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David LABBÉ

DEVELOPMENT AND PREVALIDATION OF A MEASUREMENT TOOL FOR THE PIVOT SHIFT PHENOMENON OF THE KNEE

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JURY PRESENTATION

THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS

Ms Nicola Hagemeister, Thesis director
Département du génie de la production automatisée à l'École de technologie supérieure

M. Jacques A. de Guise, Thesis co-director
Département du génie de la production automatisée à l'École de technologie supérieure

M. Jean Arteau, President of the jury
Département de génie mécanique à l'École de technologie supérieure

M. Rachid Aissaoui, Member of the jury
Département du génie de la production automatisée à l'École de technologie supérieure

M. Michael J. Dunbar, External examinator
Department of orthopaedic surgery at Dalhousie University

THIS THESIS HAS BEEN PRESENTED AND DEFENDED

BEFORE A BOARD OF EXAMINERS AND PUBLIC

DECEMBER 14TH 2009

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

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DEVELOPMENT AND PREVALIDATION OF A MEASUREMENT TOOL FOR THE PIVOT SHIFT PHENOMENON OF THE KNEE

David LABBÉ

ABSTRACT

Rupture of the anterior cruciate ligament (ACL) is one of the sports injuries with the highest incidence. The ACL is essential to knee joint stability; it's function is to limit anterior subluxation and internal rotation of the tibia relative to the femur. When a rupture occurs, the knee joint presents increased laxity and a rotational instability. During daily activities, this instability often results in a feeling that the knee is slipping, or giving way.

Traditional clinical tests measure the increase in knee laxity. Such measures are useful for diagnosing a rupture but they give no indication of the impact of the rupture on knee joint function. The pivot shift test is a clinical test that reproduces and grades the rotational instability following ACL-rupture. It is the only test that has been shown to correlate to subjective criteria of knee joint function such as patient satisfaction, return to physical activity and episodes of giving way. The pivot shift test is graded based on the clinician's interpretation of a subjective scale, rendering it poorly reliable, especially in the hands of a less experienced clinician. There is currently no objective method for grading the pivot shift. The objective of this thesis was therefore to develop such an objective method to attribute the grade based on recorded knee joint kinematics.

To do so, we first developed a system to attach electromagnetic sensors to the lower limb and record the knee joint kinematics of subjects during the pivot shift test. Two separate data acquisition protocols ensued. In the first, three orthopaedic surgeons each performed the test on twelve different subjects and subjectively graded the pivot shift they produced. The aim of this phase was to develop a method capable of diminishing the variability introduced in the recordings by the clinicians' gestures. In the second phase, an additional 53 subjects were evaluated by one of eight different surgeons. The subjective grades they attributed were used as a gold standard for data analysis. Principal component analysis (PCA) was used to determine which features of the kinematics explain most of the variability between recordings. Using these features, a support vector machine (SVM) based classifier was developed to automatically attribute the pivot shift grade.

The results showed that the variability between clinicians could be diminished by an average of 20% using the velocity of flexion applied by the evaluating clinician. This yielded significant differences between the pivot shift grades for many kinematic parameters. The ACP analysis showed that translation is the most important component of the pivot shift and that its velocity and acceleration are more important than its actual amplitude. Using the most important features, the SVM-based classifier obtained substantial agreement with the clinicians, with 95% of the recordings being classified within one grade of the clinician's attribution.

This thesis has shown that the most important kinematic features of the pivot shift are not those that have traditionally been the focus of quantitative studies. It has also demonstrated the feasibility of objectively attributing the pivot shift grade based on a recording of its kinematics.

Keywords: anterior cruciate ligament, pivot shift, knee joint instability, knee joint kinematics, grade classification

DÉVELOPPEMENT ET PRÉ-VALIDATION D'UN OUTIL DE MESURE DU PHÉNOMÈNE DE PIVOT SHIFT DANS L'ARTICULATION DU GENOU

David LABBÉ

RÉSUMÉ

La rupture du ligament croisé antérieur (LCA) est une des blessures sportives les plus fréquentes. Le LCA est essentiel pour la stabilité du genou; ses fonctions principales sont de limiter la translation antérieure et la rotation interne du tibia par rapport au fémur. Lorsqu'une rupture survient, le genou montre une laxité accrue et une instabilité rotatoire. Durant les activités quotidiennes, cette instabilité résulte souvent en un sentiment de glissement où les patients ont l'impression que leur genou cède sous leur poids.

Les tests cliniques traditionnels mesurent la laxité du genou. Cette laxité est utile pour diagnostiquer une rupture mais ne donne aucune information relative à l'état fonctionnel du genou. Le test du *pivot shift* est un test clinique qui reproduit l'instabilité rotatoire et lui attribue un grade. Il s'agit du seul test qui corrèle avec des critères subjectifs de l'état fonctionnel du genou tels que la satisfaction du patient, son retour à l'activité physique et le nombre de fois que son genou cède. Ce test est gradé selon l'interprétation du clinicien et suivant une échelle subjective, ce qui le rend peu fidèle, particulièrement pour des cliniciens moins expérimentés. Actuellement, il n'existe aucune méthode objective d'attribuer le grade du *pivot shift*. L'objectif de cette thèse était donc de développement une telle méthode subjective pour attribuer le grade à partir d'un enregistrement de la cinématique du genou.

Pour ce faire, nous avons développé un système pour fixer des capteurs électromagnétiques au membre inférieur et enregistrer la cinématique du genou des sujets pendant le test du *pivot shift*. Deux protocoles d'acquisition de données s'en sont suivis. Dans le premier, trois orthopédistes ont chacun exécuté le test du pivot shift sur douze sujets et ont subjectivement gradé le *pivot shift* produite. L'objectif de cette phase était de développer une méthode capable de diminuer la variabilité introduite dans les enregistrements par le geste des cliniciens. Dans la seconde phase, 53 sujets additionnels ont été évalués par un de huit orthopédistes différents. Les grades attribués par les orthopédistes ont servis de *gold standard* pour l'analyse subséquente. L'analyse par composantes principales (ACP) a été utilisée pour déterminer quelles caractéristiques cinématiques expliquent la plus grande partie de la variabilité entre les enregistrements. À partir de ces caractéristiques, un classificateur de type machine à vecteurs de support (MVS) a été développé pour automatiquement attribuer le grade du *pivot shift*.

Les résultats ont montré que la variabilité entre les enregistrements des différents cliniciens peut être diminué de 20%, en moyenne, en utilisant la vitesse de flexion appliquée par chaque clinicien. Cette diminution permet des différences significatives entre les différents grades de *pivot shift* pour plusieurs caractéristiques cinématiques. L'analyse par ACP a montré que la translation est la composante la plus importante du *pivot shift* et que son accélération et sa vitesse sont plus importantes que son amplitude. En utilisant les caractéristiques les plus importantes, le classificateur MVS a obtenu une concordance substantielle avec les cliniciens. Quatre-vingt quinze pourcent des enregistrements ont été classifiés à un garde ou moins de celui attribué par le clinicien.

Cette thèse a démontré que les caractéristiques les plus importantes du *pivot shift* ne sont pas ceux qui ont traditionnellement fait l'objet d'études quantitatives. Elle a aussi démontré la faisabilité d'attribuer objectivement le grade du *pivot shift* à partir d'un enregistrement de la cinématique du genou.

Mot clés: ligament croisé antérieur, pivot shift, instabilité du genou, cinématique de l'articulation du genou, classification du grade

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LIST OF ABBREVIATIONS AND ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
AC	Alternating current
ACL	Anterior cruciate ligament
ACLD	Anterior cruciate ligament deficient
AM	Anteromedial
ANOVA	Analysis of variance
DOF	Degrees of freedom
EBM	Evidence-based medicine
PCA	Principal component analysis
PCL	Posterior cruciate ligament
PL	Posterolateral
LCL	Lateral collateral ligament
MCL	Medial collateral ligament
MRI	Magnetic resonance imaging
RMS	Root mean square
SVM	Support vector machine

LIST OF SYMBOLS AND UNITS

mm	millimeter
mm/sec	millimeter per second
mm/sec^2	millimeter per second squared
N	Newton
°	degree

INTRODUCTION

Evidence-based medicine (EBM) is described as “the conscientious, explicit and judicious use of current best evidence in making decisions about the care of individual patients”[1]. Different elements of evidence-based medicine (EBM) have been applied for many years but its major concepts were only popularized by Cochrane in 1972[2] and the term “evidence-based medicine” first appeared in medical literature in 1992[3]. Since that time, EBM has gained in popularity and its benefits have gained widespread acceptance.

The use of EBM implies the capacity to evaluate a subject’s status or outcome using scientific methods. In EBM, evaluations made by so-called “medical experts” are the least valid form of evidence. To scientifically evaluate a subject’s status or outcome, one must have access to objective and reliable measures that can be compared to those found in the literature or to measures taken prior to treatment. Such a measure is not readily available for the evaluation of knee joint function following rupture of the anterior cruciate ligament (ACL).

