脚落地、双脚起跳，以及尽力向4个方向跳跃，即垂直、向前、向右及向左。收集数据后，调整站立状态作进一步分析。然后通过坐标和测力板测量动力学和动态数据，这在评估膝关节松弛度中非常重要，同时还需要测量受损或重建的膝关节和正常膝关节。

在真正的比赛状态中，运动员无法预测下一步行动。大多数情况下，着陆及突然转向等动作通常是非预期的。实验室测试和真正的运动竞技会产生不同的生物力学表现。神经肌肉的生物力学研究显示，非预期的急转动作被认定为一种非接触性前交叉韧带损伤。为了制造这种非预期效果，我们设计了一种有光电接收器和光源的设备，布置在跑道上。在患者前面放置一个平面显示屏，为急转动作和跳跃动作方向提供随机的视觉提示。当患者通过该设备时，设备连接的电脑产生信号，从而制造了运动的视觉提示。这样的实验室装置可使测试者在短时间内作出决定，从而实现了在实验室内模拟比赛动作(图10-8-5)。

（四）讨论

至于中轴运动，在中轴旋转膝关节的站立状态时，从最初着陆接触到旋转后站起，各方面进行评估。因为中轴运动可使膝关节受到强旋转压力，因此我们侧重于此项研究。当开始中轴旋转时，上半身及股骨外旋，同时作为轴心的前脚钉在地面，导致胫

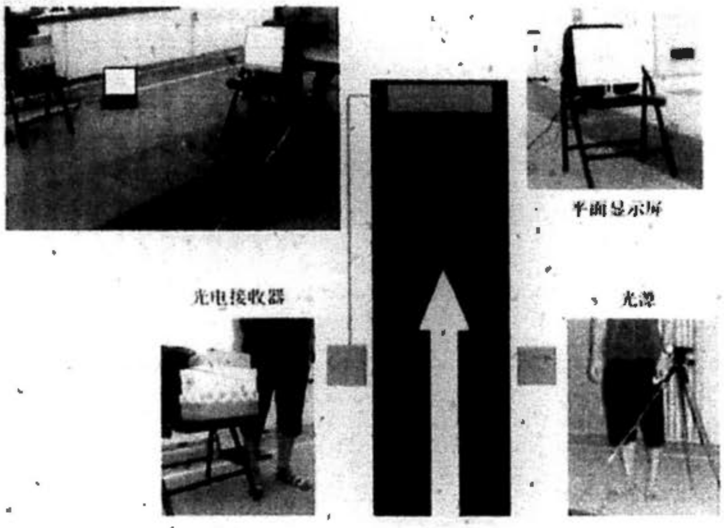


图 10-8-5　非预期效应的实验室设置

骨内旋至最大值。研究报道指出，受损膝关节的内旋范围明显要大于正常膝关节。但是该报告中并未提到着陆状态时外翻角度等其他动态数据，而这些数据也是前交叉韧带损伤患者不稳定的重要特征。总之，动态研究得到了相似的结果，不仅进一步确定了前交叉韧带损伤患者的旋转松弛度，也为双束前交叉韧带重建的长期评估提供了正确的测量方法。

五、手术时评估前交叉韧带重建

（一）电脑辅助导航系统

过去 10 年中，电脑辅助置换手术得到了很大的发展。其中之一是电脑导航系统，现用于脊椎手术和全关节手术。电脑导航系统包括两个基本组成部分：①特制摄像系统，用于确定手术关节和患肢的位置，以及扫描手术部位；②电脑程序，用于结合影像和手术信息，以及在手术期间辅助医师。

电脑可提供器械与骨之间的即时变化并且在手术期间辅助医师。此外，系统能够精确测量矢状面、横断面及冠状面的动态数据。这项技术在全膝关节置换手术中用以引导韧带平衡。同样，电脑辅助导航系统可用于手术时收集前交叉韧带重建前后不同平面的膝关节松弛度信息。因此，电脑辅助导航系统可有效地测量前交叉韧带重建的即时效果，特别适用于单束重建和双束重建技术之间的比较。

（二）手术技术

单束前交叉韧带重建手术使用腘绳肌腱作为移植物，通过标准的关节镜操作植入。电脑导航指引下，在矢状面 55° 作胫骨隧道，导针置于后交叉韧带前方 7mm 处。在导针线上，过顶点前方 5mm 处，11 点方向，钻股骨隧道。导针实为股骨隧道的轴心，在双束重建中前内束也处于同一位置。经股骨、胫骨隧道，由远端到近端穿入肌腱，固定前以手动拉紧。用 endo-button (Smith & Nephrew Endoscopy, Andover, Massachusetts) 和挤压螺钉固定股骨端，用挤压螺钉和门钉固定胫骨端。

双束前交叉韧带重建手术中使用腘绳肌腱作为移植物，通过双入路关节镜、前内侧辅助小切口植入。用半腱肌腱移植物复制前内束，股薄肌腱复制后外束。关节镜下从双入路分别建立胫骨与股骨隧道。胫骨隧道的角度分别为 45° 和 55°。如 Yagi 等所述，在附加的前内入路辅助建立股骨隧道。移植肌腱由远端到近端穿入隧道，在固定前手动拉紧。用 endobutton (Smith & Nephrew Endoscopy, Andover, Massachusetts) 和挤压螺钉将双束固定在股骨上。手动拉紧半腱肌腱（前内束），先在屈膝 15°，将其固定，然后固定后外束。

（三）导航细节及测量

在进行导航之前，小切口下用两个直径为 2.5mm 的克氏针将股骨与胫骨接受器固定于股骨与胫骨中（图 10-8-6）。同时建立关节外标记并输入系统，以确立股骨与胫骨隧道的位置。然后通过导航系统（图 10-8-7）测量手术内的膝关节动态数据。分

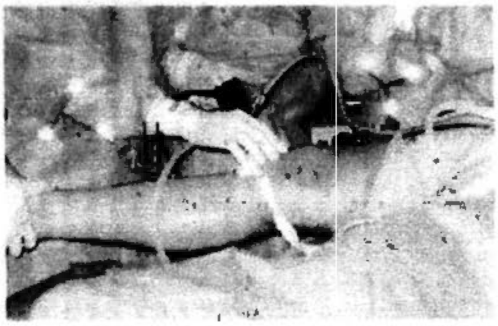


图 10-8-6 导航过程中，股骨与胫骨接受器固定入股骨与胫骨中

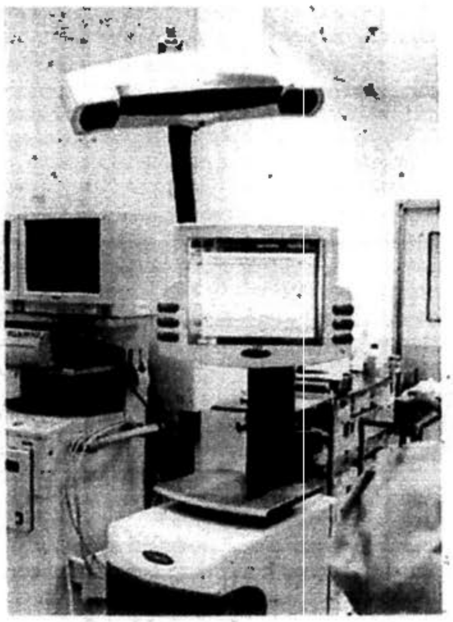


图 10-8-7 电脑导航系统辅助前交叉韧带重建

别在屈膝 0°、30° 和 90° 时，手动使前后胫骨最大平移，使胫骨最大内、外旋移动及胫骨最大内、外翻移动，同时测量和记录。前交叉韧带重建前后均进行各项测量并记录。记录前向轴移测试中胫骨旋转的变化。所有测量均在两名指定测量员提供最大的作用力下进行，其结果取最大值。

（四）讨论

在导航系统的帮助下，Pivot Shift 测试的数据记录更加客观。目前对于后侧束加前内束是否能提高动态旋转的稳定性，仍然存在争议，需要更多的相关研究。此外，Pivot Shift 测试并非是简单的单平面活动，而是前后向平移运动。在 Pivot Shift 测试中，这套软件只能产生胫骨旋转的结果。如果能产生平移运动，则能够获得更多的信息。本研究中，我们尝试找出单束及双束前交叉韧带重建的区别。目前我们只能肯定，成功的前交叉韧带重建可减少前后向松弛度，但在两种重建技术中，没有任何迹象表明胫骨旋转的最大角度在不同屈膝度时会产生变化。

（林默涵 何鸿仁 罗勤业 张粮泽 陈启明 容树恒 方通培）

评述与展望

——膝关节运动学测试于前交叉韧带损伤之应用

1. 膝关节运动学测试对于前交叉韧带受伤的患者可以分为 3 个阶段：临床测试、手术中测试及功能测试。

2. 临床测试用于确定前交叉韧带受伤，一般由专科骨科医生或有经验的测试者进行，以确保测试的准确性。

3. 当应用临床测试来确定前交叉韧带受伤时，患者需仰卧在床上并放松受测试一侧的肌肉；测试者于胫骨施以向前拉力，但要留意测试前胫骨的位置，以免错误确定为后交叉韧带受伤。

4. 手术中测试为前交叉韧带重建手术的患者应进行即时膝关节运动学测试，以评估手术的即时成效，以及用于比较不同的手术方法。

5. 电脑辅助导航系统不但能协助医生在手术中准确地为患者重建前交叉韧带，也能提供膝关节运动学的即时结果，其中包括此手术最侧重的前后方向及旋转方向稳定性。

6. 目前，手术中的测试只能靠医生在患者身上进行临床测试，此方法不能有效地控制和重复力量的准确性。未来发展应考虑在手术室中使用仪器准确控制力量，以使测试膝关节运动学。

7. 功能测试有别于一般的临床检查，患者需主动做出不同的特定动作，动作分析仪器会把动作录下，然后计算出此动作中的膝关节稳定性。

8. 特定动作应以临床测试为基础，并依据受伤原理及康复后的需要来决定。

9. 进行动作分析时，反光球应贴于骨头的特定位置，光反球的数量则视不同参数而改变。

10. 个体差异及性别差异均会影响膝关节的稳定性。如果患者只有单侧受伤，所有膝关节运动学

的测试应比较受伤及正常膝关节的差异。

（林默涵）

参 考 文 献

1. Besier T F, Lloyd D G, et al. Anticipatory effects on knee joint loading during running and cutting maneuvers. Medicine and Science in Sports and Exercise, 2001, 33(7): 1176-1181
2. Bull A M, H N Andersen, et al. Incidence and mechanism of the pivot shift. An in vitro study. Clinical Orthopaedics and Related Research, 1999(363): 219-231
3. Bull A M, Earnshaw P H, et al. Intraoperative measurement of knee kinematics in reconstruction of the anterior cruciate ligament. Journal of Bone and Joint Surgery-British Volume, 2002, 84(7): 1075-1081
4. Cavanagh P R, Lafortune M A, et al. Ground reaction forces in distance running. Journal of Biomechanics, 1980, 13(5): 397-406
5. Duthon V B, Barea C, et al. Anatomy of the anterior cruciate ligament. Knee Surgery Sports Traumatology Arthroscopy, 2006, 14(3): 204-213
6. Ferretti A, Monaco E, et al. Double-bundle anterior cruciate ligament reconstruction: a computer-assisted orthopaedic surgery study. American Journal of Sports Medicine, 2008, 36(4): 760-766
7. Girgis F G, Marshall J L, et al. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clinical Orthopaedics and Related Research, 1975(106): 216-231
8. Grood E S, Suntay W J. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. Journal of Biomechanical Engineering, 1983, 105(2): 136-144
9. Hara K, Kubo T, et al. Reconstruction of the anterior cruciate ligament using a double bundle. Arthroscopy, 2000, 16(8): 860-864
10. Holly L T, Foley K T. Intraoperative spinal navigation. Spine, 2003, 28(15 Suppl): S54-61
11. Hughes G, Watkins J. A risk-factor model for anterior cruciate ligament injury. Sports Medicine, 2006, 36(5): 411-428
12. Jonsson T, Althoff B, et al. Clinical diagnosis of ruptures of the anterior cruciate ligament: a comparative study of the Lachman test and the anterior drawer sign. American Journal of Sports Medicine, 1982, 10(2): 100-102
13. Kanamori A, Zeminski J, et al. The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. Arthroscopy, 2002, 18(4): 394-398
14. Kvist J. Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation. Sports Medicine, 2004, 34(4): 269-280
15. Landry SC, Mckean KA, et al. Neuromuscular and lower limb biomechanical differences exist between male and femal elite adolescent soccer players during an unanticipated side-cut maneuver. American Journal of Sports Medicine, 2007, 35(11): 1888-1900
16. Laskin R S, Beksac B. Computer-assisted navigation in TKA: where we are and where we are going. Clinical Orthopaedics & Related Research, 2006(452): 127-131
17. Norwood L A, Cross M J. Anterior cruciate ligament: functional anatomy of its bundles in rotatory instabilities. American Journal of Sports Medicine, 1979, 7(1): 23-26
18. Ostrowski J A. Accuracy of 3 diagnostic tests for anterior cruciate ligament tears. Journal of Athletic Training, 2006, 41(1): 120-121
19. Ristanis S, Giakas G, et al. The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs. Knee Surgery Sports Traumatology Arthroscopy, 2003, 11(6): 360-365
20. Robinson J, Carrat L, et al. Influence of anterior cruciate ligament bundles on knee kinematics: clinical assessment using computer-assisted navigation. American Journal of Sports Medicine, 2007, 35(12): 2006-2013
21. Siebold R, Dehler C, et al. Prospective randomized comparison of double-bundle versus single-bundle anterior cruciate ligament reconstruction. Arthroscopy, 2008, 24(2): 137-145
22. Vaughan C L, Davis B L, et al. Dynamics of Human Gait. Human Kinetics Publishers Champaign [s.l.]: [s.n.], 1992
23. Woo S L, Debski R E, et al. Biomechanics of knee ligaments. American Journal of Sports Medicine, 1999, 27(4): 533-543
24. Woo S L, Kanamori A, et al. The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon: a cadaveric study comparing anterior tibial and rotational loads. Journal of Bone and Joint Surgery-American Volume, 2002, 84-A(6): 907-914
25. Yagi M, Kuroda R, et al. Double-bundle ACL reconstruction can improve rotational stability. Clinical Orthopaedics and Related Research, 2007(454): 100-107

Editorial Manager(tm) for Knee Surgery, Sports Traumatology, Arthroscopy
Manuscript Draft

Manuscript Number:

Title: A systematic review on the biomechanical techniques to evaluate tibial rotation

Article Type: Review Paper

Corresponding Author: Daniel Tik-Pui Fong, PhD

Corresponding Author's Institution: The Chinese University of Hong Kong

First Author: Mak-Ham Lam

Order of Authors: Mak-Ham Lam;Daniel Tik-Pui Fong, PhD;Patrick Shu-Hang Yung;Kai-Ming Chan

Abstract: This article systematically reviewed the biomechanical techniques to evaluate tibial rotation, for the better understanding of how to choose suitable protocol with specific clinical application. A systematic search was conducted and finally 104 articles were included in this study. The articles under review were classified according to the three conditions in which the knee was examined: external load application, physical examination and dynamic task. The results showed that over 80% of the studies with external load application employed cadaveric model. The techniques used included magnetic sensing, optical tracking system and radiographic measurement. Intra-operative navigation system was used to document knee rotational kinematics when the knee was examined by clinical tests. To further evaluate knee rotational stability in terms of tibial rotation during dynamic tasks, optical motion analysis with skin reflective marker and radiographic measurement could be employed. Similar biomechanical techniques were summarized for discussion. Orthopaedic specialists and sport biomechanists are encouraged to better understand these techniques for the various needs of measurement of tibial rotation.