Rupture of the ACL is amongst the most common musculoskeletal injuries with an incidence of over 100 000 each year in the United States[4]. Assuming a similar incidence in Canada, that’s over 10 000 such injuries annually. The impact of an ACL rupture varies greatly from one patient to the next and while objective measurements of knee laxity can be used for diagnosing a rupture, only a more complex and dynamic test called the pivot shift test can assess the functional impact of the injury on the affected knee[5]. This test is applied in an unconstrained and therefore variable manner and the clinician performing the test evaluates its result subjectively[5].

In this thesis we conducted two sets of experimentations with the general objective of developing a more objective means of evaluating the pivot shift test. To do so, we first took into account the complex kinematics of the knee joint and the pathomechanics of the ACL-deficient knee. We also considered the clinical tests used to evaluate these pathomechanics, with a focus on the pivot shift test (Chapter 1). In light of this, we established the problem statement and the specific objectives of this thesis (Chapter 2). Next, we conducted a review of current literature about the pivot shift test and the various factors that impact its results. We explored the methods, results and shortcomings of previous studies that were aimed at objectifying the pivot shift test (Chapter 3). In Chapter 4, we present the methodological choices we made in conducting our study and go on to situate the three articles within the context of the larger study and its objectives.

The first of these articles presents a method for reducing the inter-observer variability of the pivot shift maneuver and identifies kinematic parameters related to the pivot shift grade (Chapter 5). The second article presents a novel method for identifying the kinematic parameters that explain most of the variability between pivot shift recordings (Chapter 6). The third and final article presents a classification method that objectively attributes the pivot shift grade. It does so based on the recorded knee joint kinematics, using the methods described in the first two articles (Chapter 7). A general discussion of the study is presented in Chapter 9, followed by the conclusion and outlook (Chapter 10).

This study advances the understanding of the kinematics of the pivot shift and takes it one step further by providing a method for objective grade attribution based on these kinematics. Moreover, it represents a big step towards the development of a quantitative measure of the pivot shift phenomenon.

CHAPTER 1

THEORETICAL FRAMEWORK

1.1 Introduction

The knee is the largest and most complex joint of the human body. It is composed of two separate articulations: that of the tibia with the femur (the tibiofemoral joint) and that of the patella with the femur (the patellofemoral joint). In this study, we focus on the tibiofemoral joint, which is primarily a hinge joint, but its hinge movements are combined with gliding and sliding, making it a triaxial joint[6].

This chapter focuses on the anatomy and complex kinematics of the asymptomatic tibiofemoral joint as well as the impact of an ACL rupture on tibiofemoral joint kinematics and function. The different types of clinical tests used to evaluate this impact are presented and the relevance of each is discussed.

1.2 Anatomy of the tibiofemoral joint

The knee is a synovial joint, which means that a fibrous capsule, called a synovial capsule, surrounds it. The cavity formed by this capsule contains synovial fluid that lubricates the articulating surfaces. The capsule of the knee is unique in that it does not completely surround the joint. Rather, it covers the lateral and posterior faces of the knee and is deficient on the medial and anterior faces, where the patellar ligament and medial patellar retinaculum fill most of the gap. The capsule is supplemented and strengthened by the five extracapsular ligaments (patellar ligament, fibular collateral ligament, tibial collateral ligament, oblique popliteal ligament and arcuate popliteal ligament)[6].

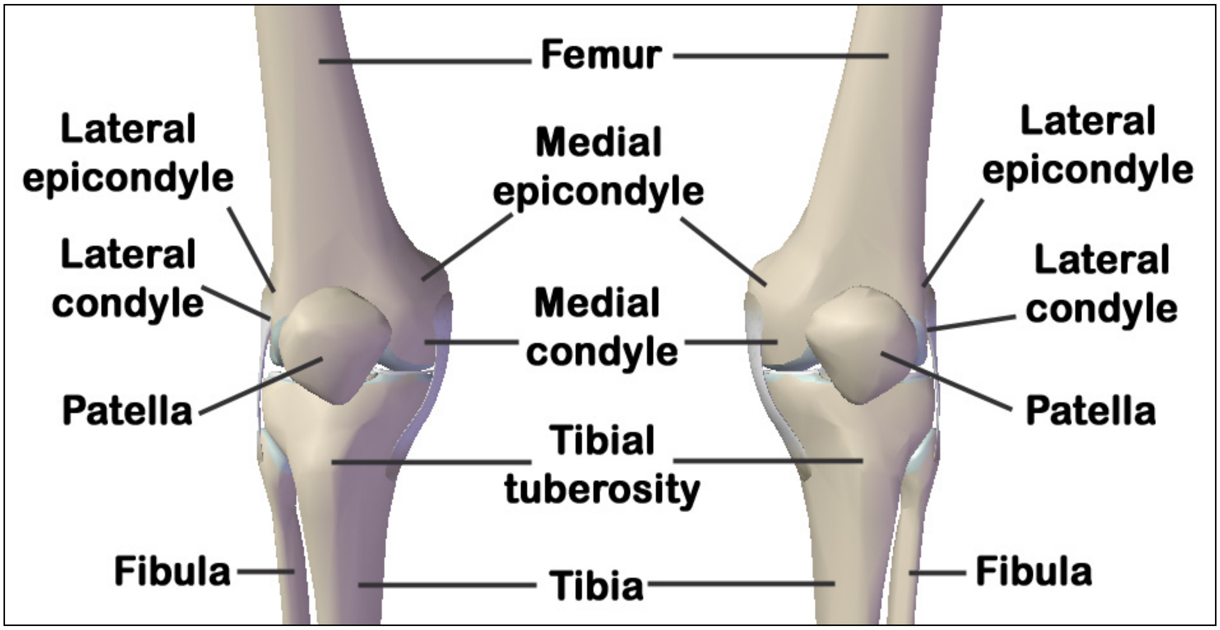

Figure 1.1 The bony structures of the knee joint.
Adapted from Visible Body

The three main bones of the knee joint are: the femur, the tibia and the patella (Figure 1.1). The femoral condyles rest atop the tibial plateau, forming the tibiofemoral joint. The lateral and medial menisci lie on the tibial plateau and serve to disperse the weight of the body and reduce friction between the tibia and the femur. These menisci are crescent-shaped fibrocartilaginous structures and are fused to the tibia along their outer circumference but are detached from it on their inner edge. They have a concave geometry that espouses the shape of the femoral condyles.

The stability of the knee joint is the result of its surrounding soft tissue structures (Figure 1.2): the synovial capsule, the extraarticular ligaments, the intraarticular ligaments and several tendons of muscles that act on the knee joint. The main tendons that act as stabilizers of the knee are the tendons of the quadriceps muscles and the tendon of the semitendinosis. The aforementioned five extracapsular ligaments are tense when the knee is in extension and they play a role in limiting hyperextension. The medial and lateral collateral ligaments also resist valgus and varus stress, respectively[6].

The intracapsular ligaments of the knee are called the cruciate ligaments because they cross each other in the intercondylar fossa of the femur. Because this work is aimed at measuring the pivot shift, which is a symptom of ACL rupture, the anatomy and function of the cruciate ligaments are presented in greater detail.