Suggested Reviewers: Chih-Hwa Chen
chihhwachen@gmail.com

TITLE: A systematic review on the biomechanical techniques to evaluate tibial rotation

KEYWORDS: Kinematics, methodology, stability

ABSTRACT

This article systematically reviewed the biomechanical techniques to evaluate tibial rotation, for the better understanding of how to choose suitable protocol with specific clinical application. A systematic search was conducted and finally 104 articles were included in this study. The articles under review were classified according to the three conditions in which the knee was examined: external load application, physical examination and dynamic task. The results showed that over 80% of the studies with external load application employed cadaveric model. The techniques used included magnetic sensing, optical tracking system and radiographic measurement. Intra-operative navigation system was used to document knee rotational kinematics when the knee was examined by clinical tests. To further evaluate knee rotational stability in terms of tibial rotation during dynamic tasks, optical motion analysis with skin reflective marker and radiographic measurement could be employed. Similar biomechanical techniques were summarized for discussion. Orthopaedic specialists and sport biomechanists are encouraged to better understand these techniques for the various needs of measurement of tibial rotation.

1. INTRODUCTION

The knee is the most commonly injured body sites during sports, accounting for about 40% of all sports injuries [67]. Traumatic knee injury such as ligament tear would lead to knee instability, prohibiting athletes from returning to sports, and resulting in early retirement [78] or even premature end to sport career [56]. Functional knee stability is one of the key return-to-sport criteria [56] as high demanding movements that stress on knee are always involved in real game situation. In clinical practice, knee laxity evaluation is based on physical examination performed by trained physician. Force or torque are manually applied to the knee joint to see if there is any abnormal motion when compared to the intact side. However, clinical examination has a few limitation [65], including inability to produce sufficient magnitude of force to simulate physical activity and subjective grading from physician's experience.

In the literature, there are various studies to assess knee laxity and stability. Besides clinical examination, self-reported outcome questionnaire is often used in clinical research. Knee stability items that reflect patients' functional limitation and instability are included in these questionnaires such as IKDC subjective knee evaluation scores. Another passive knee laxity assessment includes stressed magnetic resonance imaging [89] and objective clinical devices [27,105]. These assessments involve a controlled stress to the knee joint in a specific direction followed by an objective biomechanical rating for the corresponding laxity. In the contrary, dynamic movement is directly performed so that knee stability would be monitored during specific motion. For example, previous studies suggested that abnormal joint kinematics during dynamic movements after anterior cruciate ligament (ACL) reconstruction would contribute to long-term joint degeneration [85,102].

In view of the way to assess knee laxity and stability, biomechanics plays an important role. With the advanced biomechanical techniques, assessments have become objective, practical and accurate that suits the increasing demand on measuring knee rotational laxity and stability such as the role of knee structure, injury diagnosis and effect of ligament reconstruction. Therefore, there is a need to understand and familiar with the biomechanical techniques for its quantification and evaluation. In this review, we include techniques that have been used in cadaveric studies since research that lead to a better understanding of knee laxity and stability would not be ethical to employ on living human, for example validation of measurement tools.

In the current study, tibial rotation is defined as the relative movement of femur and tibia in the transverse plane. The biomechanical techniques would be classified when the knee is examined with different conditions: (1) under a certain external load [116], (2) physical examination by physician [55], or (3) a specific dynamic task performed by subjects [111]. Since there is a wide spectrum of measuring tools, there is a need for orthopaedic specialists and sport biomechanists to understand the overview and to choose the most suitable one for specific application. This paper systematically reviews the biomechanical techniques for measurement of tibial rotation.

2. METHOD

A systematic literature search of MEDLINE (from 1966) was conducted during the last week of December in 2010. The search keyword was (knee OR tibial OR tibia) AND (rotation OR rotational OR rotatory OR pivot OR pivoting) AND (biomechanics OR biomechanical OR kinematics OR displacement) AND (stability OR laxity), which appeared in the title, abstract or keyword fields. After duplicates were removed, the initial total number of articles in the database was 532. The title and abstract of each entry was read to identify. Non-English articles, review and surgical technique, animal studies and non-related articles were excluded. After this subsequent trimming, the count was reduced to 190. Online and library searches for the full text of these articles were conducted. Articles not available in the library of The Chinese University of Hong Kong were requested from libraries in other local universities. Only full text of two articles could not be retrieved, and the final number of articles with full text was 180.

The full text of each of the 180 retrieved articles was read to determine the inclusion and exclusion criteria in the systematic review. To be included in the systematic review, three criteria must be fulfilled: (1) the study must employ human, either cadaver specimen or living subject, (2) the study must present tibial rotation, measuring the relative movement of femur and tibia in the transverse plane, as a dependent parameter to quantify the knee rotational laxity and stability, (3) the study must not involve total knee arthroplasty or the prescription of knee prosthesis, since the knee anatomy is greatly altered in these studies. Current concepts, reviews, case reports, computerized model such as finite element model and studies without detailed description of the measuring technique were excluded. After the screening process, the final number of articles included in the analysis was 104.

The 104 selected articles were categorized by the conditions of how the knee was examined: (1) external load application   when the knee was under a certain rotational load in a controlled manner, (2) physical examination   when the knee was being clinically examined by an orthopaedic specialist, a physiotherapist or a biomechanist; (3) dynamic task – when the patient was performing a specific dynamic movement. Demographic data of all studies, including year of study, testing subject, biomechanical techniques and the study application were summarized.

3. RESULT

For all included studies, 69 articles (66%) employed human specimen for experiment and the rest 35 studies (34%) were living human. The earliest study in the search was conducted by Shoemaker and his coworkers [95] in 1982. Increasingly, the studies between 1980 and 1989, 1990 and 1999, 2000 and 2010 were 12, 16 and 76 respectively. The application all included studies vary from investigating knee structures to the effect of taping and bracing. The most common interest for researchers was ACL followed by posterolateral corner. The biomechanical technique that was employed in the included studies was shown in the following.

3.1 External load application

Of the 104 included articles, 74 articles (71%) were classified in this session. Sixty one studies (82%) applied on human cadaver for the testing subjects and the rest (13 studies) applied to living human.

3.1.1 Direct displacement measurement

The most direct way to measure rotational displacement was by employing a goniometer [2,35,54,90,107,114,115] or electrogoniometer [10,66,75,93,112]. Goniometer, also termed as protractor [86], potentiometer [4,24,46,69,94,95,100], transducer [21,22,31,57,92,110], was a general term and hence they all followed the same principle: While both sides of the knee were fixed, the goniometer was placed on the plane, which was perpendicular to the axis of rotation of tibia. The rotational displacement, therefore, was presented in a two dimensional plane on which the tibia rotation was controlled during load application. In addition, one study [39] employed bony pin to define rotational displacement such that the movement was restricted in transverse plane and relative movement between pins was then documented.

3.1.2 Magnetic sensing

Sixteen studies were found employing magnetic sensing technique since 1996. The technique was applicable to cadaver [3,7,8,9,15,17,33,63,73,79,80,88,106] and living human [96,97,105]. In cadaveric studies, magnetic sensors were directly attached to femur and tibia, and relative movement between both sides was monitored externally. Sensors were rigidly fixed to both sides using nylon posts [15] or fiberglass cylinders

[88]; on the contrary, it was necessary to attach sensors on the skin when it applies to living human. The lateral aspect of the subject's thigh and the tibial shaft were recommended as a reference site according to Shultz et al.'s study [97]. Different from direct displacement measurement, signal generated from an external receiver were extracted with the help of a computer-assisted program, which provided three dimensional position and orientation of the sensors [77]. Sometimes self-complied program is need for calculation of knee kinematics [3,106].

3.1.3 Optical tracking system

Optical instrument is one of the recent techniques for measurement of tibial rotation. Eight studies [26,53,58,59,68,72,76,82], with the earliest one published in 1990 [72], employed this technique and all applied to cadavers except one study [82] investigating gender difference in passive knee laxity test. The principle was similar to magnetic instrument. Clusters consisting of three to four infrared emitting spherical markers [26,59] were rigidly fixed to femur and tibia with metaphyseal bone screws [68]. Instead of an external magnetic receiver, infrared camera, was used to locate three-dimensional coordinates of markers that needed to be further digitized to establish an anatomically based coordinate system [34,117]. The rotational displacement was finally presented after mathematical calculation by the system software or self-complied program.

3.1.4 Radiographic measurement

Radiographic method was treated as the most accurate technique for validation over the other measurements [32] since it provided direct bone-to-bone information. Roentgen stereophotogrammetric analysis (RSA) was firstly developed in 1989 among a group of researchers from Sweden [47,50], applying to living human to measure knee rotational kinematics. Three to six tantalum markers with 0.8mm diameter were inserted to femur and tibia by means of arthroscopy or under local anesthesia. Bi-planar roentgenographic exposure films with 2-4Hz was collected 1-2 months later when the testing knee was under controlled rotational torque. The two dimensional coordinates of the markers were plotted on roentgen films and therefore three dimensional coordinates were computed in relation to laboratory coordinate system. The displacement was then calculated by customized program. Since invasive procedure was involved when inserting markers into femur and tibia, this technique was only employed in cadaveric studies [29,49].

3.2 Physical examination

Physical examination is commonly used in clinics to evaluate knee stability after ligamentous injury. Pivot shift test is commonly used in clinical setting for evaluating knee rotational stability while some clinicians apply external and internal rotation torque manually. However, the outcome of these tests is subjective grading but no objective kinematics data can be provided. Therefore, it was of researchers' interest to obtain knee kinematics by means of biomechanical techniques. In this category, fifteen studies were included (table 2). All studies were conducted after 2002. The three major techniques for measuring tibial rotation when examiner performed clinical tests were goniometer [91,113,123], electromagnetic sensing [36,37,118] and intra-operative navigation system [14,16,38,43,44,45,74,98,121]. These techniques were applicable on both cadaver and living human.

3.2.1 Intra-operative navigation

Computer assisted navigation system was a newly developed technique which especially designed for helping surgeons during operation. In the early stage of navigation development, it was used to assist orthopaedic surgeon to improve accuracy of reconstruction and replacement surgery [83]. New software recently allowed for research based 6 degree of freedom (DOF) knee kinematics measurement [38]. Therefore, it would provide an immediate evaluation of the surgical outcome [16]. For example, the effect of anteromedial and posterolateral bundles during anatomical double-bundle ACL reconstruction could be evaluated during operation in terms of knee kinematics [44].

Navigation was firstly applied to living human in 2005. The navigation system consisted of two transmitter with four markers attached, one calibration pointer and high speed camera connected to computer for exporting data. There were a few procedures to proceed knee kinematics measurement [44]. Radiographic film was assessed pre-operatively for creating virtual bone model in the computer system. Two set external reflective markers on each transmitter were firmly fixed on femur and tibia. To locate the relative movement, several intra-articular and extra-articular landmarks were manually digitized and were registered by the system using a straight pointer. After defining the 6 DOF directions between femur and tibia were defined, continuous real time knee kinematics could be obtained in the computer while clinical tests were being performed.

3.3 Dynamic task

All fifteen included studies were published after 2000 except two from 1980s. To be included in this section, knee kinematics should be quantified while the testing subjects were performing specific dynamic tasks. In the early years, electrogoniometer was used for measuring knee rotational displacement during treadmill running [18,52]. Before RSA was applied on living human in 2001 [12], there were about 10 years of vacuity where no journal papers were reported specifically investigating on knee rotational stability during dynamic task. The main techniques were summarized below.

3.3.1 Optical motion analysis with reflective skin markers

Motion analysis is a study of locomotion using continuous photographic technique. Advanced technique using motion analysis system with reflective skin markers to measure knee rotational stability was reported in 2003 [30]. Skin markers were placed on typical bony landmarks and subjects were asked to perform specific motions, which probably would give a rotational stress to the knee, while the three dimensional coordinates of the markers were captured by optical instruments. The markers' global coordinates were firstly collected through high speed optical cameras and then transformed to femoral and tibial reference frames. Relative displacements between both were finally calculated by computer programs based on published description of knee kinematics [34,117]. Marker-set, therefore, was critical in which location and number of markers varied. One of the frequently used models developed by Vaughan [109] consisted of 15 markers on lower extremities. Kinematics of hip, knee and ankle joint including tibial rotation could be derived from markers' global coordinates and 20 anthropometric measurements of the subject.

3.3.2 Radiographic measurement

In 2001, Brandsson and his coworkers [12,13] employed RSA to investigate knee rotation on subjects after ACL tear. Before the experiment, 4-5 tantalum markers were inserted into the distal femur and proximal tibia through arthroscopy surgery. Two radiographic tubes were used to obtain simultaneous exposures at 2-4 Hz. The radiographs were measured manually to digitized images using a scanner for subsequent digital analysis. In recent years, the radiographic measurement of tibial rotation in several studies [20,62,81,108] has reduced its invasiveness during the procedure. The subjects' knees were magnetic resonance scanned before their motions were captured by fluoroscopic testing system. The system combined the pre-scanned knee model and adjusted in 6 DOF until its projections matched the outlines of the bones in the fluoroscopic images. The 6 DOF knee position was reproduced using this knee model.

4. DISCUSSION

4.1 External load application

In the cadaveric studies, the both femur and tibia were mounted in fixation systems, which provided three to 6 DOF including primary motion (flexion-extension) and secondary motion (anterior-posterior translation, internal-external rotation and abduction-adduction) [23] for free movement under certain testing conditions. Among these fixation systems, a robotic/universal force moment sensor testing system was developed since 1996 [87] and was frequently applied to tissue biomechanical research [1,19,122] and simulated clinical testing research [42,48,119,120]. In addition, there were a few studies recruiting living human as subjects [10,46,64,66,95,97,100,118]. These studies employed a self-customized fixation system, in which rotational stress was applied to subjects until their limit of comfort [60].

The external load applied on the testing specimens or subjects included isolated external internal rotation torque [2], valgus varus torque [66], anterior tibial load [40], muscle load [61] and increased graft tension [11]. These specific loads provided a controlled situation that was widely applicable to research-based studies. Due to its experimental nature, it is not ethical to apply load to living human and it explains why 80% of the studies used cadaveric model. However, there were a few studies [60,82] recruiting living human as subjects that load was applied until the subjects' limit of comfort. The amount of load should be specifically designed and carefully estimated before employing to living human. In view of the amount of torque applied, over 50% of the cadaveric studies used 5Nm while other studies varied from 1.5Nm to 20Nm. The torque was much lower when applied to living subjects, ranging from 1.5Nm to 10Nm with 4 out of 12 studies using 5Nm as the testing torque.

Among the four techniques, magnetic sensing was reported to have highest accuracy with 0.15 degree [80] followed by radiographic measurement with 0.2 degree and reproducibility with 1.4 degrees [50]. Since most of the included studies used cadavers, measuring tools such as magnetic sensor or pin marker could be directly attached or implanted to bone, which inevitably results in a high accuracy measurement. On the other hand, there is always a concern that skin motion artifact exists when measuring knee rotation on living human and there would be an ethical problem of direct bony pin implantation. Skin artifact would be a considerable error if load was applied to living human that magnetic sensors attached over the skin involved muscle movement during load application. The ethical problem aside, RSA with bony marker implantation would be considered the best technique for measuring tibial rotational on living human.

4.2 Physical examination

Physical examination is one of the most feasible and practical way to evaluate knee rotational stability in orthopaedic clinics. The main defect, its subjective and discontinuous rating, has limited its application to research study. Different from experimental laboratory, setting operation theatre is not an ideal place to provide controlled load of application due to instrument size and hygiene concern. With no doubt, intra-operative navigation system would be the most suitable measurement tool in operation theatre. Since the torque to the knee should be applied manually by the tester, it is suggested that all physical examinations should be performed by one tester and reliability test should be conducted to ensure good consistency across studies.

Intra-operative navigation system provides immediate evaluation of surgical treatment. This technique spent an extra 10-minute time on average in addition to original procedures [71]. The extra time is considered acceptable as it provides a more reliable clinical result [84] and an objective way to quantify knee kinematics. Moreover, this technique gave a good repeatability [71] and a comparable result with mechanical testing devices (KT1000 and goniometer) [51]. Implementing the high precision navigation technique for comparing different reconstruction methods [99] and extending to other knee surgeries [70] would be one of the key research areas in the future.

Despite the fact that there are a number of advantages as discussed above, more attention should be paid to address the drawbacks. One should be reminded that the procedure involves invasiveness that may cause extra wounds in the thigh and shank of the subjects. To accurately locate the relative movement, transmitters with markers were screwed into femur and tibia. The invasive procedure would result in additional bone loss and surgical scars to patients. To minimize the invasive effect, an alternative way would be magnetic sensors attached on skin by plastic braces [118]. However, validation between two techniques should be established before its application to living human.

4.3 Dynamic task

Compared with the cadaveric study which is of limited clinical utility [28], dynamic task provided more important information of knee stability no matter the testing knee was intact [104], injured [41] or reconstructed [13]. In early years, techniques involving external fixation structure attached to subjects' limb would highly affect the gait pattern [18]. Optical motion analysis and radiographic measurement have therefore become the most frequently adopted techniques recently to measure knee rotational stability.

When comparing the drawbacks of the two techniques, RSA obviously involves invasive procedures and radiation exposure. Although the amount of exposure was reported to be similar to a single clinical knee computerized tomography scan [102], the controversial issue of implanting bony markers through arthroscopic surgery was another difficulty for subject recruitment. On the other hand, error due to skin movement when applying optical motion analysis with reflective skin marker was claimed [103]. A point cluster method was developed in 1998 [6] to tackle the problem. This method aimed to minimize the effects of skin motion artifact by employing an overabundance of markers on each segment. Its limitation of computational complexity [5] has become the major technical challenge to orthopaedic specialists while biomechanists are advised to understand the principle behind in order to achieve high accuracy result.

Motion analysis with skin marker technique is non-invasive, practical and applicable not only in research laboratory settings but also in orthopaedic clinics. The system consists of two or above high-speed cameras and a few spherical markers. Commercialized software system also includes auto-digitizing and kinematics calculation. Nevertheless, results of knee internal and external rotation from different marker-set protocols were poorly correlated [25]. For example, Thambyah et al. [104] used 17 skin markers while Georgoulis et al. [23] adopted the model with 15 skin markers developed by Vaughan [109]. Self-compiled program for calculating knee kinematics was also not standardized and comparison between studies with different marker-set protocols would be highly difficult if not impossible.

In recent years, Tashman and coworkers [101,102] employed RSA technique to evaluate knee kinematics of human ACL reconstructed knee during treadmill running after the application to canine ACL deficient knee in 2003. Similar to the similar protocol of biplane radiography generation with a transverse plane computer tomography scan to determine transformations between marker-based and anatomical coordinate systems, the exposure frequency of the RSA technique was highly increased to 250Hz, which enhanced a sufficient smooth continuous kinematics data during most of the human dynamics movements.

The biomechanics technique for measuring tibial rotational is well developed in cadaveric model. Accuracy of most of the techniques is reported to be high as bone to bone information could be obtained directly. There is still room of improvement on the techniques applied on living human, especially in the development of a practical and accurate technique for dynamic tasks. The future studies should focus on validity between magnetic measurement and radiographic measurement because the non-invasive magnetic sensor would be useful in orthopaedic clinics if it could produce reliable and valid measurement. Moreover, regarding the optical motion analysis with skin reflective marker, consensus should be obtained for standardized market-set protocol for measurement of tibial rotation during dynamic task.

5. CONCLUSION

The biomechanical techniques to measure tibial rotational were summarized, providing an overview of knee rotational kinematics measurement techniques. We systematically reviewed, from fundamental cadaveric studies to newly developed intra-operative tests, the measurement techniques according to the condition in which the knee was examined: external load application, physical examination and dynamic task. To choose a suitable measurement technique for specific clinical application, study purpose should be first identified, and more attention should be paid on whether cadaveric model would be employed, and also the way of stress applied to the knee.

6. REFERENCES

1. Allen CR, Wong EK, Livesay GA, Sakane M, Fu FH, and Woo SL, *Importance of the medial meniscus in the anterior cruciate ligament-deficient knee*. Journal of Orthopaedic Research, 2000. 18(1): p. 109-15.
2. Andersen HN and Dyhre-Poulsen P, *The anterior cruciate ligament does play a role in controlling axial rotation in the knee*. Knee Surgery, Sports Traumatology, Arthroscopy, 1997. 5(3): p. 145-9.
3. Anderson CJ, Westerhaus BD, Pietrini SD, Ziegler CG, Wijdicks CA, Johansen S, Engebretsen L, and Laprade RF, *Kinematic impact of anteromedial and posterolateral bundle graft fixation angles on double-bundle anterior cruciate ligament reconstructions*. Am J Sports Med, 2010. 38(8): p. 1575-83.
4. Anderson K, Wojtys EM, Loubert PV, and Miller RE, *A biomechanical evaluation of taping and bracing in reducing knee joint translation and rotation*. American Journal of Sports Medicine, 1992. 20(4): p. 416-21.
5. Andriacchi TP and Alexander EJ, *Studies of human locomotion: past, present and future*. Journal of Biomechanics, 2000. 33(10): p. 1217-24.
6. Andriacchi TP, Alexander EJ, Toney MK, Dyrby C, and Sum J, *A point cluster method for in vivo motion analysis: applied to a study of knee kinematics*. Journal of Biomechanical Engineering, 1998. 120(6): p. 743-9.
7. Apsingi S, Nguyen T, Bull AM, Unwin A, Deehan DJ, and Amis AA, *A comparison of modified Larson and 'anatomic' posterolateral corner reconstructions in knees with combined PCL and posterolateral corner deficiency*. Knee Surgery, Sports Traumatology, Arthroscopy, 2009. 17(3): p. 305-12.
8. Apsingi S, Nguyen T, Bull AM, Unwin A, Deehan DJ, and Amis AA, *Control of laxity in knees with combined posterior cruciate ligament and posterolateral corner deficiency: comparison of single-bundle versus double-bundle posterior cruciate ligament reconstruction combined with modified Larson posterolateral corner reconstruction*. American Journal of Sports Medicine, 2008. 36(3): p. 487-94.
9. Apsingi S, Nguyen T, Bull AM, Unwin A, Deehan DJ, and Amis AA, *The role of PCL reconstruction in knees with combined PCL and posterolateral corner deficiency*. Knee Surgery, Sports Traumatology, Arthroscopy, 2008. 16(2): p. 104-11.
10. Baxter MP, *Assessment of normal pediatric knee ligament laxity using the genucom*. Journal of Pediatric Orthopedics, 1988. 8(5): p. 546-50.
11. Brady MF, Bradley MP, Fleming BC, Fadale PD, Hulstyn MJ, and Banerjee R,

Effects of initial graft tension on the tibiofemoral compressive forces and joint position after anterior cruciate ligament reconstruction. American Journal of Sports Medicine, 2007. 35(3): p. 395-403.

12. Brandsson S, Karlsson J, Eriksson BI, and Karrholm J, *Kinematics after tear in the anterior cruciate ligament: dynamic bilateral radiostereometric studies in 11 patients.* Acta Orthopaedica Scandinavica, 2001. 72(4): p. 372-8.

13. Brandsson S, Karlsson J, Sward L, Kartus J, Eriksson BI, and Karrholm J, *Kinematics and laxity of the knee joint after anterior cruciate ligament reconstruction: pre- and postoperative radiostereometric studies.* American Journal of Sports Medicine, 2002. 30(3): p. 361-7.

14. Brophy RH, Voos JE, Shannon FJ, Granchi CC, Wickiewicz TL, Warren RF, and Pearle AD, *Changes in the length of virtual anterior cruciate ligament fibers during stability testing: a comparison of conventional single-bundle reconstruction and native anterior cruciate ligament.* American Journal of Sports Medicine, 2008. 36(11): p. 2196-203.

15. Bull AM, Andersen HN, Basso O, Targett J, and Amis AA, *Incidence and mechanism of the pivot shift. An in vitro study.* Clinical Orthopaedics & Related Research, 1999(363): p. 219-31.

16. Colombet P, Robinson J, Christel P, Franceschi JP, and Djian P, *Using navigation to measure rotation kinematics during ACL reconstruction.* Clinical Orthopaedics & Related Research, 2007. 454: p. 59-65.

17. Coobs BR, Wijdicks CA, Armitage BM, Spiridonov SI, Westerhaus BD, Johansen S, Engebretsen L, and Laprade RF, *An in vitro analysis of an anatomical medial knee reconstruction.* Am J Sports Med, 2010. 38(2): p. 339-47.

18. Czerniecki JM, Lippert F, and Olerud JE, *A biomechanical evaluation of tibiofemoral rotation in anterior cruciate deficient knees during walking and running.* American Journal of Sports Medicine, 1988. 16(4): p. 327-31.

19. Darcy SP, Kilger RH, Woo SL, and Debski RE, *Estimation of ACL forces by reproducing knee kinematics between sets of knees: A novel non-invasive methodology.* Journal of Biomechanics, 2006. 39(13): p. 2371-7.

20. Defrate LE, Papannagari R, Gill TJ, Moses JM, Pathare NP, and Li G, *The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis.[see comment].* American Journal of Sports Medicine, 2006. 34(8): p. 1240-6.

21. Draganich LF, Reider B, Ling M, and Samuelson M, *An in vitro study of an intraarticular and extraarticular reconstruction in the anterior cruciate ligament deficient knee.* American Journal of Sports Medicine, 1990. 18(3): p.

262-6.

22. Draganich LF, Reider B, and Miller PR, *An in vitro study of the Muller anterolateral femorotibial ligament tenodesis in the anterior cruciate ligament deficient knee.* American Journal of Sports Medicine, 1989. 17(3): p. 357-62.

23. Dyrby CO and Andriacchi TP, *Secondary motions of the knee during weight bearing and non-weight bearing activities.* Journal of Orthopaedic Research, 2004, 22(4): p. 794-800.

24. Engebretsen L, Lew WD, Lewis JL, Hunter RE, and Benum P, *Anterolateral rotatory instability of the knee. Cadaver study of extraarticular patellar-tendon transposition.* Acta Orthopaedica Scandinavica, 1990. 61(3): p. 225-30.

25. Ferrari A, Benedetti MG, Pavan E, Frigo C, Bettinelli D, Rabuffetti M, Crenna P, and Leardini A, *Quantitative comparison of five current protocols in gait analysis.* Gait Posture, 2008. 28(2): p. 207-16.

26. Ferrari DA, Wilson DR, and Hayes WC, *The effect of release of the popliteus and quadriceps force on rotation of the knee.* Clinical Orthopaedics & Related Research, 2003(412): p. 225-33.

27. Fink C, Hoser C, Hackl W, Navarro RA, and Benedetto KP, *Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture - is sports activity a determining variable?* International Journal of Sports Medicine, 2001. 22(4): p. 304-9.

28. Fu FH and Zollo BA, *Rotational instability of the knee: editorial comment.* Clinical Orthopaedics and Related Research, 2007. 454: p. 3-4.

29. Gaasbeek RD, Welsing RT, Verdonschot N, Rijnberg WJ, van Loon CJ, and van Kampen A, *Accuracy and initial stability of open- and closed-wedge high tibial osteotomy: a cadaveric RSA study.* Knee Surgery, Sports Traumatology, Arthroscopy, 2005. 13(8): p. 689-94.

30. Georgoulis AD, Papadonikolakis A, Papageorgiou CD, Mitsou A, and Stergiou N, *Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking.* American Journal of Sports Medicine, 2003. 31(1): p. 75-9.

31. Gollehon DL, Torzilli PA, and Warren RF, *The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study.* Journal of Bone & Joint Surgery - American Volume, 1987. 69(2): p. 233-42.

32. Granberry WM, Noble PC, and Woods GW, *Evaluation of an electrogoniometric instrument for measurement of laxity of the knee.[see comment].* Journal of Bone & Joint Surgery - American Volume, 1990. 72(9): p. 1316-22.

33. Griffith CJ, LaPrade RF, Johansen S, Armitage B, Wijdicks C, and Engebretsen L, *Medial knee injury: Part 1, static function of the individual components of the main medial knee structures.* American Journal of Sports Medicine, 2009. 37(9): p. 1762-70.

34. Grood ES and Suntay WJ, *A joint coordinate system for the clinical description of three-dimensional motions: application to the knee.* Journal of Biomechanical Engineering, 1983. 105(2): p. 136-44.

35. Gupte CM, Bull AM, Thomas RD, and Amis AA, *The meniscofemoral ligaments: secondary restraints to the posterior drawer. Analysis of anteroposterior and rotary laxity in the intact and posterior-cruciate-deficient knee.* Journal of Bone & Joint Surgery - British Volume, 2003. 85(5): p. 765-73.

36. Hagemeister N, Duval N, Yahia L, Krudwig W, Witzel U, and de Guise JA, *Comparison of two methods for reconstruction of the posterior cruciate ligament using a computer based method: quantitative evaluation of laxity, three-dimensional kinematics and ligament deformation measurement in cadaver knees.* Knee, 2002. 9(4): p. 291-9.

37. Hagemeister N, Duval N, Yahia L, Krudwig W, Witzel U, and de Guise JA, *Computer based method for the three-dimensional kinematic analysis of combined posterior cruciate ligament and postero-lateral complex reconstructions on cadaver knees.* Knee, 2003. 10(3): p. 249-56.

38. Hofbauer M, Valentin P, Kdolsky R, Ostermann RC, Graf A, Figl M, and Aldrian S, *Rotational and translational laxity after computer-navigated single- and double-bundle anterior cruciate ligament reconstruction.* Knee Surg Sports Traumatol Arthrosc, 2010. 18(9): p. 1201-7.

39. Hofmann AA, Wyatt RW, Bourne MH, and Daniels AU, *Knee stability in orthotic knee braces.* American Journal of Sports Medicine, 1984. 12(5): p. 371-4.

40. Hoher J, Harner CD, Vogrin TM, Baek GH, Carlin GJ, and Woo SL, *In situ forces in the posterolateral structures of the knee under posterior tibial loading in the intact and posterior cruciate ligament-deficient knee.* Journal of Orthopaedic Research, 1998. 16(6): p. 675-81.

41. Houck J and Yack HJ, *Giving way event during a combined stepping and crossover cutting task in an individual with anterior cruciate ligament deficiency.* Journal of Orthopaedic & Sports Physical Therapy, 2001. 31(9): p. 481-9; discussion 490-5.

42. Hsu WH, Fisk JA, Yamamoto Y, Debski RE, and Woo SL, *Differences in torsional joint stiffness of the knee between genders: a human cadaveric study.*

American Journal of Sports Medicine, 2006. 34(5): p. 765-70.

43. Ishibashi Y, Tsuda E, Fukuda A, Tsukada H, and Toh S, *Intraoperative biomechanical evaluation of anatomic anterior cruciate ligament reconstruction using a navigation system: comparison of hamstring tendon and bone-patellar tendon-bone graft*. American Journal of Sports Medicine, 2008. 36(10): p. 1903-12.

44. Ishibashi Y, Tsuda E, Tazawa K, Sato H, and Toh S, *Intraoperative evaluation of the anatomical double-bundle anterior cruciate ligament reconstruction with the OrthoPilot navigation system*. Orthopedics, 2005. 28(10 Suppl): p. s1277-82.

45. Ishibashi Y, Tsuda E, Yamamoto Y, Tsukada H, and Toh S, *Navigation evaluation of the pivot-shift phenomenon during double-bundle anterior cruciate ligament reconstruction: is the posterolateral bundle more important?* Arthroscopy, 2009. 25(5): p. 488-95.