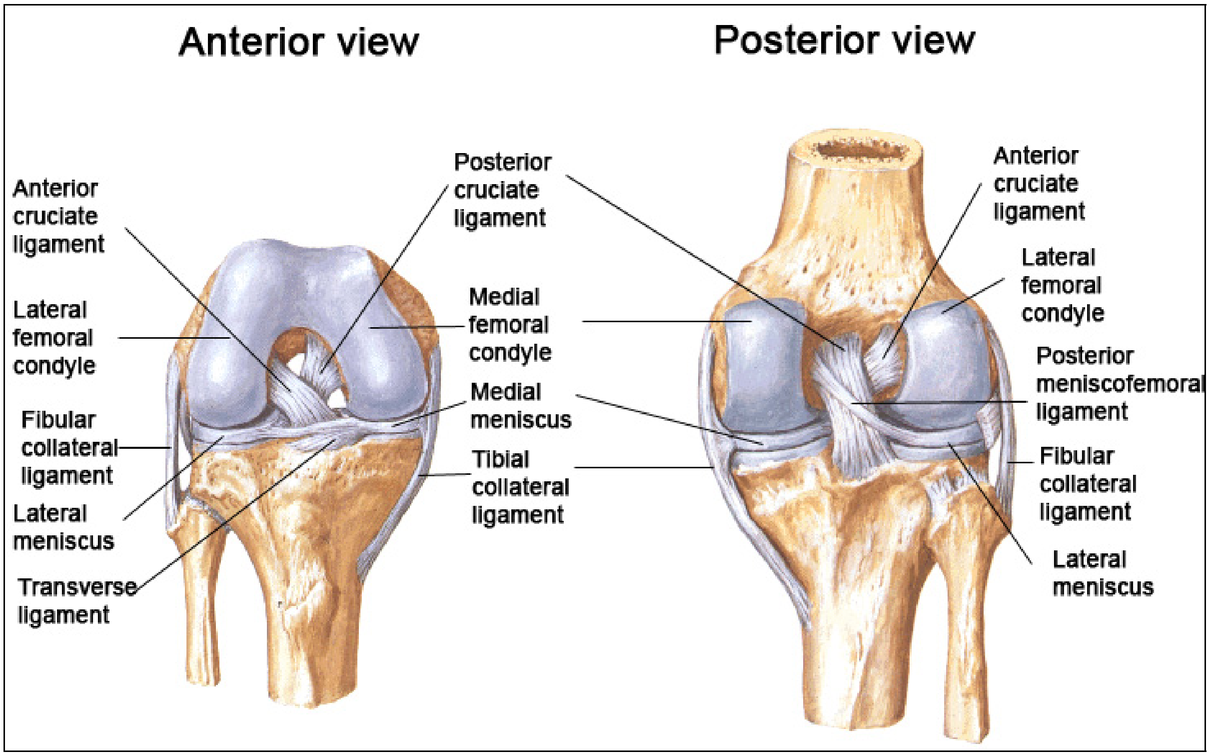

Figure 1.2 The ligaments and menisci of the knee joint.
Adapted from Netter's Atlas of Anatomy

1.2.1 The cruciate ligaments

The cruciate ligaments are named according to their insertion site on the tibia. Thus, the posterior cruciate ligament (PCL) inserts posteriorly to the ACL on the tibia, 1-1.5 cm inferior to the posterior rim of the tibia, in the PCL fovea. On the femoral side, it inserts to the anterolateral border of the medial femoral condyle. The average PCL is 38 mm long but because its femoral fixation is extracapsular, its intracapsular length is shorter than that of the

ACL and it has a less oblique orientation. Its average width is 13 mm and like the ACL, it is composed of two main bundles: anterolateral (AL) and posteromedial (PM). The AL bundle is tense during in flexion and the PL bundle is tense in extension[7].

The PCL's primary function is to limit posterior translation of the tibia relative to the femur. Its secondary functions are to resist varus and valgus forces as well as hyperextension. A PCL rupture leads to an increased posterior translation of up to 20 mm. The PCL's resistance to tension is generally considered to be above 2000 N, slightly higher than that of the ACL. Hyperextensions and posterior impacts to the proximal tibia are the most frequent injury mechanisms[7].

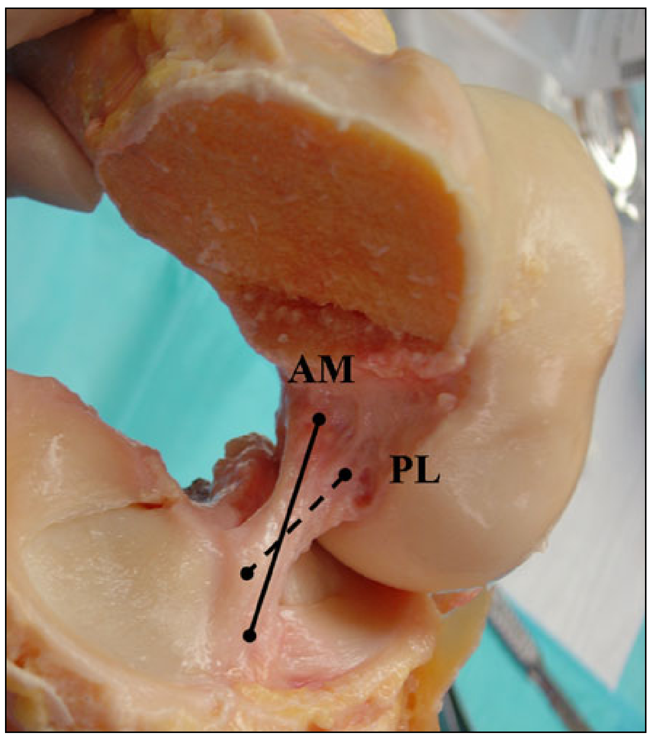

Figure 1.3 The anteromedial (AM) and posterolateral (PL) bundles of the ACL.
Taken from Fu[8]

The ACL inserts to the tibia posteromedially to the anterior horn of the lateral meniscus. Its posterior limit is approximately 2 mm anterior to the tibial fixation of the PCL. On the femoral side, it fixes to the posteromedial border to the lateral condyle. The average length of an ACL is 38 mm with an average width of 10 mm. When tension is applied to it, it stretches and lengthens by 1-2 mm. The ACL is composed of interlaced collagen fibers contained within a synovial membrane. The tibial nerve innervates it and its blood supply comes primarily from the middle genicular artery[7]. The ACL is known to have a proprioceptive function[9, 10] and approximately 1% of its volume is comprised of nerve structures[11].

As is the case for the PCL, the ACL is composed of two distinct bundles. These bundles, named for their fixation points, distinguish themselves by the orientation of their collagen fibers, which run parallel to their axes. The posterolateral bundle is tense in full extension and slight hyperextension and the anteromedial bundle is tense in flexion (Figure 1.3).

The ACL's primary function is to limit anterior translation of the tibia relative to the femur. Its secondary functions are to limit internal tibial rotation, varus and valgus stresses and hyperextension. On average, the ACL can resist a tension of close to 2000 N and has a rigidity of 242 N/mm. During passive knee extension, the ACL is only tensed between 170 and 180 degrees. Active knee extension between 50 and 110 degrees does not tense the ACL[7]. However, additional contraction of the quadriceps and hamstring muscles does affect the tensile loading of the ACL within this range. It has been demonstrated in vitro that a quadriceps force of 400N increases the tensile force of the ACL up to 60 degrees of flexion. At higher angles, the same force relieves the load. Hamstring activation reduces the load on the ACL throughout the entire range of flexion of the knee[12].

The ACL is most frequently torn without contact, usually during a rapid deceleration combined with a pivot. Other injury mechanisms include hyperextension and excessive internal tibial rotation[13].

1.3 Kinematics of the asymptomatic knee

The asymptomatic tibiofemoral joint has a much larger range of motion in flexion/extension than in the other axes but it is nonetheless not strictly a hinge type joint. In fact, the tibiofemoral joint allows some degree of rotation in all 3 anatomical axes (Figure 1.4). The gliding of the femur on the tibia also produces translations in the 3 anatomical axes.

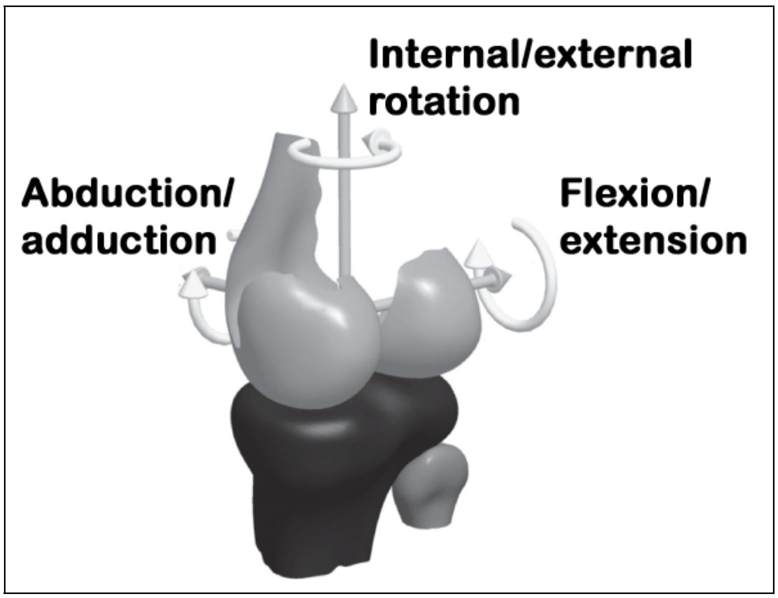

Figure 1.4 The anatomical axes of the knee and the rotations about these axes.
Adapted from Trilha et al.[14]

On average, the knee can flex over a range of approximately 140-160 degrees. This arc of flexion can be divided into three subarcs: (1) the arc of terminal extension, also called *screw-home*, which ranges from maximum extension to about 10° of flexion; (2) the arc of active function which ranges from about 10 to about 120°; and (3) the arc of passive flexion which ranges from about 120° to maximum flexion [15].

As the knee extends from 10-20° of flexion towards the limit of passive extension (-5 to 5), the medial femoral condyle glides on the tibia's medial condyle, which produces an external tibial rotation. This mechanism is due to a combination of bony geometry and of the restraint applied by the ACL. When the knee is in full extension, no significant tibial rotation is possible without concomitant flexion[15].