46. Johannsen HV, Lind T, Jakobsen BW, and Kroner K, *Exercise induced knee joint laxity in distance runners*. British Journal of Sports Medicine, 1989. 23(3): p. 165-8.

47. Jonsson H and Karrholm J, *Brace effects on the unstable knee in 21 cases. A roentgen stereophotogrammetric comparison of three designs*. Acta Orthopaedica Scandinavica, 1990. 61(4): p. 313-8.

48. Kanamori A, Zeminski J, Rudy TW, Li G, Fu FH, and Woo SL, *The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test*. Arthroscopy, 2002. 18(4): p. 394-8.

49. Kaneda Y, Moriya H, Takahashi K, Shimada Y, and Tamaki T, *Experimental study on external tibial rotation of the knee*. American Journal of Sports Medicine, 1997. 25(6): p. 796-800.

50. Karrholm J, Elmqvist LG, Selvik G, and Hansson LI, *Chronic anterolateral instability of the knee. A roentgen stereophotogrammetric evaluation*. American Journal of Sports Medicine, 1989. 17(4): p. 555-63.

51. Kendoff D, Meller R, Citak M, Pearle A, Marquardt S, Krettek C, and Hufner T, *Navigation in ACL reconstruction - comparison with conventional measurement tools*. Technology & Health Care, 2007. 15(3): p. 221-30.

52. Knutzen KM, Bates BT, Schot P, and Hamill J, *A biomechanical analysis of two functional knee braces*. Medicine & Science in Sports & Exercise, 1987. 19(3): p. 303-9.

53. Kondo E, Merican AM, Yasuda K, and Amis AA, *Biomechanical comparisons of knee stability after anterior cruciate ligament reconstruction between 2*

clinically available transtibial procedures: anatomic double bundle versus single bundle. Am J Sports Med, 2010. 38(7): p. 1349-58.

54. Krudwig WK, Witzel U, and Ullrich K, *Posterolateral aspect and stability of the knee joint. II. Posterolateral instability and effect of isolated and combined posterolateral reconstruction on knee stability: a biomechanical study.* Knee Surgery, Sports Traumatology, Arthroscopy, 2002. 10(2): p. 91-5.

55. Kubo S, Muratsu H, Yoshiya S, Mizuno K, and Kurosaka M, *Reliability and usefulness of a new in vivo measurement system of the pivot shift.* Clinical Orthopaedics and Related Research, 2007. 454: p. 54-58.

56. Kvist J, *Rehabilitation following anterior cruciate ligament injury: current recommendations for sports participation.* Sports Medicine, 2004. 34(4): p. 269-80.

57. Lane JG, Irby SE, Kaufman K, Rangger C, and Daniel DM, *The anterior cruciate ligament in controlling axial rotation. An evaluation of its effect.* American Journal of Sports Medicine, 1994. 22(2): p. 289-93.

58. Laprade RF, Engebretsen L, Johansen S, Wentorf FA, and Kurtenbach C, *The effect of a proximal tibial medial opening wedge osteotomy on posterolateral knee instability: a biomechanical study.* American Journal of Sports Medicine, 2008. 36(5): p. 956-60.

59. LaPrade RF, Johansen S, Wentorf FA, Engebretsen L, Esterberg JL, and Tso A, *An analysis of an anatomical posterolateral knee reconstruction: an in vitro biomechanical study and development of a surgical technique.[see comment].* American Journal of Sports Medicine, 2004. 32(6): p. 1405-14.

60. Leven H, *Radiologic determination of rotational instability of the knee joint.* Acta Radiologica: Diagnosis, 1978. 19(4): p. 599-608.

61. Li G, Gill TJ, DeFrate LE, Zayontz S, Glatt V, and Zarins B, *Biomechanical consequences of PCL deficiency in the knee under simulated muscle loads--an in vitro experimental study.* Journal of Orthopaedic Research, 2002. 20(4): p. 887-92.

62. Li G, Papannagari R, Li M, Bingham J, Nha KW, Allred D, and Gill T, *Effect of posterior cruciate ligament deficiency on in vivo translation and rotation of the knee during weightbearing flexion.* American Journal of Sports Medicine, 2008. 36(3): p. 474-9.

63. Lie DT, Bull AM, and Amis AA, *Persistence of the mini pivot shift after anatomically placed anterior cruciate ligament reconstruction.* Clinical Orthopaedics & Related Research, 2007. 457: p. 203-9.

64. Louie JK and Mote CD, Jr., *Contribution of the musculature to rotatory laxity and torsional stiffness at the knee.* Journal of Biomechanics, 1987. 20(3): p.

281-300.

65. Lubowitz JH, Bernardini BJ, and Reid JB, 3rd, *Current concepts review: comprehensive physical examination for instability of the knee.* American Journal of Sports Medicine, 2008. 36(3): p. 577-94.

66. Lundberg M and Messner K, *Decrease in valgus stiffness after medial knee ligament injury. A 4-year clinical and mechanical follow-up study in 38 patients.* Acta Orthopaedica Scandinavica, 1994. 65(6): p. 615-9.

67. Majewski M, Susanne H, and Klaus S, *Epidemiology of athletic knee injuries. A 10-year study.* Knee, 2006. 13(3): p. 184-8.

68. Mannel H, Marin F, Claes L, and Durselen L, *Anterior cruciate ligament rupture translates the axes of motion within the knee.* Clinical Biomechanics, 2004. 19(2): p. 130-5.

69. Markolf KL, Jackson SR, and McAllister DR, *A comparison of 11 o'clock versus oblique femoral tunnels in the anterior cruciate ligament-reconstructed knee: knee kinematics during a simulated pivot test.* Am J Sports Med, 2010. 38(5): p. 912-7.

70. Martelli S, Zaffagnini S, Bignozzi S, Bontempi M, and Marcacci M, *Validation of a new protocol for computer-assisted evaluation of kinematics of double-bundle ACL reconstruction.* Clinical Biomechanics, 2006. 21(3): p. 279-87.

71. Martelli S, Zaffagnini S, Bignozzi S, Lopomo N, and Marcacci M, *Description and validation of a navigation system for intra-operative evaluation of knee laxity.* Computer Aided Surgery, 2007. 12(3): p. 181-8.

72. Matsumoto H, *Mechanism of the pivot shift.* Journal of Bone & Joint Surgery - British Volume, 1990. 72(5): p. 816-21.

73. McCarthy M, Camarda L, Wijdicks CA, Johansen S, Engebretsen L, and Laprade RF, *Anatomic posterolateral knee reconstructions require a popliteofibular ligament reconstruction through a tibial tunnel.* Am J Sports Med, 2010. 38(8): p. 1674-81.

74. Miura K, Ishibashi Y, Tsuda E, Fukuda A, Tsukada H, and Toh S, *Intraoperative comparison of knee laxity between anterior cruciate ligament-reconstructed knee and contralateral stable knee using navigation system.* Arthroscopy, 2010. 26(9): p. 1203-11.

75. Morin PM, Reindl R, Harvey EJ, Beckman L, and Steffen T, *Fibular fixation as an adjuvant to tibial intramedullary nailing in the treatment of combined distal third tibia and fibula fractures: a biomechanical investigation.* Canadian Journal of Surgery, 2008. 51(1): p. 45-50.

76. Mueller CA, Eingartner C, Schreitmueller E, Rupp S, Goldhahn J, Schuler F,

Weise K, Pfister U, and Suedkamp NP, *Primary stability of various forms of osteosynthesis in the treatment of fractures of the proximal tibia.* Journal of Bone & Joint Surgery - British Volume, 2005. 87(3): p. 426-32.

77. Musahl V, Bell KM, Tsai AG, Costic RS, Allaire R, Zantop T, Irrgang JJ, and Fu FH, *Development of a simple device for measurement of rotational knee laxity.* Knee Surgery Sports Traumatology Arthroscopy, 2007. 15(8): p. 1009-12.

78. Myklebust G and Bahr R, *Return to play guidelines after anterior cruciate ligament surgery.* British Journal of Sports Medicine, 2005. 39(3): p. 127-31.

79. Nau T, Chevalier Y, Hagemeister N, Deguise JA, and Duval N, *Comparison of 2 surgical techniques of posterolateral corner reconstruction of the knee.* American Journal of Sports Medicine, 2005. 33(12): p. 1838-45.

80. Nau T, Chevalier Y, Hagemeister N, Duval N, and deGuise JA, *3D kinematic in-vitro comparison of posterolateral corner reconstruction techniques in a combined injury model.* Knee Surgery, Sports Traumatology, Arthroscopy, 2005. 13(7): p. 572-80.

81. Papannagari R, Gill TJ, Defrate LE, Moses JM, Petruska AJ, and Li G, *In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation.* American Journal of Sports Medicine, 2006. 34(12): p. 2006-12.

82. Park HS, Wilson NA, and Zhang LQ, *Gender differences in passive knee biomechanical properties in tibial rotation.* Journal of Orthopaedic Research, 2008. 26(7): p. 937-44.

83. Picard F, DiGioia AM, Moody J, Martinek V, Fu FH, Rytel M, Nikou C, LaBarca RS, and Jaramaz B, *Accuracy in tunnel placement for ACL reconstruction. Comparison of traditional arthroscopic and computer-assisted navigation techniques.* Computer Aided Surgery, 2001. 6(5): p. 279-89.

84. Plaweski S, Cazal J, Rosell P, and Merloz P, *Anterior cruciate ligament reconstruction using navigation: a comparative study on 60 patients.* American Journal of Sports Medicine, 2006. 34(4): p. 542-52.

85. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, and Georgoulis AD, *Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction.* Arthroscopy, 2005. 21(11): p. 1323-9.

86. Robinson JR, Bull AM, Thomas RR, and Amis AA, *The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity.* American Journal of Sports Medicine, 2006. 34(11): p. 1815-23.

87. Rudy TW, Livesay GA, Woo SL, and Fu FH, *A combined robotic/universal*

force sensor approach to determine in situ forces of knee ligaments. Journal of Biomechanics, 1996. 29(10): p. 1357-60.

88. Samuelson M, Draganich LF, Zhou X, Krumins P, and Reider B, *The effects of knee reconstruction on combined anterior cruciate ligament and anterolateral capsular deficiencies.* American Journal of Sports Medicine, 1996. 24(4): p. 492-7.

89. Scarvell JM, Smith PN, Refshauge KM, Galloway H, and Woods K, *Comparison of kinematics in the healthy and ACL injured knee using MRI.* Journal of Biomechanics, 2005. 38(2): p. 255-62.

90. Scopp JM, Jasper LE, Belkoff SM, and Moorman CT, 3rd, *The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts.* Arthroscopy, 2004. 20(3): p. 294-9.

91. Sekiya JK, Whiddon DR, Zehms CT, and Miller MD, *A clinically relevant assessment of posterior cruciate ligament and posterolateral corner injuries. Evaluation of isolated and combined deficiency.* Journal of Bone & Joint Surgery - American Volume, 2008. 90(8): p. 1621-7.

92. Shahane SA, Ibbotson C, Strachan R, and Bickerstaff DR, *The popliteofibular ligament. An anatomical study of the posterolateral corner of the knee.* Journal of Bone & Joint Surgery - British Volume, 1999. 81(4): p. 636-42.

93. Shapiro MS, Markolf KL, Finerman GA, and Mitchell PW, *The effect of section of the medial collateral ligament on force generated in the anterior cruciate ligament.* Journal of Bone & Joint Surgery - American Volume, 1991. 73(2): p. 248-56.

94. Shoemaker SC and Markolf KL, *Effects of joint load on the stiffness and laxity of ligament-deficient knees. An in vitro study of the anterior cruciate and medial collateral ligaments.* Journal of Bone & Joint Surgery - American Volume, 1985. 67(1): p. 136-46.

95. Shoemaker SC and Markolf KL, *In vivo rotatory knee stability. Ligamentous and muscular contributions.* Journal of Bone & Joint Surgery - American Volume, 1982. 64(2): p. 208-16.

96. Shultz SJ and Schmitz RJ, *Effects of transverse and frontal plane knee laxity on hip and knee neuromechanics during drop landings.* American Journal of Sports Medicine, 2009. 37(9): p. 1821-30.

97. Shultz SJ, Shimokochi Y, Nguyen AD, Schmitz RJ, Beynnon BD, and Perrin DH, *Measurement of varus-valgus and internal-external rotational knee laxities in vivo--Part II: relationship with anterior-posterior and general joint laxity in males and females.* Journal of Orthopaedic Research, 2007. 25(8): p.

989-96.

98. Song EK, Seon JK, Park SJ, Hur CI, and Lee DS, *In vivo laxity of stable versus anterior cruciate ligament-injured knees using a navigation system: a comparative study.* Knee Surgery, Sports Traumatology, Arthroscopy, 2009. 17(8): p. 941-5.

99. Steckel H, Murtha PE, Costic RS, Moody JE, Jaramaz B, and Fu FH, *Computer evaluation of kinematics of anterior cruciate ligament reconstructions.* Clinical Orthopaedics & Related Research, 2007. 463: p. 37-42.

100. Stoller DW, Markolf KL, Zager SA, and Shoemaker SC, *The effects of exercise, ice, and ultrasonography on torsional laxity of the knee.* Clinical Orthopaedics & Related Research, 1983(174): p. 172-80.

101. Tashman S, Collon D, Anderson K, Kolowich P, and Anderst W, *Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction.* American Journal of Sports Medicine, 2004. 32(4): p. 975-83.

102. Tashman S, Kolowich P, Collon D, Anderson K, and Anderst W, *Dynamic function of the ACL-reconstructed knee during running.* Clinical Orthopaedics and Related Research, 2007. 454: p. 66-73.

103. Taylor WR, Ehrig RM, Duda GN, Schell H, Seebeck P, and Heller MO, *On the influence of soft tissue coverage in the determination of bone kinematics using skin markers.* Journal of Orthopaedic Research, 2005. 23(4): p. 726-34.

104. Thambyah A, Thiagarajan P, and Goh Cho Hong J, *Knee joint moments during stair climbing of patients with anterior cruciate ligament deficiency.* Clinical Biomechanics, 2004. 19(5): p. 489-96.

105. Tsai AG, Musahl V, Steckel H, Bell KM, Zantop T, Irrgang JJ, and Fu FH, *Rotational knee laxity: reliability of a simple measurement device in vivo.* BMC Musculoskeletal Disorders, 2008. 9: p. 35.

106. Tsai AG, Wijdicks CA, Walsh MP, and Laprade RF, *Comparative kinematic evaluation of all-inside single-bundle and double-bundle anterior cruciate ligament reconstruction. a biomechanical study.* Am J Sports Med, 2010. 38(2): p. 263-72.

107. Ullrich K, Krudwig WK, and Witzel U, *Posterolateral aspect and stability of the knee joint. I. Anatomy and function of the popliteus muscle-tendon unit: an anatomical and biomechanical study.* Knee Surgery, Sports Traumatology, Arthroscopy, 2002. 10(2): p. 86-90.

108. Van de Velde SK, Gill TJ, DeFrate LE, Papannagari R, and Li G, *The effect of anterior cruciate ligament deficiency and reconstruction on the patellofemoral joint.* American Journal of Sports Medicine, 2008. 36(6): p. 1150-9.

109. Vaughan CL, Davis BL, and O'Conner JC, *Dynamics of Human Gait*. 1992: Human Kinetics Publishers Champaign

110. Veltri DM, Deng XH, Torzilli PA, Maynard MJ, and Warren RF, *The role of the popliteofibular ligament in stability of the human knee. A biomechanical study.* American Journal of Sports Medicine, 1996. 24(1): p. 19-27.