In the arc of active function, the medial femoral condyle rotates to produce a combination of flexion and longitudinal (internal/external) rotation but barely any translation (1.5 mm at most). The lateral condyle rolls but also slides anteroposteriorly (15 mm during flexion). This allows longitudinal rotation around an axis that passes through the medial condyle and flexion about an axis that passes through both condyles. As result of this asymmetrical sliding, between 10° and 120° of flexion, the tibia rotates internally about 30°[15].

At 90° of flexion, the tibia is free to rotate about 30° longitudinally without concomitant flexion. Conversely, the knee can flex from 20 to 90° without concomitant tibial rotation. Throughout its entire arc of flexion, very little abduction/adduction occurs in the weight-bearing knee. In the non weight-bearing knee, a range of 15 degrees is normally attainable[15].

In arc of passive flexion, both condyles roll back onto the posterior horns of the menisci and lose contact with the tibia itself. The knee can thus be said to be subluxed. This range of flexion, between 120 and 140 to 160° is only possible with externally applied forces[15].

1.4 The ACL-deficient knee

As previously stated, the primary function of the ACL is to limit anterior translation of the tibia and its secondary functions include limiting internal tibial rotation. Therefore, the ACL-deficient knee displays increased anterior translation and tibial rotation when subjected to external forces and moments[16]. A medial translation of the tibia and increased abduction rotation has also been linked to ACL-deficiency, especially in low flexion angles[17]. In weight bearing conditions, the tibial plateau is persistently subluxed anteriorly between 0 and 90° of flexion[18].

Clinical evaluation of a knee suspected of being ACL-deficient involves two categories of manual tests that are used to verify the restraints applied by the ACL and thus the ligament's integrity: static tests and dynamic tests (Figure 1.5).

The objective of the static tests is to isolate a specific ligament, the ACL in this instance, by applying a force that is almost parallel to its collagen fibers. The clinician aims to test the restraint due to the ACL while limiting solicitation of surrounding soft tissues. The two most popular static tests for testing the ACL's integrity are the Lachman test[19] and the anterior drawer test[20].

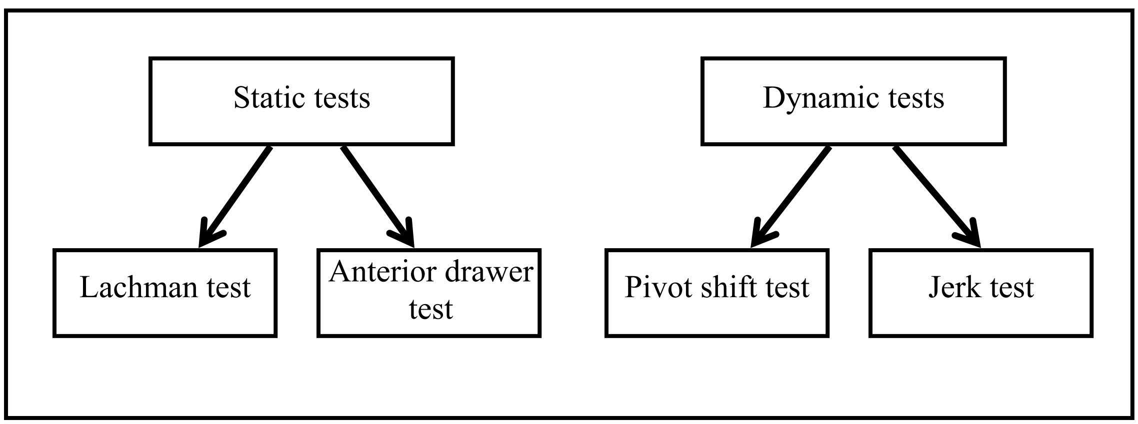

Figure 1.5 The most widespread clinical tests for ACL deficiency, divided by type.

As for the dynamic tests, they aim to reproduce a more complex rotational and translational instability, called the pivot shift[21]. The pivot shift was first described as a slipping knee because patients complained of slipping and a feeling of insecurity. Other patients described the feeling as the knee giving way or crumpling up. They described a feeling of complete insecurity when the knee moved into a position of flexion.

Anatomically, the pivot shift is characterized by an anterior subluxation of the lateral tibial plateau relative to the femoral condyle as the knee approaches extension and the spontaneous reduction of subluxation during flexion[22]. Figure 1.6 shows the subluxed and reduced positions of the tibial plateau. The subluxation has a rotational as well as a translational component so that the subluxation is greater on the lateral side of the tibial plateau than on the medial side. Both the pivot shift test[23] and the jerk test[24] are used to reproduce this symptom in a clinical setting.

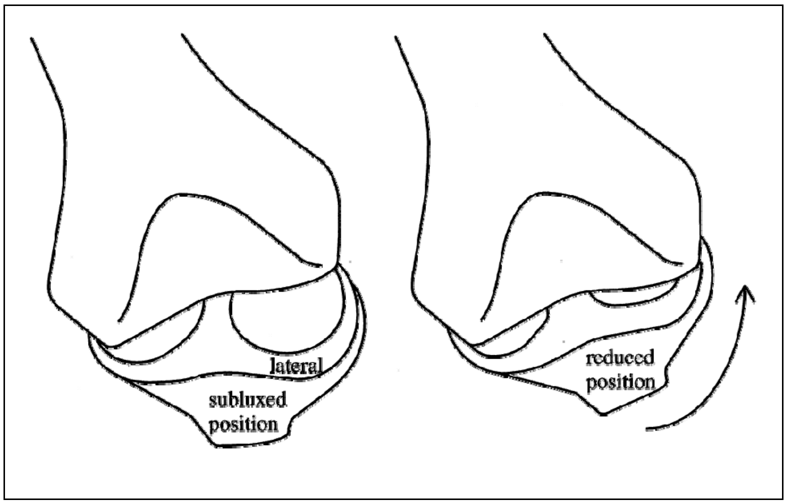

Figure 1.6 Illustration of the tibia subluxed and after its sudden reduction, called the pivot shift.
Taken from Bull et al.21

1.4.1 Static tests

The so-called static clinical tests are used to evaluate the amount of AP laxity in the tibiofemoral joint. The Lachman test is performed with the patient in supination and his knee flexed approximately 20°. The clinician stabilizes the femur with one of his hands and applies an anterior force to the tibia with his other hand (Figure 1.7).

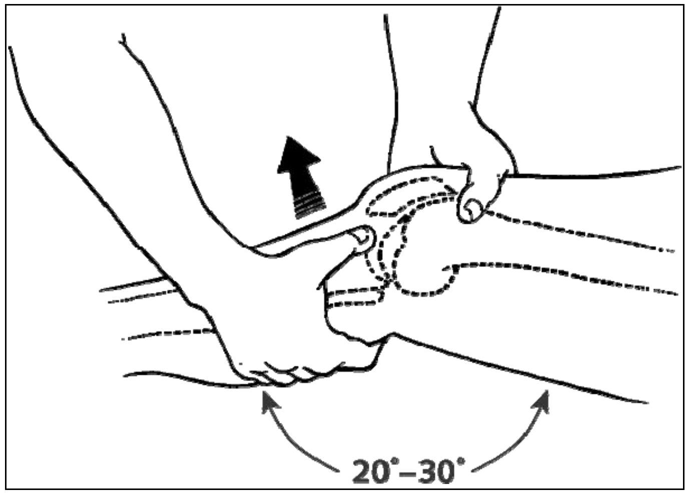

Figure 1.7 Illustration of a clinician performing the Lachman test.
Taken from Ebell et al.[25]

The clinician evaluates the amount of anterior translation produced in order to verify the integrity of the ACL. As originally described by Torg et al. [19], an evaluation is considered positive when there is noticeable anterior translation with a soft or mushy endpoint. Nowadays, the Lachman test is usually graded using the amplitude of translation produced, but different authors have used different grading systems. The International Knee Documentation Committee (IKDC) separates knee laxity into 4 grades: grade A, normal (0-2 mm); grade B, nearly normal (3-5 mm); grade C, abnormal (6-10 mm); and grade D, severely abnormal (> 10 mm). The clinician can approximate the amount of translation or use an arthrometer such as the KT-1000, as will be discussed in the literature review. Many clinicians also compare the amount of translation produced on the examined knee to that produced on the controlateral knee and look for significant difference as an indicator of ACL deficiency.

The anterior drawer test is also performed with the patient in supination but for this test the examined knee is flexed between 60 and 90 degrees with the foot resting flat on the examining table. The clinician places both hands around the tibia, near the knee and jerks the tibia anteriorly (Figure 1.8). As is the case with the Lachman test, high anterior translation is an indicator of rupture and the difference in translation between both knees has been shown to be more telling than the actual translation[26]. The grading systems used for the anterior drawer test are generally identical to those used to grade the Lachman test.

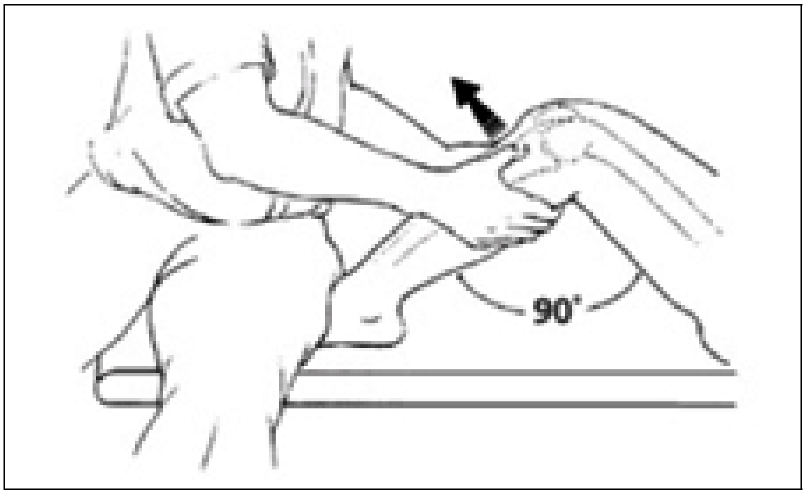

Figure 1.8 An illustration of the anterior drawer test.
Taken from Ebell et al.[25]

Although both static tests presented here aim to evaluate AP laxity, their sensitivity in diagnosing ACL rupture is very different. Many studies have compared the sensitivity (percentage of true positives) and specificity (percentage of true negatives) of both these tests [26-30]. The consensus has been that both tests have high specificity but only the Lachman test has high sensitivity. In fact, the Lachman test has been shown to be a sufficiently sensitive diagnostic means to warrant surgery without confirmation using MRI[29, 31]. The anterior drawer test, on the other hand, has been shown to be unreliable[28] and of little use in diagnosing ACL ruptures[26]. A recent meta-analysis of more than 10 comparative studies puts the average sensitivity of the Lachman test at 86% versus 62% for the anterior drawer test[32].

1.4.2 Dynamic tests

As their name implies, dynamic tests are performed in a dynamic manner while applying forces and moments to the joint. They allow for an evaluation of more complex bone movements that cannot be evaluated using static tests. However, they are performed in a much less constrained manner, which implies that they are more variable and the produced movements are harder to quantify.

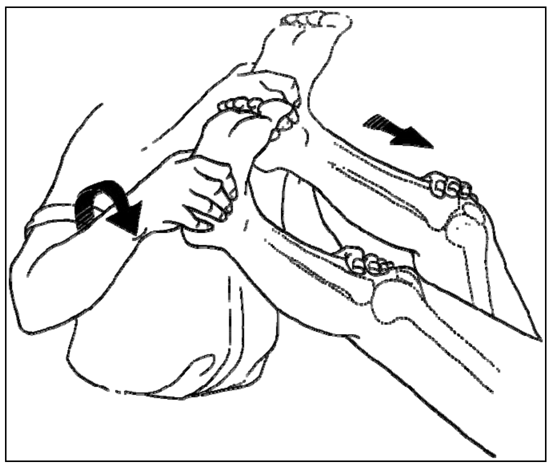

Figure 1.9 Illustration of a clinician performing the pivot shift test.
Taken from Ebell et al.[25]

Many dynamic clinical tests have been proposed. They can be separated into two main categories: reduction tests and subluxation tests[21]. In the reduction tests, the leg is initially in full extension and is slowly flexed under a valgus moment (the knee is held in place with one hand placed against its lateral side while the other hand applies an abductor force to the lower leg).

During flexion, a sudden reduction of the anteriorly subluxed lateral tibial plateau (the pivot shift) is observed in the ACL-deficient knee. This reduction is graded as 0 (none), 1 (glide), 2 (clunk) or 3 (gross clunk) by the evaluating clinician. The first documented reduction test was described by Galway et al. in 1972[23] and consists of conducting the aforementioned test with the patient supine (Figure 1.9). MacIntosh (a coauthor of Galway's work) later described his version of the pivot shift test as being similar to Galway's but with the foot of the examined limb internally rotated[21]. This test (known as the pivot shift test), which is widely used by clinicians, has thus been attributed to both authors. Other reduction tests, such as that of Slocum et al.[33] have been proposed but their use is not widespread.

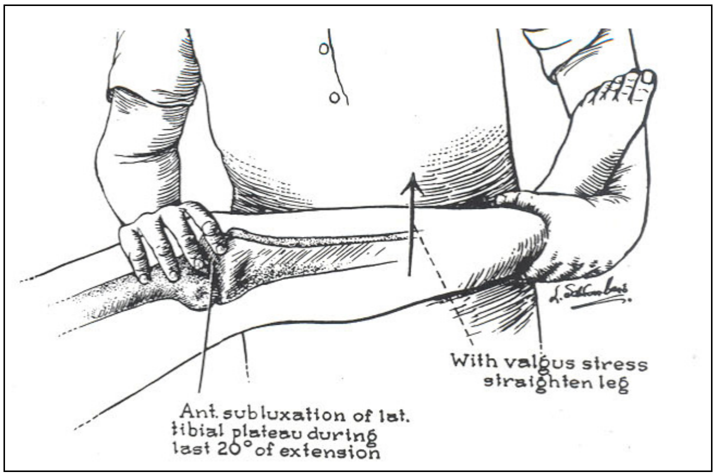

Figure 1.10 Illustration of a clinician performing the jerk test, a subluxation test.
Taken from Losee et al.[34]

The subluxation tests are essentially the opposite of reduction tests. In subluxation tests, the knee is initially flexed and is extended under a valgus moment and an internal rotation of the tibia as seen in Figure 1.10. During extension, the lateral tibial plateau suddenly subluxates anteriorly. The first and most widely used variation of the subluxation test is called the jerk test[24]. In the jerk test, the knee is initially flexed to 90° with the hip flexed to 45° and the tibia internally rotated (Figure 1.10). During extension the subluxation of the lateral femorotibial articulation is maximal around 30° and then as extension continues, a spontaneous relocation occurs, which is known as a jerk. The authors claim that this jerk test is more sensitive than reduction tests[24]. However, this claim is not backed by any data in their publication.

Nonetheless, the pivot shift test (which is a reduction test) remains the most widely used clinical test for observing the rotational and translational instability of the knee. A combination of both tests is sometimes used, as one is the opposite of the other. In that sense, if the knee is placed under valgus moment and the tibia is placed under internal rotation while the knee is flexed and extended, both tests are being combined and the instability should be observed during both flexion and extension. The pivot shift test is discussed in further detail in Chapter 3.

1.5 Increased laxity versus knee joint stability

As stated, the sensitivity of the Lachman test in diagnosing ACL ruptures has been shown to be very high[26, 28, 29, 32]. Several studies have compared the sensitivity of the pivot shift test to that of the Lachman test. There is a consensus amongst these studies that the Lachman test is more sensitive but there is considerable disagreement as to the sensitivity of the pivot shift test. It has been reported to be as low as 18%[35] and as high as 90%[28]. In their recent meta-analysis, Benjaminse et al.[36] found sensitivity to be in the 30-40% range without anesthesia and in the 85-90% range with anesthesia (the effect of anesthesia on the pivot shift test is discussed in Chapter 3).

Its specificity, on the other hand, has consistently been reported as being very high and superior to that of the other tests. Another recent meta-analysis, this one by Scholten et al. [32], confirms the finding that the Lachman test is the most sensitive and the pivot shift test, the most specific (**Table 1.1**). Benjaminse et al. [36] reported similar results. In other words, a positive pivot shift test indicates an ACL rupture and a negative Lachman test rules it out.

Table 1.1 The mean sensitivity and specificity values of three clinical tests for diagnosis of ACL rupture, from a meta-analysis
Adapted from Scholten et al.[32]

	Mean sensitivity	Mean specificity
Lachman test	86%	91%
Anterior drawer test	62%	88%
Pivot shift test	35%	98%

Although it is obviously relevant to diagnose an ACL rupture, it is often the level of knee joint function that is of most interest and that clinicians aim to restore. The evaluation of knee joint function is generally done using any number of subjective variables and validated functional scales, such as the Lysholm scale[37]. Several studies have demonstrated that no significant relationship exists between anterior laxity (instrumented or not) and subjective measures of functional outcome[38-42].

A recent study involving 202 subjects has shown that the pivot shift does have significant associations with satisfaction, partial giving way, full giving way, difficulty cutting, difficulty twisting, activity limitation, overall knee function, sports participation and Lysholm score[38]. Subjects with higher-grade pivot shift tests had less satisfaction, more limitations and lower knee function. The authors conclude that their findings support the functional importance of the pivot shift phenomenon and the clinical relevance of the pivot shift test.

The presence of a post-operative pivot shift has recently been shown to correlate with poor patient subjective evaluations and poor knee function scores[43]; patients with a post-operative pivot shift were 14.4 times more likely to have an unsatisfactory outcome than patients without a pivot shift.