111. Waite JC, Beard DJ, Dodd CA, Murray DW, and Gill HS, *In vivo kinematics of the ACL deficient limb during running and cutting.* Knee Surgery Sports Traumatology Arthroscopy, 2005. 13(5): p. 377-84.

112. Wascher DC, Grauer JD, and Markoff KL, *Biceps tendon tenodesis for posterolateral instability of the knee. An in vitro study.* American Journal of Sports Medicine, 1993. 21(3): p. 400-6.

113. Whiddon DR, Zehms CT, Miller MD, Quinby JS, Montgomery SL, and Sekiya JK, *Double compared with single-bundle open inlay posterior cruciate ligament reconstruction in a cadaver model.* Journal of Bone & Joint Surgery - American Volume, 2008. 90(9): p. 1820-9.

114. Wojtys EM, Goldstein SA, Redfern M, Trier E, and Matthews LS, *A biomechanical evaluation of the Lenox Hill knee brace.* Clinical Orthopaedics & Related Research, 1987(220): p. 179-84.

115. Wojtys EM, Loubert PV, Samson SY, and Viviano DM, *Use of a knee-brace for control of tibial translation and rotation. A comparison, in cadavera, of available models.[see comment].* Journal of Bone & Joint Surgery - American Volume, 1990. 72(9): p. 1323-9.

116. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, and Fu FH, *The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon . A cadaveric study comparing anterior tibial and rotational loads.* Journal of Bone and Joint Surgery - American Volume, 2002. 84-A(6): p. 907-14.

117. Wu G and Cavanagh PR, *ISB recommendations for standardization in the reporting of kinematic data.* Journal of Biomechanics, 1995. 28(10): p. 1257-61.

118. Yagi M, Kuroda R, Nagamune K, Yoshiya S, and Kurosaka M, *Double-bundle ACL reconstruction can improve rotational stability.* Clinical Orthopaedics and Related Research, 2007. 454: p. 100-107.

119. Yamamoto Y, Hsu WH, Fisk JA, Van Scyoc AH, Miura K, and Woo SL, *Effect of the iliotibial band on knee biomechanics during a simulated pivot shift test.* Journal of Orthopaedic Research, 2006. 24(5): p. 967-73.

120. Yamamoto Y, Hsu WH, Woo SL, Van Scyoc AH, Takakura Y, and Debski RE, *Knee stability and graft function after anterior cruciate ligament*

22/23

reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. American Journal of Sports Medicine, 2004. 32(8): p. 1825-32.

121. Zaffagnini S, Bruni D, Martelli S, Imakiire N, Marcacci M, and Russo A. *Double-bundle ACL reconstruction: influence of femoral tunnel orientation in knee laxity analyzed with a navigation system - an in-vitro biomechanical study.* BMC Musculoskeletal Disorders, 2008. 9: p. 25.

122. Zantop T, Herbort M, Raschke MJ, Fu FH, and Petersen W. *The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation.* American Journal of Sports Medicine, 2007. 35(2): p. 223-7

123. Zehms CT, Whiddon DR, Miller MD, Quinby JS, Montgomery SL, Campbell RB, and Sekiya JK. *Comparison of a double bundle arthroscopic inlay and open inlay posterior cruciate ligament reconstruction using clinically relevant tools: a cadaveric study.* Arthroscopy, 2008. 24(4): p. 472-80.

Appendix F

Editorial Manager(tm) for Knee Surgery, Sports Traumatology, Arthroscopy
Manuscript Draft

Manuscript Number:

Title: A biomechanical device to quantify knee rotational laxity: validity and reliability on human specimens

Article Type: Original Paper

Corresponding Author: Daniel Tik-Pui Fong, PhD

Corresponding Author's Institution: The Chinese University of Hong Kong

First Author: Mak-Ham Lam

Order of Authors: Mak-Ham Lam;Patrick Shu-Hang Yung;Daniel Tik-Pui Fong, PhD;Aaron See-Long Hung;Wood-Yee Chan;Kai-Ming Chan

Abstract: Background: Biomechanical measurement tools have been developed and widely used to precisely quantify knee anterior-posterior laxity after anterior cruciate ligament (ACL) injury. However, objective device to document knee rotational laxity has not been well established in the literature. The proposed knee rotational laxity meter would accurately and reliably measure tibial rotation. Methods: A new biomechanical device to quantify knee internal and external rotation under different applied torques (1-10Nm) to the knee joint was developed. Its reliability and validity were tested using cadaveric human specimens. Intra-rater and inter-rater reliability were quantified in terms of intraclass correlation (ICC) coefficient among trials and between testers. Validity was verified by comparing data from a computer assisted navigation system. Mean, standard deviation and 95% confident interval of the difference as well as the root mean square difference were calculated. The correlations were deemed to be reliable if the ICC was above 0.75. Results: The intra-rater and inter-rater reliability achieved high correlation for both internal and external rotation, ranged from 0.959 to 0.992. For the validity, ICC for both internal and external rotation was 0.78. The mean differences between the proposed meter and the navigation system were 2.3 degrees and 2.5 degrees for internal and external rotation respectively.Conclusions: A new knee rotational laxity meter was proposed in this study. Its reliability and validity were verified by showing high correlation among trials, between testers and when compared to a golden standard of measurement. This non-invasive and simple device might be used in a wide field to document knee rotational laxity with various purposes, especially after ACL injury.

Suggested Reviewers: Chih-Hwa Chen
chihhwachen@gmail.com

Olaf Lorbach
olaf.lorbach@gmx.de

TITLE

A biomechanical device to quantify knee rotational laxity: validity and reliability on human specimens

AUTHOR LIST

Mak-Ham LAM[1,2], Patrick Shu-Hang YUNG[1,2], Daniel Tik-Pui FONG[1,2], Aaron See-Long HUNG[1,2], Wood-Yee CHAN[3], Kai-Ming CHAN[1,2]

Institutions:

[1]Department of Orthopaedics and Traumatology, Prince of Wales, Hospital, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China.

[2]The Hong Kong Jockey Club Sports Medicine and Health Sciences Centre, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China

[3]School of Biomedical Sciences, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China

CORRESPONDING AUTHOR

Dr. Daniel FONG, Department of Orthopaedics and Traumatology, Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong, Hong Kong, China. dfong@ort.cuhk.edu.hk

ACKNOWLEDGEMENTS

This research project was made possible by equipment/resources donated by The Hong Kong Jockey Club Charities Trust.

ABSTRACT

Background: Biomechanical measurement tools have been developed and widely used to precisely quantify knee anterior-posterior laxity after anterior cruciate ligament (ACL) injury. However, objective device to document knee rotational laxity has not been well established in the literature. The proposed knee rotational laxity meter would accurately and reliably measure tibial rotation.

Methods: A new biomechanical device to quantify knee internal and external rotation under different applied torques (1-10Nm) to the knee joint was developed. Its reliability and validity were tested using cadaveric human specimens. Intra-rater and inter-rater reliability were quantified in terms of intraclass correlation (ICC) coefficient among trials and between testers. Validity was verified by comparing data from a computer assisted navigation system. Mean, standard deviation and 95% confident interval of the difference as well as the root mean square difference were calculated. The correlations were deemed to be reliable if the ICC was above 0.75.

Results: The intra-rater and inter-rater reliability achieved high correlation for both internal and external rotation, ranged from 0.959 to 0.992. For the validity, ICC for both internal and external rotation was 0.78. The mean differences between the proposed meter and the navigation system were 2.3 degrees and 2.5 degrees for internal and external rotation respectively.

Conclusions: A new knee rotational laxity meter was proposed in this study. Its reliability and validity were verified by showing high correlation among trials, between testers and when compared to a golden standard of measurement. This non-invasive and simple device might be used in a wide field to document knee rotational laxity with various purposes, especially after ACL injury.

Key Terms: Tibial rotation, knee stability, measurement, laxity

INTRODUCTION

The knee is the most commonly injured body site in sports, which accounts for 10-40% [8,20]. Among all sport-related knee injuries, around 45% is related to ligamentous injury [10,22]. An accurate diagnosis of knee ligamentous injury relies on comprehensive physical examination, which relates to symptoms and functional instability of the injured patients [13]. Since some of the physical examinations for assessing anterior-posterior laxity of the knee are greatly influenced by the examiners' experience and skill [16,21], objective tools [24,31,33] have been developed and proven to precisely quantify knee laxity after anterior cruciate ligament (ACL) injury.

The restoration of knee rotational stability is recently being emphasized because anatomic double-bundle ACL reconstruction has been suggested to restore rotational stability better than single-bundle ACL reconstruction [6]. However, it is still highly controversial. Pivot shift test and dial test are often employed by clinicians to measure knee rotational stability before and after ACL reconstruction [15,23,38]. Again, these manual examinations are subjective and dependent on examiners' experience and skill. Therefore, an objective tool that measures tibial rotation would be of great value to document knee rotational laxity of healthy and injured knees.

The procedures for measuring knee laxity should be simple, easy and practical in clinical setting. It may not be practical to use motion analysis system with skin marker, although it has been utilized in previous research to quantify tibial rotation [17,29,36]. Motion sensor was employed by a recent study [25], in which three electromagnetic (EM) sensors were attached to the lower limb to measure knee rotational laxity in a relaxed state. The device was only proven to be reliable on cadaver and human subjects [35] but no validity data was presented. Moreover, computer assisted navigation system [2,5,11] has been used to measure intra-operative knee kinematics during ACL reconstruction. Though it was reported that the system could achieve an accuracy of 1 degree [14], the procedure is invasive to the patient as it involves rigid fixation of bone markers pins.

In this study, a new meter for measuring tibial rotation was presented. The meter consisted of an ankle orthosis, torque sensor and one motion sensor. The orthosis design aimed to provide a more simple way to prevent any ankle motion over the previous boot design. Furthermore, only one motion sensor was used to avoid calculation complexity among the three sensors reported previously. Torque and motion sensors were used to measure the applied torque and the corresponding tibial rotation. The objective of this study was to measure the validity, inter-rater and intra-rater reliability of the proposed meter. It was hypothesized that the meter would accurately and reliably measure tibial rotation.

METHODS

We presented here the details of the knee rotational laxity meter, which aimed to measure external and internal tibial rotation. The meter consisted of an ankle orthosis, a torque sensor with a handle bar and one motion sensor at the bottom of the meter (Figure 1). The orthosis is a common orthotic device that is used to immobilize the ankle joint of patients suffering from ankle related injuries. Three sizes of orthosis that accommodated patients with different sizes of foot were fabricated in the Department of Prosthetics and Orthotics. Next, a torque sensor (FUTEK, USA), which monitored the value of applied torque, was mounted at the bottom of each orthosis. A handle bar fixed on the torque sensor allowed tester to apply torques to the knee joint. One EM motion sensor with acquisition frequency 120Hz (trakSTAR

Ascension Technologies Corporation, USA) was further attached to the other side of the torque sensor such that its longitudinal axis was along the tibia's axis of rotation. The motion sensor provided six degrees of freedom of its orientation and position with high speed and accurate tracking data. The orientation data were outputted to a laptop computer. It was used to measure tibial rotation during the laxity test.

In this study, three preserved human specimens of the lower extremity, including hip, knee and ankle joints, were used. The experiment was conducted in mortuary of Prince of Wales Hospital, Faculty of Medicine, The Chinese University of Hong Kong. The specimens were checked by inspection, palpation and physical examination to exclude any obvious bony deformity, previous fracture, arthritic change and ligamentous hyper laxity.

For all the specimens, femur was sawed at 15 cm above the joint line. Two 30 cm long bone pins were drilled through the femur from medial to lateral side. It was then fixed on an autopsy table using two custom-made clamps that allowed free movement of tibia for conducting biomechanical testing. Two pairs of 4.5 mm pins were inserted over the anterior side of the distal femur and proximal tibia. These pins were used for anchoring trackers of the computer assisted navigation system.

An intra-operative navigation system (BrainLAB, Germany) with ACL Reconstruction System Version 2.0 was employed as a golden standard for measuring internal and external tibial rotation with accuracy less than one degree. It also used to monitor the knee flexion angle throughout the experiment. Before the start of the experiment, two sets of infrared optical motion trackers were fixed to the pins that had drilled into femur and tibia previously. The trackers were oriented such that it could be visualized within the full range of motion by the navigation system camera. The system was calibrated by using an infrared pointer to digitize required points inside and outside the knee joint. A three dimensional model of the knee was calculated by the system that presented a real time specific movements of the knee including flexion, extension, internal rotation and external rotation.

Two independent testers were included in the experiment for measuring knee laxity using the proposed meter. The orthosis was secured to the leg with a tourniquet and the leg was held at 30 degrees of knee flexion and neutral position of rotation, which was determined by the navigation system. At this point, the reading of torque sensor was set to zero. Each tester applied external torque to the handle bar until 10Nm torque was reached and then 10Nm torque of internal rotation was applied in the same way (Figure 2). A maximum of 10Nm torque was applied because human comfortable limit was reported to be between 5-10Nm [27]. The measurements were repeated three times for each tester. The first tester repeated the whole procedure for the rest of the knee specimens. The data from the navigation system was recorded by a technician while the EM sensor data were automatically recorded in the computer for further analysis.

For statistical analysis, single measures intraclass correlation (ICC) with 95% confidence interval (CI) was used to gauge intra-rater and inter-rater reliability and validity. For intra-rater reliability, the ICC across three trials was calculated for both testers. The average of the three trials for tester 1 was compared to the average of the three trials for tester 2 to determine inter-rater reliability. For validity, data from the proposed meter and the navigation system would be compared. Mean, standard deviation and 95% CI of the difference as well as root mean square difference at different applied torques were calculated. All parameters were reported for internal and external rotations separately. A reliable correlation was shown if the single measures ICC was above 0.75.

RESULTS

The EM sensor at the bottom of the proposed meter measured tibial rotation relative to femur. The internal and external rotation angles increased with applied torque to the knee for both the proposed meter and the navigation system (Figure 3). At 5Nm applied torque, the total range of rotation measured from the proposed meter (from the navigation system) was 38.0±2.0 (34.0±2.6) degrees with 21.3±0.6 (19.7±1.5) degrees internal rotation and 16.7±2.5 (14.3±1.2) degrees external rotation. The highest applied torque of 10Nm resulted in the total range of rotation of 59.3±3.5 (43.3±1.2) degrees with 32.7±2.5 (24.0±2.0) degrees internal rotation and 26.7±3.2 (19.3±1.2) degrees external rotation.

For reliability, intra-rater and inter-rater reliability achieved high correlation for both internal and external rotation, ranged from 0.959 to 0.992 (Table 1). For validity, when compared with the navigation system as a golden standard, ICC for both internal and external rotation was 0.78, which was regarded a reliable correlation. The mean differences between the proposed meter and the navigation system were 2.3 degrees and 2.5 degrees for internal and external rotation respectively. The root mean square difference varied with the applied torque, which ranged from 1.0 degree to 8.8 degrees (Table 2).

DISCUSSION

In this study, a new biomechanical device for measuring knee rotational laxity was developed, and its reliability and validity were tested in a cadaveric model. Results showed that the correlations between and within subjects were high, which supported our hypothesis that the proposed meter was a reliable measurement tool. Though the validity correlation between the proposed meter and the navigation system was not as high as the reliability correlation, its ICC was above the pre-set value. Moreover, the mean difference for internal and external rotation between the two measurement tools was below 2.5 degrees. The results also supported that the meter was an accurate device to measure tibial rotation for assessing knee rotational laxity.

The overall reliability of the proposed meter was high and comparable to other previous studies. The ICC coefficient was reported to be above 0.94 for all intra-tester and inter-tester reliability in a similar cadaveric study in which a device for measurement of rotational knee laxity was developed [25]. With the same device, it was further applied on living human and revealed an ICC coefficient of 0.81-0.88 and 0.77 for inter-tester and test-retest reliability respectively [35]. Other studies reported the reliability from 0.86 to 0.98 depending on the value of applied torque, rotation direction and side of the knee [19,32].