Such studies underline the importance of the pivot shift and of its grade, in contrast to the Lachman test. Both tests are important parts of a clinical evaluation but serve different purposes. The pivot shift test's specificity makes it a valuable complement to the Lachman test in establishing a diagnosis but more importantly, the pivot shift test is the only test which can be used to assess the level of knee joint function and predict long term outcome. As such, many studies have now concluded that the objective of reconstructive surgery should be to eliminate the presence of a pivot shift and not to simply diminish AP laxity[43-46].

CHAPTER 2

PROBLEM STATEMENT AND OBJECTIVES

2.1 Problem statement

As mentioned in the introduction, the main problem with current clinical evaluations following ACL rupture is that only the pivot shift test, a highly subjective test, can assess knee joint function. The clinician attributes the grade of the pivot shift relying on his interpretation and experience[5, 21]. Moreover, the nature of the grading scale renders the grade poorly repeatable[5]. Indeed, it has been shown that different clinicians frequently attribute different grades to a same patient[47].

No objective method for evaluating the pivot shift test currently exists, despite several attempts in the literature[48-53]. In the absence of an objective pivot shift measurement tool, it is difficult for less experienced clinicians to attribute a grade with a sufficiently high level of confidence for it to be used in determining the course of treatment. Moreover, a subjective measure is inadequate for following the progression of a patient's status or for comparing pre- and post-operative evaluations. This is an obstacle not only to evaluating the success of individual surgeries but, more importantly, to comparing the outcomes of different surgical procedures. Similarly, it is difficult to compare the cohorts of different studies in terms of the pivot shift grade. As a consequence of the lack of an objective measure, the anteroposterior laxity, as evaluated by Lachman's test using the KT-1000, is generally used for comparing outcomes or subjects. As established in Chapter 1, AP laxity has no significant correlation to knee joint function.

Many obstacles stand in the way of the development of a pivot shift measurement tool and one of the most important is the ability to record the kinematics of the tibia and femur with high precision. The artifacts caused by skin to bone displacement around the knee are important enough in relation to the bone movements to mask critical information[54, 55]. It has been demonstrated that surface mounted markers near the knee move up to 17 mm rms relative to the underlying bone during passive knee flexion[54]. A study by Amis et al.[48] has recently shown that the sudden reduction of the tibial plateau that defines the pivot shift was clearly recorded by a motion capture device fixed to the bones using intra-cortical screws. However, a non-invasive attachment system that was simultaneously recording knee joint kinematics recorded only a very small percentage of this translation. While it may be foreseeable to use intra-cortical screws for some per-operative evaluations of the pivot shift, this solution is obviously not one that can be transferred to a clinical setting. Thus, recording knee joint kinematics in a non-invasive manner and with sufficient precision remains a major concern in developing a measurement tool.

Skin displacement artifacts are a problem that pertains to the recording of the pivot shift but the nature of the pivot shift itself introduces additional challenges. The interpretation of what constitutes a given grade is not the only aspect that differs between clinicians. The pivot shift test is an unconstrained test, meaning that the clinician’s gesture is not guided and there is no measure of applied forces. As such, it is inevitable that the applied forces and moments and the resulting kinematics will differ somewhat between clinicians. It has been shown that the position of the limb during the test as well as the amount of force applied directly impact the produced pivot shift kinematics[56, 57]. Thus, not only are clinicians interpreting differently from their colleagues, they are also producing different bone displacements. A study by Noyes et al.[47] showed that the anterior subluxation of the medial tibial plateau induced by 11 clinicians performing the pivot shift test on a cadaveric knee varied from 6 mm to 16.9 mm.

2.2 Hypotheses

Our main hypothesis for this thesis is that the kinematics of the tibia and of the femur can be recorded during the pivot shift test and that they can be used to attribute the grade in a more objective manner. This hypothesis relies on four specific hypotheses:

- We hypothesize that significant differences exist between the kinematics of different grades of the pivot shift.

- We hypothesize that tibiofemoral joint kinematics can be recorded with sufficient reliability to allow for these differences to be revealed.

- We hypothesize that inter-clinician variability can be reduced using particularities of each clinician's gesture such that the aforementioned kinematic differences are still observed when the evaluations are performed by many different clinicians.

- We hypothesize that variability between recordings of a same grade can be reduced sufficiently such that a classification algorithm can distinguish the different grades with high accuracy.

2.3 Objectives

The main objective of this study is to develop an objective method of attributing the pivot shift grade. Our specific objectives in doing so are:

- To develop a tool capable of recording the knee joint kinematics of the pivot shift phenomenon.

- To diminish the variability introduced by the clinician in order to increase the kinematic differences between each pivot shift grade.

- To characterize the kinematics of the pivot shift and identify which aspects of these kinematics are important in grading the pivot shift.

- To develop a classifier capable of attributing the pivot shift grade in a manner similar to that of an experienced clinician based solely on a kinematic recording of the pivot shift test.

CHAPTER 3

LITTERATURE REVIEW

3.1 Introduction

This chapter will present an overview of research that has been conducted about the pivot shift test: its grading, the different variations of technique that have been proposed and the reliability of the test. Different knee evaluation devices developed to quantify the static tests will be presented and their strengths and weaknesses discussed. The impact of skin movement artifacts and different possible solutions will then be presented, as this is a major obstacle when passing from the quantification of a static test to that of a more dynamic test such as the pivot shift test. This will be followed by a detailed look at the methodology and results of previous studies that have attempted to measure and quantify the pivot shift.

This literature review will set the table for the methodological choices and show how this thesis is positioned with regards to previous work.

3.2 The pivot shift phenomenon

3.2.1 Grading the pivot shift

When performing the pivot shift test, the clinician must not only determine whether or not the pivot shift is present but also grade it, if it is present. The grade indicates the severity of the instability. For grading to be possible and relevant, the criteria must allow examiners to clearly distinguish between different grades. This grading serves three purposes. First of all, it is claimed that the test is subtle enough for examiners to assess different injuries and discriminate between them based on the grade. The severity of the pivot shift is also critical in determining which type of treatment is appropriate[21, 58]. Finally, grading is useful in a research perspective as it allows for comparisons between limbs with similar degrees of pivot shift.

According to the grading system that was originally described by Galway et al.[23], the pivot shift is graded as a 0 (absent or negative), 1+ (slight slip), 2+ (moderate slip) or 3+ (momentary locking). Bach et al.[59] suggested a minor change to this grading, suggesting a grade of 0.5 be added for “trace”. This proposed change was never widely adopted.

Jakob et al.[57] proposed a grading system that is less subjective, yet it doesn’t require a measuring device. They suggest that performing the test using internal, neutral and external tibial rotation and noting in which positions a pivot shift is elicited can indicate the grade. Figure 3.1 shows the three positions in which the test is performed. This grading system is in fact less subjective because the examiner does not have to quantify the displacement. It has however been refuted by other authors[59] and its use has been very limited.

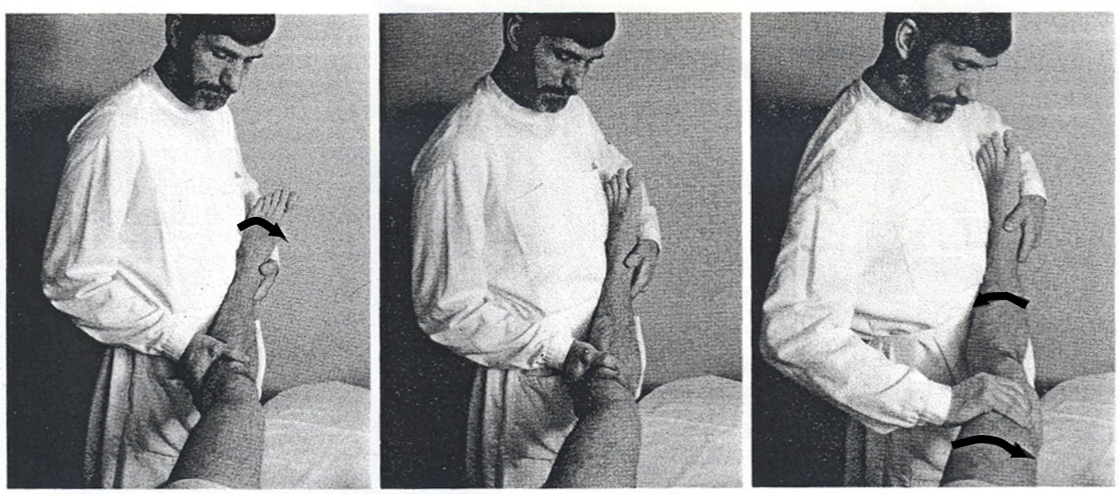

Figure 3.1 A clinician performing the pivot shift test with the tibia in the three positions suggested by Jacob et al.: internal rotation, neutral and external rotation.
Adapted from Jacob et al.[57]

Despite these proposed adaptations, the standard grading remains similar to that initially described by Galway. The grading scale of the IKDC is now the one that is used in a majority of studies. Its grades are described as: 0 (absent), 1 (glide), 2 (clunk) and 3 (gross).