When checking criterion validity of a measurement tool, a comparative instrument as a golden standard should be used and the correlation coefficient between the two measurement tools should preferably be above 0.70 [30]. In this study, the navigation system was employed as a golden standard for measuring tibial rotation. Since the relative movement between femur and tibia was based on two sets of bone pin markers, the navigation system has been regarded as an accurate method [4,28,34].

However, because of its invasive procedure, the validity of the proposed meter could only be achieved in cadaveric model. That made our finding hardly comparable to others previous studies. Musahl and coworkers [25] tested in a best case scenario for their new device, in which the EM sensors were directly fixed to the femur and tibia. Therefore, no validity was tested in their study. In another cadaveric study [18], a similar device was validated with a navigation system, and the correlation achieved was from 0.83 to 0.95. However, the tibial bone was fixed with screws to a metal bar which was cemented in a custom-made inside-boot. Conceivably, this allowed accurate measurement for bone motion [26]. In the current study, the ICC coefficient between our device and the navigation system was above the preferred value. Together with the low mean difference, we provided evidence of the validity of our proposed device.

In the present study, the validity of the proposed meter was quantified. Lower extremity specimens including knee and ankle joints, thigh, shank and foot segments were used to simulate a clinically relevant situation. To minimize ankle joint rotation and motion between the leg and the device when applying rotational torque, an orthosis was secured with a tourniquet such that the rotational torque was directly applied to the knee joint. The motion sensor was longitudinally placed at the bottom of the foot segment (attached to the device) such that its rotational axis was in line with tibia rotational axis. The assumption we made here was that the shank segment was cylindrical and therefore the motion sensor and the tibia rotated along the same axis. One advantage of this idea was to avoid placing the motion sensor directly on the skin, which would cause error up to 13 degrees in measuring rotations [1], especially in obese patients. From Figure 1, the error increased during small and high applied torques though the two measurement values were highly correlated. It was possibly because pre-loading was necessary before the motion sensor value became stable.

This finding was also comparable to the previous study [18] that the error at 10Nm applied torque was 8.4 degrees and even up to 14.2 degrees at 15Nm. It suggested that the motion between the leg and the device would not be completely avoided, especially at large applied torque. Moreover, 5Nm torque was commonly adopted in the previous studies for measuring knee rotational laxity [3,9,37]. In consideration of clinical application, torques ranged 4-6Nm were suggested in the future study employing our device because of its small error.

The proposed meter was designed to be clinically relevant. It would be a simple, easy operating and practical device for quantifying knee rotational laxity, especially for patients after ACL injuries in orthopaedic settings. This was why a new design was modified from previously study[25]. An ankle orthosis was used instead of an ankle boot because orthosis is easier for patients to put on and get secured with tourniquet. Moreover, only one motion sensor was used in order to provide a real time reading for the operator. This is important since it allows a quick and simple assessment in orthopaedics clinic. In the present study, 30 degrees of knee flexion was chosen for validating the device. One of the reasons was that this particular knee flexion angle might be sensitive to detect knee rotational laxity for healthy, ACL deficient and reconstructed patients since ACL has its maximum elongation peak at this flexion angle [7]. Moreover, biomechanical investigations demonstrated that ACL injuries mostly occur in slight flexion angles [13]. Furthermore, one should bear in mind that reproducibility should be verified again in human subjects before applying in clinical field. A standardized procedure for securing orthosis with different sizes to the leg should also be considered.

This study was limited by the fact that it was a cadaveric experimental test although the device would hopefully be applied on living humans. However, as pointed out previously, it was not ethical to employ invasive procedures in human subjects when validating the device. The only way to conduct such kind of research was to apply on human cadaveric specimens. Although great efforts were made to simulate a clinically relevant situation, one limitation was that the femur was firmly attached to the autopsy table by bone bins and clamps, which was not possible when measuring laxity in real patients. Therefore, future studies were suggested to investigate a non-invasive way to stabilize the thigh and verify its effect in living human subjects. This would be important as minimizing the femur rotation would enhance accurate torque to be applied to the knee joint. Other limitations also included low sample size that existed in most cadaveric experiments and preserved human specimen. Due to the limited availability of fresh cadavers in different locations, the specimen number was minimized to fulfill the statistical requirement.

CONCLUSION

A new knee rotational laxity meter was proposed in this study. Its reliability and validity were verified in a cadaveric model by showing high correlation among trials and as compared to a golden standard of measurement. This non-invasive and simple device might be used in a wide field to document knee rotational laxity with various purposes.

FIGURE AND TABLE CAPTIONS

Figure 1: A knee rotational laxity meter consisting of an ankle orthosis, a torque sensor with a handle bar and one motion sensor at the bottom of the meter

Figure 2: Experimental setup for validating knee rotational laxity meter

Figure 3: Internal and external rotational angle under different applied rotational torque (1-10Nm)

Table 1: Reliability of knee rotational laxity meter

Table 2: Validity of knee rotational laxity meter

REFERENCES

1. Benoit DL, Ramsey DK, Lamontagne M, Xu L, Wretenberg P, and Renstrom P, *Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo*. Gait and Posture, 2006. 24(2): p. 152-64.
2. Bignozzi S, Zaffagnini S, Lopomo N, Fu FH, Irrgang JJ, and Marcacci M, *Clinical relevance of static and dynamic tests after anatomical double-bundle ACL reconstruction*. Knee Surg Sports Traumatol Arthrosc, 2010. 18(1): p. 37-42.
3. Branch TP, Browne JE, Campbell JD, Siebold R, Freedberg HI, Arendt EA, Lavoie F, Neyret P, and Jacobs CA, *Rotational laxity greater in patients with contralateral anterior cruciate ligament injury than healthy volunteers*. Knee Surg Sports Traumatol Arthrosc, 2010. 18(10): p. 1379-84.
4. Colombet P, Robinson J, Christel P, Franceschi JP, and Djian P, *Using navigation to measure rotation kinematics during ACL reconstruction*. Clinical Orthopaedics and Related Research, 2007. 454: p. 59-65.
5. Ferretti A, Monaco E, Labianca L, De Carli A, Maestri B, and Conteduca F, *Double-bundle anterior cruciate ligament reconstruction: a comprehensive kinematic study using navigation*. American Journal of Sports Medicine, 2009. 37(8): p. 1548-53.
6. Fu FH and Zelle BA, *Rotational instability of the knee: editorial comment* Clinical Orthopaedics and Related Research, 2007. 454: p. 3-4.
7. Gabriel MT, Wong EK, Woo SL, Yagi M, and Debski RE, *Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads*. Journal of Orthopaedic Research, 2004. 22(1): p. 85-9.
8. Hinton RY, Lincoln AE, Almquist JL, Douoguih WA, and Sharma KM, *Epidemiology of lacrosse injuries in high school-aged girls and boys: a 3-year prospective study*. American Journal of Sports Medicine, 2005. 33(9): p. 1305-14.
9. Ho EP, Lam MH, Chung MM, Fong DT, Law BK, Yung PS, Chan WY, and Chan KM, *Comparison of 2 surgical techniques for reconstructing posterolateral corner of the knee: a cadaveric study evaluated by navigation system*. Arthroscopy, 2011. 27(1): p. 89-96.
10. Ingram JG, Fields SK, Yard EE, and Comstock RD, *Epidemiology of knee injuries among boys and girls in US high school athletics*. Am J Sports Med, 2008. 36(6): p. 1116-22.
11. Kanaya A, Ochi M, Deie M, Adachi N, Nishimori M, and Nakamae A, *Intraoperative evaluation of anteroposterior and rotational stabilities in*

anterior cruciate ligament reconstruction: lower femoral tunnel placed single-bundle versus double-bundle reconstruction. Knee Surg Sports Traumatol Arthrosc, 2009. 17(8): p. 907-13.

12. Kocher MS, Steadman JR, Briggs KK, Sterett WI, and Hawkins RJ, *Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction.* American Journal of Sports Medicine, 2004. 32(3): p. 629-34.
13. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, and Krosshaug T, *Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball.* Am J Sports Med, 2010. 38(11): p. 2218-25.
14. Koh J, *Computer-assisted navigation and anterior cruciate ligament reconstruction: accuracy and outcomes.* Orthopedics, 2005. 28(10 Suppl): p. S1283-7.
15. Kondo E, Yasuda K, Azuma H, Tanabe Y, and Yagi T, *Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients.* Am J Sports Med, 2008. 36(9): p. 1675-87.
16. Lam MH, Fong DTP, Yung PSH, Ho EPY, Chan WY, and Chan KM, *Knee stability assessment on anterior cruciate ligament injury: Clinical and biomechanical approaches.* Sports Med Arthrosc Rehabil Ther Technol, 2009. 1(1): p. 20.
17. Lam MH, Fong DTP, Yung PSH, Ho EPY, Fung KY, and Chan KM, *Knee rotational stability during pivoting movement is restored after anatomic double-bundle anterior cruciate ligament reconstruction.* Am J Sports Med, (inpress).
18. Lorbach O, Wilmes P, Maas S, Zerbe T, Busch L, Kohn D, and Seil R, *A non-invasive device to objectively measure tibial rotation: verification of the device.* Knee Surg Sports Traumatol Arthrosc, 2009. 17(7): p. 756-62.
19. Lorbach O, Wilmes P, Theisen D, Brockmeyer M, Maas S, Kohn D, and Seil R, *Reliability testing of a new device to measure tibial rotation.* Knee Surg Sports Traumatol Arthrosc, 2009. 17(8): p. 920-6.
20. Louw QA, Manilall J, and Grimmer KA, *Epidemiology of knee injuries among adolescents: a systematic review.* British Journal of Sports Medicine, 2008. 42(1): p. 2-10.
21. Lubowitz JH, Bernardini BJ, and Reid JB, 3rd, *Current concepts review: comprehensive physical examination for instability of the knee.* American

Journal of Sports Medicine, 2008. 36(3): p. 577-94.

22. Majewski M, Susanne H, and Klaus S, *Epidemiology of athletic knee injuries: A 10-year study.* Knee, 2006. 13(3): p. 184-8.

23. Meredick RB, Vance KJ, Appleby D, and Lubowitz JH, *Outcome of single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a meta-analysis.* Am J Sports Med, 2008. 36(7): p. 1414-21.

24. Monaco E, Labianca L, Maestri B, De Carli A, Conteduca F, and Ferretti A, *Instrumented measurements of knee laxity: KT-1000 versus navigation.* Knee Surg Sports Traumatol Arthrosc, 2009. 17(6): p. 617-21.

25. Musahl V, Bell KM, Tsai AG, Costic RS, Allaire R, Zantop T, Irrgang JJ, and Fu FH, *Development of a simple device for measurement of rotational knee laxity.* Knee Surgery Sports Traumatology Arthroscopy, 2007. 15(8): p. 1009-12.

26. Musahl V and Fu FH, *Influence of the anteromedial and posterolateral bundles of the anterior cruciate ligament on external and internal tibiofemoral rotation.* Am J Sports Med, 2010. 38(9): p. NP1; author reply NP1-2.

27. Park HS, Wilson NA, and Zhang LQ, *Gender differences in passive knee biomechanical properties in tibial rotation.* Journal of Orthopaedic Research, 2008. 26(7): p. 937-44.

28. Pearle AD, Solomon DJ, Wanich T, Moreau-Gaudry A, Granchi CC, Wickiewicz TL, and Warren RF, *Reliability of navigated knee stability examination: a cadaveric evaluation.* American Journal of Sports Medicine, 2007. 35(8): p. 1315-20.

29. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, and Georgoulis AD, *Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction.* Arthroscopy, 2005. 21(11): p. 1323-9.

30. Scholtes VA, Terwee CB, and Poolman RW, *What makes a measurement instrument valid and reliable?* Injury, (inpress).

31. Schuster AJ, McNicholas MJ, Wachtl SW, McGurty DW, and Jakob RP, *A new mechanical testing device for measuring anteroposterior knee laxity.* Am J Sports Med, 2004. 32(7): p. 1731-5.

32. Shultz SJ, Shimokochi Y, Nguyen AD, Schmitz RJ, Beynnon BD, and Perrin DH, *Measurement of varus-valgus and internal-external rotational knee laxities in vivo--Part I: assessment of measurement reliability and bilateral asymmetry.* Journal of Orthopaedic Research, 2007. 25(8): p. 981-8.

33. Staubli HU and Jakob RP, *Anterior knee motion analysis. Measurement and simultaneous radiography.* Am J Sports Med, 1991. 19(2): p. 172-7.

34. Steckel H, Murtha PE, Costic RS, Moody JE, Jaramaz B, and Fu FH, *Computer evaluation of kinematics of anterior cruciate ligament reconstructions.* Clin Orthop Relat Res, 2007. 463: p. 37-42.

35. Tsai AG, Musahl V, Steckel H, Bell KM, Zantop T, Irrgang JJ, and Fu FH, *Rotational knee laxity: reliability of a simple measurement device in vivo.* BMC Musculoskeletal Disorders, 2008. 9: p. 35.

36. Waite JC, Beard DJ, Dodd CA, Murray DW, and Gill HS, *In vivo kinematics of the ACL-deficient limb during running and cutting.* Knee Surgery Sports Traumatology Arthroscopy, 2005. 13(5): p. 377-84.

37. Woo SL and Fisher MB, *Evaluation of knee stability with use of a robotic system.* J Bone Joint Surg Am, 2009. 91 Suppl 1: p. 78-84.

38. Yagi M, Kuroda R, Nagamune K, Yoshiya S, and Kurosaka M, *Double-bundle ACL reconstruction can improve rotational stability.* Clinical Orthopaedics and Related Research, 2007. 454: p. 100-107.