3.2.2 Variations of the pivot shift test

Anesthesia

The variation that has been shown to influence results of the examination the most is anesthesia. Various researchers have shown the pivot shift test consistently results in higher grades when performed under anesthesia. Anesthesia makes the surrounding muscles limp, which eliminates their effect on knee kinematics. This allows the effect of the ligaments to be isolated because without anesthesia, the muscles surrounding the knee often offer resistance to guard against pain.

Donaldson et al.[27] found that the pivot shift test was much more sensitive when performed under anesthesia. In their study, which was previously presented, they examined 101 knees with acute ACL injuries. Only 35% of ACL deficient knees had a positive pivot shift test without anesthesia versus 98% under anesthesia. Similarly, Harilainen [60] found a positive pivot shift in only 13 of 350 knees with acute ACL rupture versus 87 when under anesthesia. Norwood et al.[61] also found similar results with 36 knees evaluated with the jerk test. It is worth noting, however, that the aforementioned studies involved knees with acute injuries and that the pivot shift test is presumably more suited for evaluation of chronic injuries, when pain and swelling have subsided, allowing for less resistance to the test. On the other hand, studies have shown that the pivot shift is more sensitive under anesthesia, whether the injury is acute or chronic[62, 63].

Lower limb position

Another factor that has been investigated by many authors is the effect of the positioning of the lower limb on the results of the pivot shift test. Here, there is no consensus and there are actually many authors who have published very different results. The variant which was most often studied and which is most disputed is the rotation (internal, neutral or external) of the tibia. Other authors have investigated the effect of hip abduction and flexion.

The rotation of the tibia during the pivot shift test has been debated over the years and there is still no clear consensus. A majority of authors recommend applying internal rotation[22, 24, 64] but other recommended external rotation[34, 59, 65] or at least avoidance of internal rotation[47, 66]. Daniel et al.[67] found that the pivot shift grade was not affected by tibial rotation although they did not focus on tibia rotation but rather on comparing measurement devices.

Most studies that specifically compared different tibial rotations found that the pivot shift test gives best results when the tibia is in external rotation. Two such studies also investigated the effect of the hip joint position. The original pivot shift test, as described by Galway et al.[22], was performed with the hip in a neutral position and foot and tibia in internal rotation. In two different studies, Bach et al.[59] and Petermann et al.[56] both examined the effect of different combinations of tibial rotations and hip joint positions.

These studies show that the position that best allows for the pivot shift to be observed is with the hip in 30° abduction and the tibia in 15° external rotation. For all positions of the hip including the traditional neutral position, results are best with the tibia in external rotation. These results suggest that the traditional pivot shift test should be modified; however tests must be done to verify if these suggested improvements also apply when patients are not under general anesthesia.

3.2.3 Reliability of the pivot shift test

As discussed in chapter 2, the pivot shift test is a subjective test, meaning that there is no way to precisely measure the intensity of the pivot shift. Each examiner must rely upon his experience and judgment in determining if the pivot shift is observable and if so, to what degree. It has been well documented that different examiners elicit the pivot shift in different ways and for some patients, the pivot shift may be present under one clinician’s examination but not under another's[21, 47]. However, not many studies have investigated the reproducibility of the test. For any test to be considered a valid examination, it is important for it to be as reproducible as possible between clinicians but also between examinations of the same clinician on different days. Furthermore, the grade of the pivot shift is used to decide which type of treatment should be pursued and in research, to compare various patients. Thus, the grading must also be reproducible for it to have clinical relevance or scientific value.

Noyes et al.[47] used a single cadaveric lower limb and 10 experienced knee surgeons in order to analyze the knee motions induced when the pivot shift test is performed. The objective of this group's research was not specifically to determine the differences in grading between each examiner although their results do allow for such comparisons. For the study, the cadaveric knee was intact except for the ACL, which was cut. The femoral head was replaced with a ball and socket joint and the entire limb was mounted on an examining table. Each examiner was told to perform the pivot shift test as they normally would in their practice. Tibiofemoral motion was measured with a six degree-of-freedom instrumented spatial linkage. **Table 3.1** presents the full results for the 10 examiners.

Table 3.1 Maximum anterior translation and internal rotation reached by 10 different examiners during the pivot shit test on a cadaveric knee

Adapted from Noyes et al.[47]

	Maximum anterior translation (mm)		Maximum internal rotation (°)
	Medial side	Lateral side	
Average	11.2	17.2	15.8
Standard deviation	3.3	2.0	3.6
Maximum	16.9	19.8	24
Minimum	6.0	14.0	11

Much variability can be observed in **Table 3.1** but a few values are of particular interest. First, the maximum anterior translation induced for the medial tibial plateau varied from 6 to 16.9 mm between examiners. Those examiners who produced the most internal tibial rotation induced the least anterior tibial translation. Therefore, the amount of internal rotation that is applied has a direct impact on the pivot shift and it is recommended to limit the internal tibial torque applied during the test. The amount of anterior subluxation of the lateral tibial plateau also varied, from 14 to 19.8 mm. This variability is especially important in the grading of the pivot shift phenomenon; therefore it is possible that one examiner could have graded it a 2 while another graded it a 3.

While this test has many limitations, most of them related to the fact that a cadaveric limb was used, it does show that different clinicians may obtain very different results when performing the pivot shift test on a same patient. The authors believe this underlines the need for a clinical device able to measure anterior and posterior subluxations of the medial and lateral plateaus under controlled loading conditions to accurately grade the pivot shift and make the test more reproducible.

In a more recent study, Bull et al.[50] found that there was very large variation, between knees, in the pivot shift kinematics, despite all evaluations being performed by a single experienced orthopaedic surgeon. External tibial rotation was $13 \pm 8°$ combined with a posterior tibial translation of 12 ± 8 mm.

No studies were found that compared results for a single examiner performing the test on a same patient on different days. While there is reason to believe that under anesthesia the knee will react in the same manner day after day, a same clinician may not repeat the test with the same loads each time. When the patient is not under anesthesia, there is also the added possibility that the leg muscles might affect the pivot shift differently on different days. The muscles may be more or less fatigued or tense on different days, thus restricting the kinematics in different ways. Such an investigation would be interesting because if this is the case, it would add to the concern with regards to the reproducibility of the test.

3.3 Instrumented knee joint laxity evaluations

Efforts are currently under way to develop quantitative measurement tools for dynamic tests such as the pivot shift test. The static tests, such as Lachman's test, are much less complex and a number of measurement instruments have been commercially available for several years. Because AP displacement is a component of the pivot shift, this section will present these instruments, which were developed to quantify AP laxity. It will also present instrument for measuring the more recently described rotational laxity.

3.3.1 Anteroposterior laxity

The KT1000

The KT1000, developed to measure the position of the tibia relative to the femur in the sagittal plane, has been commercially available since 1982[68]. Since that time, many studies have assessed its accuracy and reliability and countless others have used the KT1000 as an objective measure of AP laxity to compare outcomes of different procedures for ACL-reconstructive surgery.

The KT1000, shown in Figure 3.2, is comprised of a support for both thighs and both feet to insure that the lower limbs are flexed to approximately 25° and have a similar tibial rotation[69]. The lateral face of each foot rests against the foot support, resulting in an external rotation of 15-25°. The arthrometer is fixed to the shank using Velcro straps. Two sensors are integrated to the KT1000: one is placed against the patella and the second, over the tibial tuberosity. The tibia is free to move is the AP direction when a load is applied.

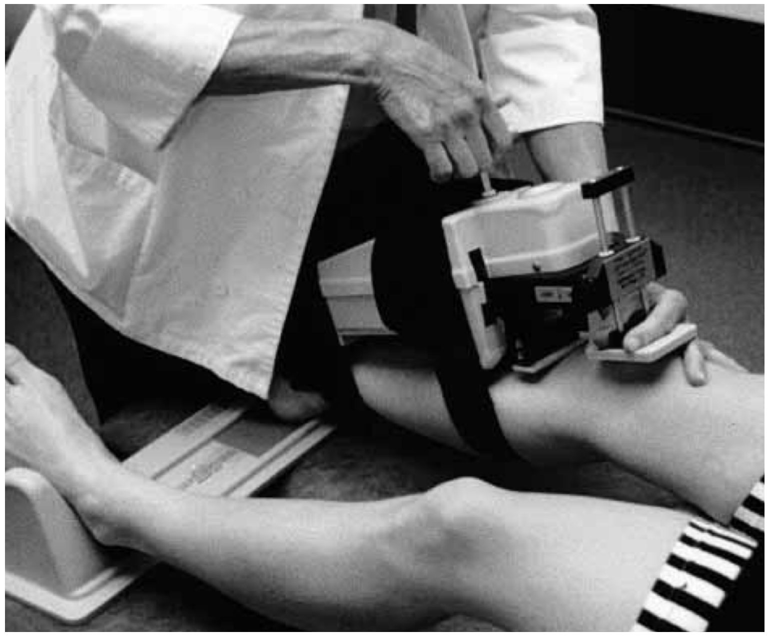

Figure 3.2 The KT1000 installed on a patient's lower limb.
Taken from Sernert et al.[70]

Using the handle situated over the tibial tuberosity, the clinician applies an anterior or posterior load to the tibial. Two distinct audible signals indicate when loads of 67 N and 89 N are attained. These are the two loads that are used for the standardized evaluation. A gauge indicates the amplitude of the displacement that is produced between the two sensors as a result of the applied load. The reference position (zero displacement) is set by applying successive loads of 89 N and then releasing until a stable return-to-normal position is obtained.