Figure1

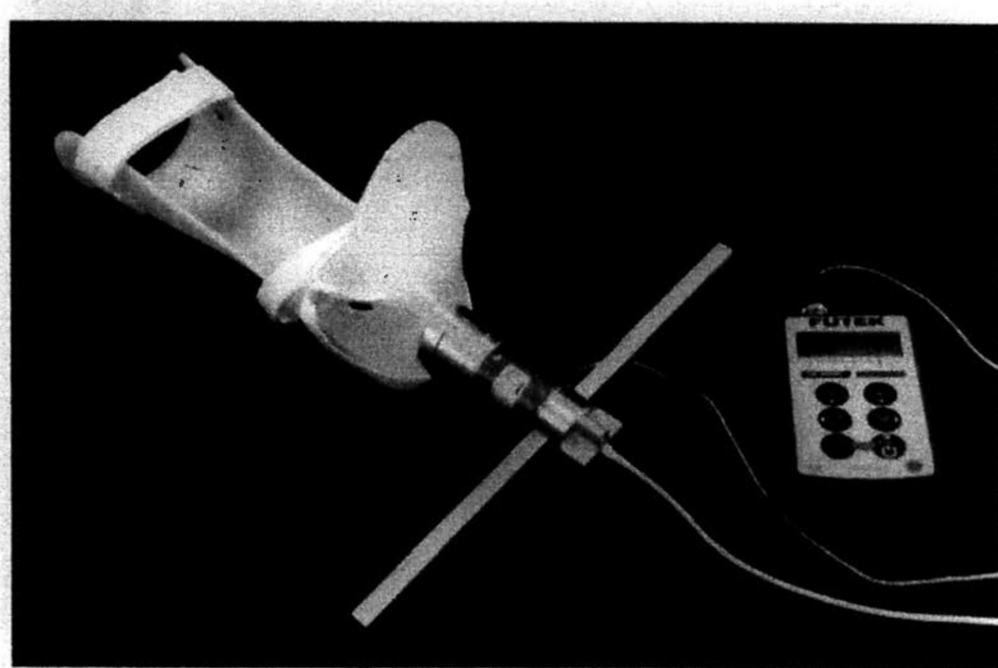


Figure2

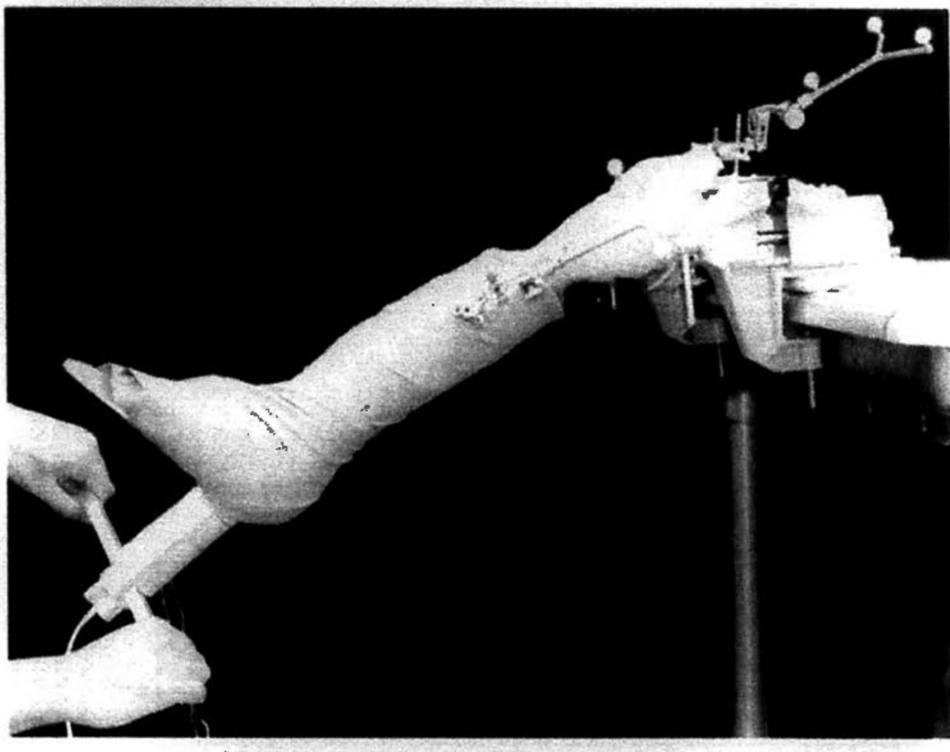


Figure3

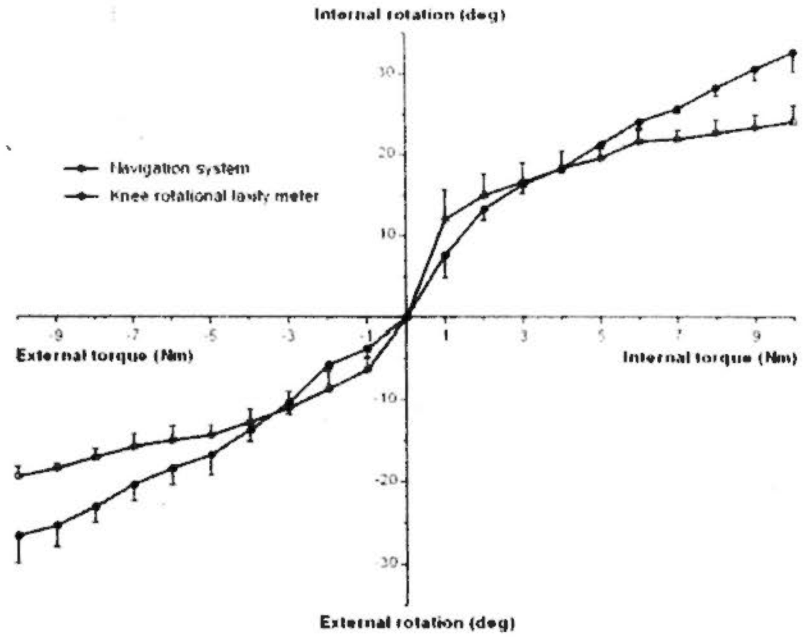


Table1

Table 1. Reliability of knee rotational laxity meter

	Intra-rater reliability				Inter-rater reliability	
	Tester 1		Tester 2		Tester 1 and 2	
	ICC	95% CI	ICC	95% CI	ICC	95% CI
Internal rotation	0.983	0.885,0.996	0.992	0.977,0.998	0.989	0.896,0.998
External rotation	0.939	0.566,0.992	0.972	0.857,0.993	0.990	0.958,0.998

ICC: intraclass correlation CI: confidence interval

Table2

Table 2. Validity of knee rotational laxity meter

	Torque (Nm)	Internal rotation	External rotation
ICC		0.78	0.78
95% CI of ICC		0.59,0.89	0.59,0.89
Mean difference (deg)		2.30	2.53
SD of difference (deg)		4.15	4.17
95% CI of mean difference (deg)		0.75,3.85	0.98,4.09
Root mean square difference (deg) at different torques	1	4.80	2.83
	2	2.08	3.42
	3	1.00	1.83
	4	1.41	2.83
	5	1.91	3.70
	6	2.52	4.16
	7	3.70	5.10
	8	5.69	6.16
	9	7.44	7.19
	10	8.83	7.53

ICC: intraclass correlation CI: confidence interval SD: standard deviation

Appendix G

Sports Biomechanics

Effect of anticipation on landing maneuver during stop-jumping task

Journal:	*Sports Biomechanics*
Manuscript ID:	Draft
Manuscript Type:	Original Research
Date Submitted by the Author:	n/a
Complete List of Authors:	Lam, Mak-Ham; The Chinese University of Hong Kong Lai, Pik-Kwan; The Chinese University of Hong Kong Fong, Daniel; The Chinese University of Hong Kong, Orthopaedics and Traumatology Yung, Patrick; The Chinese University of Hong Kong Fung, Kwai-Yau; The Chinese University of Hong Kong Chan, Kai-Ming; The Chinese University of Hong Kong
Keywords:	Knee < Body, Kinematics < Movement, Instability, functional

URL: http://mc.manuscriptcentral.com/rspb Email: ykwon@twu.edu

ABSTRACT

Knee stability during functional assessment such as stop-jumping task is a key factors to determine if an athlete is adequately rehabilitated after knee ligamentous injury. This study aimed to investigate the effect of anticipation on landing maneuvers during planned and unplanned stop-jumping tasks. Knee kinematics of ten healthy male participants was collected using an optical motion analysis system during planned and unplanned stop-jumping tasks. A photocell gate was set on the walkway in laboratory such that an instruction signal was triggered on a monitor when the participants passed through the gate. Data at the time of foot strike were considered for investigating the anticipation effect during the stop-jumping tasks. Knee kinematics data were compared between planned and unplanned tasks. Statistical significance was wet at $p<0.05$ level. External rotational angle showed significant decreased in unplanned stop-jumping task during forward ($p<0.05$) and right ($p<0.05$) jump when compared to that of planned tasks. Flexion angle and abduction angle during forward, vertical and right jump were significantly decreased in the unplanned tasks. Anticipation effect significantly influenced the landing maneuvers of stop-jumping task and we suggested that both planned and unplanned stop-jumping tasks should be considered when monitoring the rehabilitation progress after knee ligamentous injury.

INTRODUCTION

The knee is the most commonly injured body site in sports, which accounts for 10-40% (Hinton, Lincoln, Almquist, Douoguih, & Sharma, 2005; Louw, Manilall, & Grimmer, 2008) of all injuries. Among all sport-related knee injuries, around 45% is related to ligamentous injury (Ingram, Fields, Yard, & Comstock, 2008; Majewski, Susanne, & Klaus, 2006). Athletes who suffer from ligament disruption would experience knee instability (Veltri, Deng, Torzilli, Warren, & Maynard, 1995; Woo, Debski, Withrow, & Janaushek, 1999). Knee ligament reconstruction such as anterior cruciate ligament (ACL) reconstruction aims to restore the functional stability and allows athletes to return to sports activity (Myklebust & Bahr, 2005). Therefore, functional test is used during follow-up consultation to evaluate if an athlete is adequately rehabilitated (Risberg & Ekeland, 1994). The movement tasks employed vary with different purposes, for example running (Tashman, Kolowich, Collon, Anderson, & Anderst, 2007) is used to evaluate gait pattern while hopping (Fitzgerald, Lephart, Hwang, & Wainner, 2001) is used to test muscle power. However, knee stability is seldom considered during high demand functional task.

Knee stability is usually evaluated by clinicians and athletes themselves through subjective assessments such as clinical examination and questionnaire (Moller, Weidenhielm, & Werner, 2009; Stengel et al., 2009; Tegner & Lysholm, 1985; Tyler, McHugh, Gleim, & Nicholas, 1999). Objective assessments have been developed for assessing anterior-posterior translation (Monaco et al., 2009) and axial rotation (Musahl et al., 2007) of the knee. However, these measurement tools are limited to passive laxity test. Knee rotational stability in terms of tibial rotation has been investigated during dynamic functional tasks (Georgoulis, Ristanis, Chouliaras, Moraiti, & Stergiou, 2007; Lam et al., (inpress); Ristanis et al., 2005). These studies evaluated tibial rotation during a high demand pivoting task before and after ACL reconstruction. Besides pivoting, stop jumping task (Sell et al., 2006; Yu et al., 2005) and cutting task (Beaulieu, Lamontagne, & Xu, 2008; Besier, Lloyd, Ackland, & Cochrane, 2001; Houck, De Haven, & Maloney, 2007; Houck, Duncan, & De Haven, 2006; Pollard, Sigward, & Powers, 2007) have also been employed in kinematics studies but no study focused on knee rotational stability.

Anticipation effect refers to the phenomenon that individuals change their motion pattern when potential threats or dangers are expected (Cham & Redfern, 2002). It involves in most of the sport movements and research has revealed that unplanned movement is more danger than planned movement (Besier et al., 2001). Possible reasons suggest quick and unplanned movement affect muscle activation patterns and result abnormal joint kinematics (Beaulieu et al., 2008; Besier et al., 2001; Sell et al., 2006). For example, Besier and coworkers(Besier et al., 2001) suggested that unplanned cutting maneuvers would increase the risk of non-contact ACL injury and Sell and coworkers (Sell et al., 2006) found lateral jump was the most dangerous among 3-direction stop-jumping tasks. However, there is limited knowledge if the unplanned movements affect on knee rotational stability during functional tasks. This information would be important to decide if anticipation effect should be considered during dynamic functional assessment after knee ligamentous injury.

This study aimed to investigate the anticipation effect on knee kinematics during stop-jumping tasks in laboratory. Kinematics at foot strike (Cham & Redfern, 2002) was considered in our study as ACL injury was reported to occur 17-50 milliseconds after initial foot strike during landing (Krosshaug et al., 2007). We hypothesized that there was significant difference for landing maneuver in terms of tibial rotation between planned and unplanned stop jumping tasks. If returning to sport is the ultimate goal of knee ligament reconstruction, such information is important for sport biomechanists to design functional test protocol for assessing knee stability during and after rehabilitation of reconstructed athletes.

METHOD

Subjects: Ten healthy male participants without any injury history on lower limbs were recruited. They were recreational athletes, currently participating at least two times of their sports per week. The mean age, body mass and height of the participants were 26.4±1.78 years, 70.9±15.62kg and 1.73±0.72m respectively. The university ethics committee approved the study. Informed consents were obtained from each participant before the experiment.

Experimental Task: A series of stop-jumping tasks were performed in planned and unplanned manners randomly for each participant. For each task, the subject was instructed to run straight on a 10-meter walkway approaching a ground-mounted force plate, with a running speed of 3.1m/s to 3.5m/s (De Cock, De Clercq, Willems, & Witvrouw, 2005), as monitored by the forward speed of the sacrum marker by a motion analysis system (VICON 624, UK). Trials with running speed out of the range were discarded.

In the planned tasks, the participants were instructed to stop with both feet, with the testing foot on the force plate, and then jump immediately to one of the four directions (forward, vertical, left and right) as far as they could. In the unplanned tasks, a photocell gate was set at the subjects' hip height and at a distance of 0.7 meter in front of the force plate, allowing approximate 0.2 second to react and perform the jump. When the participant passed through the gate, a voltage signal was delivered to a computer to trigger an instruction of the movement direction as shown on a 17-inch monitor in front of the walkway. The participant then stepped on the force plate and jumped to the instructed direction in the shortest time he could (Figure 1). The four-direction instructions were delivered to the subject in a random sequence.

Experimental Procedure: All experiments were conducted in the Gait Laboratory of Alice Ho Miu Ling Nethersole Hospital, Hong Kong. An optical motion analysis system with eight cameras was employed to collect three dimensional rotation movements of lower extremities at 120Hz capturing frequency. The system was calibrated on the same day of testing and the mean residual was less than 1mm. If not, the system was recalibrated. A synchronized force plate (AMTI OR6-7, Massachusetts, USA) was used to record complete ground reaction force data at 1080Hz at the centre of the capture volume of about 3x3x3 m^3.

After explanation of study procedures, anthropometric measurements including body height and mass, anterior superior iliac spines (ASIS) breadth, high and calf length, midthigh and calf circumference, knee diameter, foot breadth and length, malleolus height and diameter were measured. A fifteen-marker model was adopted to collect lower limb kinematics during stop-jumping movements. The markers were secured with double-sided tape to the participants' bony landmark, including sacrum, ASIS, greater trochanter, femoral epicondyle, tibial tubercle, lateral malleolus, heel and fifth metatarsal head on both limbs (Davis, Ounpuu, Tyburski, & Gage, 1991). All the procedures were managed by one tester.

A trial of standing anatomical position was captured. Each participant was instructed by the same tester to stand with both feet in shoulder width and align the shank and foot segment to a neutral position. This calibration file provided a definition of zero degree for all joint angles in all planes. Video demonstration of stop-jumping tasks was shown to all participants. They were allowed to practise a series of planned and unplanned stop-jumping tasks until they were comfortable to start the test. Each participant was told to begin the task at the designated starting point, run straight towards the force plate, stop with both feet and jump as high as possible for the vertical jump and as far as possible for the forward, left and right jumps. Thirty seconds of rest was allowed between each jump and one minute of rest was also given to subjects between the planned and the unplanned tasks.

Data Collection and Reduction: Three successful trials for each direction for planned and unplanned tasks were collected. For each successful trial, data from the motion analysis system were trimmed before and after the time of foot strike. A foot contact was determined by the force plate when the vertical ground reaction force exceeded 5% of the participants' body weight. Three dimensional coordinates of every marker were exported from the VICON software. The knee joint kinematics was calculated with the anthropometric data measured previously (Davis et al., 1991). All calculations were conducted using self compiled program (Mathworks, Massachusetts, USA). The main dependent variable was knee external rotational angle. Knee flexion angle and knee abduction angle were also calculated at the time of foot strike (Cham & Redfern, 2002), as this suggested if the unanticipated effect was significant to the preparatory stage of the stop-jumping task.

Data Analysis: All data were analyzed for the right side only and were averaged across three trials for each condition. Two-way multivariate analysis of variance (MANOVA) with repeated measures was employed to examine the interactive effects (anticipation effect x direction) of knee kinematics. If the interactive effect was found, stratified paired t-tests were conducted for each parameter to demonstrate the anticipation effect at each jumping direction. The level of significance was set at 0.05.

RESULTS:

MANOVA showed significant interactive effect (Wilks' Lambda value=0.353, F=3.614, p<0.05). Therefore, stratified paired t-tests were conducted for each parameter between planned and unplanned tasks. The result of the knee kinematics at the time of foot strike was summarized in the Table 1. Besides left jump, all variables of planned jumps are larger than unplanned jumps. Significant differences were found in external rotation angle during forward and right jumps, abduction angle during forward, vertical and right jumps, flexion angle during right jump.

DISCUSSION:

In laboratory setting, functional tests allowed subjects to pre-plan movement patterns and it might not reflect the real movement patterns performed in competition during which athletes must react to unanticipated events (Besier et al., 2001). Currently, research investigating anticipation effect on knee kinematics during stop-jumping tasks is limited. Pollard and coworkers (Pollard et al., 2007) and Landry and coworkers (Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007) reported that both male and female performed similarly in randomly cued cutting maneuver.

However, neither research group focused on stop-jumping tasks, in which most of the ACL injuries occurs during sudden stop-landing movement with a change in direction. Sell and coworkers (Sell et al., 2006) did comparison between planned and unplanned stop-jumping tasks and demonstrated increased knee joint loading characteristics such as greater knee valgus and flexion moments. The authors suggested that directional and reactive jumps should be included in research methodology based on the knee joint loading data. In a recent study (Brown, Palmieri-Smith, & McLean, 2009), it was suggested that unanticipated landing induced modifications in landing biomechanics that may increase risk of ACL injury. However, this unanticipated effect is not well-understood in terms of knee rotational kinematics.

In the present study, knee rotational stability was investigated in terms of knee external rotation angle. For three of the four directions (forward, vertical and right), our subjects demonstrated decreased knee external rotation angle during unplanned stop-jumping tasks. Significant differences between planned and unplanned tasks were found in forward ($p<0.05$) and right ($p<0.05$) stop-jumping tasks. The external rotation angles were 20.2 degrees and 13.9 degrees for forward jump and 19.6 degrees and 13.3 degrees for right jump in planned and unplanned situations respectively. It was surprised that the results did not support to previous studies (Besier et al., 2001;

Brown et al., 2009) suggesting unplanned tasks would generate more demanding stress to the knee. One of the reasons was that our subjects performed the tasks in a more 'safe' way due to the unplanned task's nature, which involved short time decision and multi-directional jumps. However, without hesitation, subjects performed confidently and showed increased knee rotation for planned tasks since enough time was allowed for them to pre-program their movement patterns before making the jump.

Athletes tend to pre-program their landing maneuver during preparation stage, which is regarded as the flight phase before landing (Chappell, Creighton, Giuliani, Yu, & Garrett, 2007). Investigators believe that ACL injuries typically occur at the time of foot strike (Krosshaug et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). In the current study, the kinematics difference between planned and unplanned jump at the time of foot strike suggested that athletes would modify their strategies before landing on the ground. In contrast to the previous studies (Sell et al., 2006; Yu et al., 2005), our subjects had a decreased abduction angle during unplanned tasks. Chappell and coworkers (Chappell et al., 2007) reported that female would have smaller flexion angle than male at the end of preparation stage. Our participants also demonstrated similar result, showing smaller flexion angle during unplanned right jump (23.0

degrees) than planned right jump (29.5 degrees). It may increase the knee joint loading and further increase the risk of ACL injury. Participants in our study performed differently in knee kinematics between planned and unplanned stop-jumping tasks during forward, vertical and right jump. The results suggested that anticipation effect would affect landing maneuver and hence it should be considered if stop-jumping task is employed during functional assessment.

None of the previous studies evaluate knee rotational stability during unplanned landing maneuver. In present study, knee rotational displacement, which is one of the major laxities in knee ligamentous injury athletes, was measured. Previous study (Chappell et al., 2007) showed that there was a gender difference in knee rotation during preparation stage of vertical stop-jumping task. The healthy subjects in our study demonstrated significant decreased knee kinematics for unplanned tasks in forward, vertical and right jump. It was believed that the difference at the time of foot strike may influence the landing phase, which would be more stressful to the ACL than that in the takeoff phase during the stop-jumping tasks (Hurd & Snyder Mackler, 2007). In the current study, we incorporated a series of high risk movements of ACL injury including a sharp deceleration, a sudden stop landing maneuver and a sudden change in direction. Since knee stability is one of the major considerations to determine if athletes could return to sports after ligament reconstruction. It would be of great value for evaluating knee stability of ligament reconstructed athletes with functional assessment such as stop-jumping task with anticipation effect.

The limitation in the present study involved known drawbacks of motion analysis, including the movement of skin markers (Reinschmidt, van den Bogert, Nigg, Lundberg, & Murphy, 1997). During the experimental procedure, the inter-tester error was minimized by having the same technician place the skin markers and measure all anthropometric data. A standing offset trial to define zero degree for all segmental movements was collected to avoid subtle misalignment of the knee joint. Moreover, as this study investigated the anticipation effect on knee kinematics in healthy participants jumping height and distance were not considered. It would be suggested that other parameters reflecting functional stability and muscles strength such as ground reaction force and electromyography data should be included in future studies for assessing athletes after ligament reconstruction.

CONCLUSION:

This study provided specific knee kinematics information during stop-jumping tasks, especially the anticipation effect on knee rotational stability. It was concluded that anticipation would affect landing manuever during stop-jumping tasks by showing different knee kinematics between planned and unplanned tasks in healthy male participants. We suggested that both planned and unplanned stop-jumping tasks should be considered as one of the functional assessments to monitor the rehabilitation progress after knee ligamentous injury

FIGURE AND TABLE CAPTIONS

Figure 1: Laboratory setting of planned and unplanned stop jumping tasks (Vertical jump: A to A; Forward jump: A to B; Left jump: A to C; Right jump: A to D)

Table 1: Paired t-test results of knee kinematics on the anticipation effect for all jumping directions.

ACKNOWLEDGEMENTS

This research project was made possible by equipment/resources donated by The Hong Kong Jockey Club Charities Trust.

REFERENCES

Beaulieu, M. L., Lamontagne, M., & Xu, L. (2008). Gender differences in time-frequency EMG analysis of unanticipated cutting maneuvers. *Medicine and Science in Sports and Exercise, 40*(10), 1795-1804.

Besier, T. F., Lloyd, D. G., Ackland, T. R., & Cochrane, J. L. (2001). Anticipatory effects on knee joint loading during running and cutting maneuvers. *Medicine and Science in Sports and Exercise, 33*(7), 1176-1181.

Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2009). Differences between Sexes and Limbs in Hip and Knee Kinematics and Kinetics during Anticipated and Unanticipated Jump Landings: Implications for ACL injury. *Br J Sports Med*.

Cham, R., & Redfern, M. S. (2002). Changes in gait when anticipating slippery floors. *Gait and Posture, 15*(2), 159-171.

Chappell, J. D., Creighton, R. A., Giuliani, C., Yu, B., & Garrett, W. E. (2007). Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. *Am J Sports Med, 35*(2), 235-241.

Davis, R. B., Ounpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. *Human Movement Science, 10*(5), 575-587.

De Cock, A., De Clercq, D., Willems, T., & Witvrouw, E. (2005). Temporal characteristics of foot roll-over during barefoot jogging: reference data for young adults. *Gait and Posture, 21*(4), 432-439.

Fitzgerald, G. K., Lephart, S. M., Hwang, J. H., & Wainner, R. S. (2001). Hop tests as predictors of dynamic knee stability. *Journal of Orthopaedic and Sports Physical Therapy, 31*(10), 588-597.

Georgoulis, A. D., Ristanis, S., Chouliaras, V., Moraiti, C., & Stergiou, N. (2007). Tibial rotation is not restored after ACL reconstruction with a hamstring graft. *Clinical Orthopaedics and Related Research, 454*, 89-94.

Hinton, R. Y., Lincoln, A. E., Almquist, J. L., Douoguih, W. A., & Sharma, K. M. (2005). Epidemiology of lacrosse injuries in high school-aged girls and boys: a 3-year prospective study. *American Journal of Sports Medicine, 33*(9), 1305-1314.

Houck, J. R., De Haven, K. E., & Maloney, M. (2007). Influence of anticipation on movement patterns in subjects with ACL deficiency classified as noncopers. *J Orthop Sports Phys Ther, 37*(2), 56-64.

Houck, J. R., Duncan, A., & De Haven, K. E. (2006). Comparison of frontal plane trunk kinematics and hip and knee moments during anticipated and unanticipated walking and side step cutting tasks. *Gait Posture, 24*(3), 314-322.

Hurd, W. J., & Snyder-Mackler, L. (2007). Knee instability after acute ACL rupture affects movement patterns during the mid-stance phase of gait. *Journal of*

Orthopaedic Research, 25(10), 1369-1377.

Ingram, J. G., Fields, S. K., Yard, E. E., & Comstock, R. D. (2008). Epidemiology of knee injuries among boys and girls in US high school athletics. *Am J Sports Med, 36*(6), 1116-1122

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., et al. (2007). Mechanisms of anterior cruciate ligament injury in basketball video analysis of 39 cases. *American Journal of Sports Medicine, 35*(3), 359-367.

Lam, M. H., Fong, D. T. P., Yung, P. S. H., Ho, E. P. Y., Fung, K. Y., & Chan, K. M. ((inpress)). Knee rotational stability during pivoting movement is restored after anatomic double-bundle anterior cruciate ligament reconstruction. *Am J Sports Med.*

Landry, S. C., McKean, K. A., Hubley-Kozey, C. L., Stanish, W. D., & Deluzio, K. J. (2007). Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver. *Am J Sports Med, 35*(11), 1888-1900.

Louw, Q. A., Manilall, J., & Grimmer, K. A. (2008). Epidemiology of knee injuries among adolescents: a systematic review. *British Journal of Sports Medicine, 42*(1), 2-10.

Majewski, M., Susanne, H., & Klaus, S. (2006). Epidemiology of athletic knee injuries: A 10-year study. *Knee, 13*(3), 184-188

Moller, E., Weidenhielm, L., & Werner, S. (2009). Outcome and knee-related quality of life after anterior cruciate ligament reconstruction: a long-term follow-up. *Knee Surg Sports Traumatol Arthrosc, 17*(7), 786-794

Monaco, E., Labianca, L., Maestri, B., De Carli, A., Conteduca, F., & Ferretti, A. (2009). Instrumented measurements of knee laxity: KT-1000 versus navigation. *Knee Surg Sports Traumatol Arthrosc, 17*(6), 617-621.

Musahl, V., Bell, K. M., Tsai, A. G., Costic, R. S., Allaire, R., Zantop, T., et al. (2007). Development of a simple device for measurement of rotational knee laxity. *Knee Surgery Sports Traumatology Arthroscopy, 15*(8), 1009-1012.

Myklebust, G., & Bahr, R. (2005). Return to play guidelines after anterior cruciate ligament surgery. *British Journal of Sports Medicine, 39*(3), 127-131.

Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *American Journal of Sports Medicine, 32*(4), 1002-1012.

Pollard, C. D., Sigward, S. M., & Powers, C. M. (2007). Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. *Clinical Journal of Sport Medicine, 17*(1), 38-42.

Reinschmidt, C., van den Bogert, A. J., Nigg, B. M., Lundberg, A., & Murphy, N.

(1997). Effect of skin movement on the analysis of skeletal knee joint motion during running. *Journal of Biomechanics, 30*(7), 729-732.

Risberg, M. A., & Ekeland, A. (1994). Assessment of functional tests after anterior cruciate ligament surgery. *Journal of Orthopaedic and Sports Physical Therapy, 19*(4), 212-217.

Ristanis, S., Stergiou, N., Patras, K., Vasiliadis, H. S., Giakas, G., & Georgoulis, A. D. (2005). Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. *Arthroscopy, 21*(11), 1323-1329.

Sell, T. C., Ferris, C. M., Abt, J. P., Tsai, Y. S., Myers, J. B., Fu, F. H., et al. (2006). The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. *American Journal of Sports Medicine, 34*(1), 43-54.

Stengel, D., Klufmoller, F., Rademacher, G., Mutze, S., Bauwens, K., Butenschon, K., et al. (2009). Functional outcomes and health-related quality of life after robot-assisted anterior cruciate ligament reconstruction with patellar tendon grafts. *Knee Surg Sports Traumatol Arthrosc, 17*(5), 446-455.

Tashman, S., Kolowich, P., Collon, D., Anderson, K., & Anderst, W. (2007). Dynamic function of the ACL-reconstructed knee during running. *Clinical Orthopaedics* *and Related Research, 454*, 66-73.

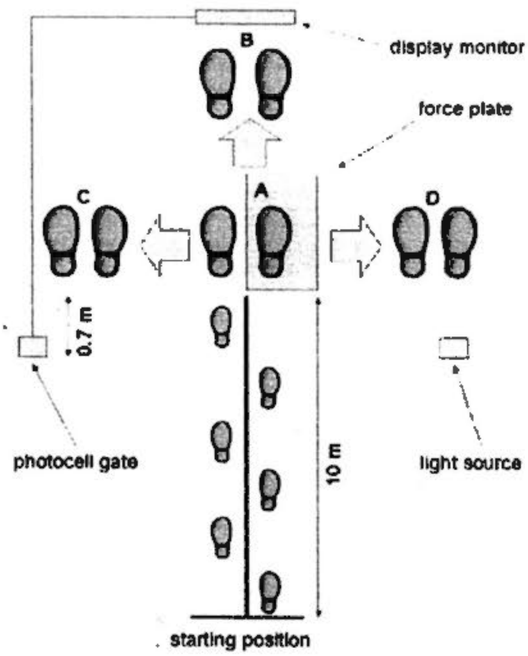
Tegner, Y., & Lysholm, J. (1985). Rating systems in the evaluation of knee ligament injuries. *Clin Orthop Relat Res*(198), 43-49.

Tyler, T. F., McHugh, M. P., Gleim, G. W., & Nicholas, S. J. (1999). Association of KT-1000 measurements with clinical tests of knee stability 1 year following anterior cruciate ligament reconstruction. *Journal of Orthopaedic and Sports Physical Therapy, 29*(9), 540-545.

Veltri, D. M., Deng, X. H., Torzilli, P. A., Warren, R. F., & Maynard, M. J. (1995). The role of the cruciate and posterolateral ligaments in stability of the knee. A biomechanical study. *Am J Sports Med, 23*(4), 436-443.

Woo, S. L., Debski, R. E., Withrow, J. D., & Janaushek, M. A. (1999). Biomechanics of knee ligaments. *American Journal of Sports Medicine, 27*(4), 533-543.

Yu, B., McClure, S. B., Onate, J. A., Guskiewicz, K. M., Kirkendall, D. T., & Garrett, W. E. (2005). Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *American Journal of Sports Medicine, 33*(9), 1356-1364.



Laboratory setting of planned and unplanned stop jumping tasks (Vertical jump: A to A; Forward jump: A to B; Left jump: A to C; Right jump: A to D)
190x254mm (96 x 96 DPI)

Table 1. Paired t-test results of knee kinematics on the anticipation effect for all jumping directions

Direction	Knee kinematics (+ve)	Planned	Unplanned	Statistical significant difference
	Flexion	25.8° (7.4)	23.8° (7.4)	No
Forward	Abduction	9.4° (8.9)	6.0° (10.9)	Yes ($p < 0.05$)
	External rotation	20.2° (8.8)	13.9° (6.4)	Yes ($p < 0.05$)
	Flexion	27.0° (12.0)	23.5° (8.5)	No
Vertical	Abduction	9.1° (10.5)	6.1° (7.9)	Yes ($p < 0.05$)
	External rotation	17.4° (8.8)	14.1° (5.4)	No
	Flexion	29.5° (3.7)	23.0° (7.1)	Yes ($p < 0.05$)
Right	Abduction	9.9° (10.4)	6.5° (10.0)	Yes ($p < 0.05$)
	External rotation	19.6° (8.6)	13.3° (3.8)	Yes ($p < 0.05$)
	Flexion	21.4° (4.4)	22.4° (4.5)	No
Left	Abduction	5.7° (10.3)	7.[illegible]° (8.9)	No
	External rotation	11.5° (10.6)	16.2° (6.8)	No