Daniel et al. [71] were the first to publish results using the KT1000. Their results were obtained from 338 healthy subjects and 89 symptomatic subjects. They obtained average anterior displacement of 5.7 mm for healthy subjects versus 13 mm for ACL deficient subjects. Moreover, 92% of healthy subjects had a difference of less than 2 mm between both knees compared with ninety-six percent of symptomatic subjects. Kowalk et al.[72] tested the KT1000's accuracy *in vitro* and found it to be good (0.13 mm). They concluded that its accuracy showed great potential for clinical application. Rijke et al.[73] showed that the tool could be used to distinguish partial from complete tears with a sensitivity of 80%. These results are positive but they do not address the tool's reliability, that is to say the reproducibility of the measure if it is taken many times by a same examiner or by different examiners.

Since, many studies have directly addressed this concern. Wroble et al.[74] evaluated the intra-observer and test-retest reliability of the KT1000 on six healthy subjects. For each subject, both knees where evaluated on six consecutive days, with 3 separate installations per day and three tests per installation. They found significant differences between days, which can hypothetically be du to subject relaxation, level of anxiety, food intake, etc. Huber et al.[75] found the KT1000 to be only moderately reliable and found it to be less reliable in the hands of novice users. This finding was echoed by Ballantyne et al.[76], who found clinician experience to be important for acceptable reliability and suggested to always use an average of repeated measures. Other authors have found substantial intra- and inter-observer variability and have expressed reservations as to the KT1000's clinical use[70, 77, 78]. Nevertheless, it remains by far the most popular instrument for measuring the laxity of the knee joint following ACL rupture.

<u>The Rolimeter</u>

The Rolimeter (Figure 3.3) is an arthrometer that was developed as a low-cost alternative to the KT1000 (it sells for approximately one fifth of the price). Different studies have compared both arthrometers and some have evaluated the reliability of this new alternative.

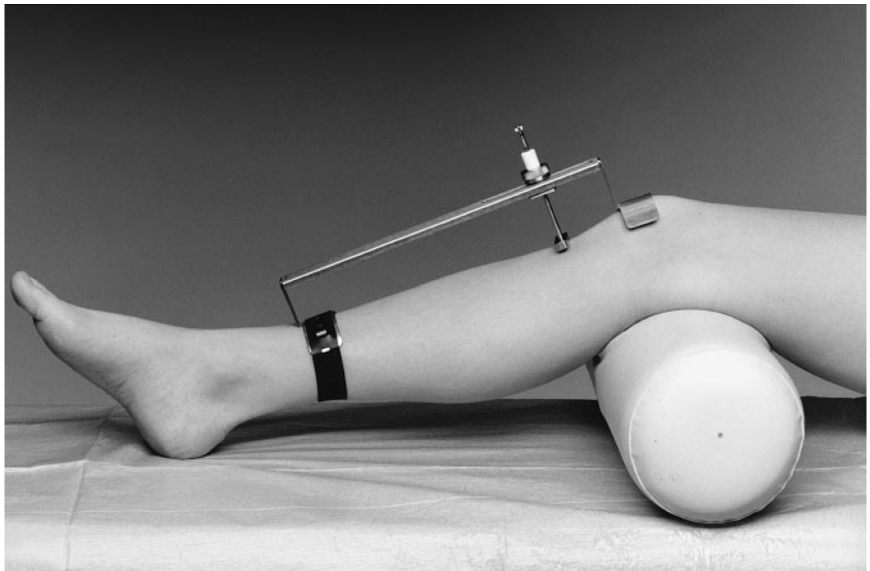

Figure 3.3 The Rolimeter arthrometer on a patient's lower limb.
Taken from Ganko et al.[79]

The results obtained from the Rolimeter were found by many studies to not be significantly different from those obtained with the KT1000[79-81]. Measures taken with the Rolimeter were consistently approximately 1 mm smaller than those obtained with the KT1000[79, 80]. Nonetheless, the correlation between the measures of both arthrometers was very high and sensitivity was found to be identical. As is the case for the KT1000, clinician experience does improve reliability a little[82].

The biggest difference between the KT1000 and the Rolimeter is that the later doesn't have the audible signals when specific loads are applied. One could expect that this would make it harder to apply the same loads for different tests and that this would result in lower reliability but no studies were found to support this hypothesis. Moreover, the Rolimeter is sterilizable which makes it a practical solution for per-operative evaluation.

The GNRB

In 2009, Robert et al.[83] published a study in which they proposed a more reliable alternative to the KT-1000 and the Rolimeter, called the GNRB (Figure 3.4). This device holds the evaluated knee at 0° of rotation and a force of 0 to 250 N is applied to the proximal tibia by a jack. The force is only applied in the absence of hamstring muscles contraction. The results of this study show the GNRB to be significantly more reproducible than the KT-1000. The effect of the examiner's experience also shown to be smaller because the forces are applied by the devise itself. Because this device is very new, its use is very limited and few studies have used or validated it.

Figure 3.4 The GNRB arthrometer.
Taken from Robert et al.[83]

3.3.2 Rotational laxity

In 2007, Musahl et al. [84] proposed a device to measure the other component of the pivot shift: tibial rotation. The device uses a commercial Aircast boot as a means of attaching electromagnetic motion sensors to the shank (Figure 3.5). A plastic brace is strapped to the distal thigh to follow to movement of the femur. A handle bar, attached to a load cell, allows the examiner to apply moments to the knee joint. These moments are recorded and the results are presented as a graph of internal/external rotation according to the applied moments.

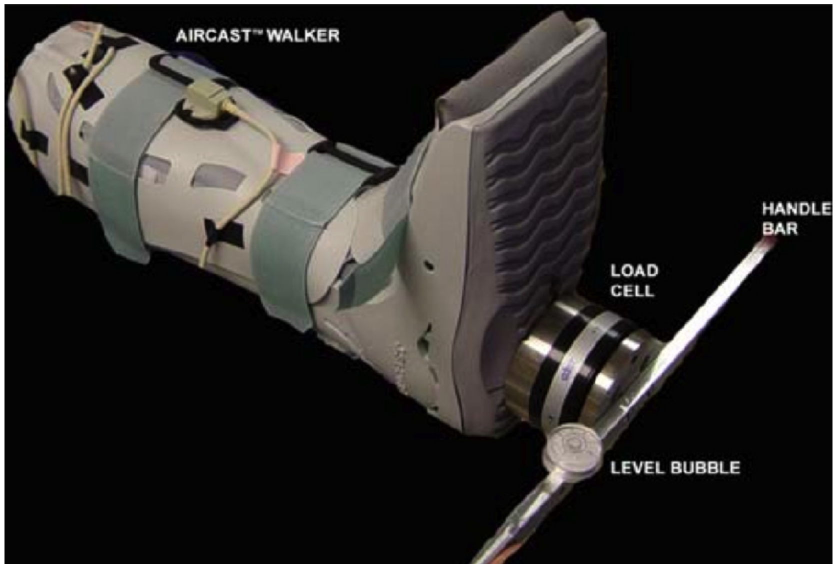

Figure 3.5 A device proposed by Musahl et al. to measure tibial rotation.
Taken from Musahl et al.[84]

The authors did not present any accuracy or sensitivity results. Rather, they evaluated the intra- and inter-observer reliability of the apparatus using four cadaver knees. For this *in vitro* study, the electromagnetic sensors were fixed to the bones using percutaneous pins. They found reliability to be very high in both settings. In a subsequent study[85], two different examiners evaluated 11 subjects. Reliability was found to be acceptable for clinical use. However, there are currently no studies that show isolated tibial rotation to be of value in diagnosing ACL rupture or in evaluating knee joint function.

One group of researchers from Japan recently published two studies where they attempted to quantify the rotatory instability of the ACL-deficient knee with static measures taken in an open MRI system[86, 87]. For this study, 18 subjects were placed on the table and asked to lie on the unaffected side. Each subject's torso and pelvis were rotated posteriorly to be 30° from the surface of the table so that the weight of the limb was borne on the heel. The knee was placed in 10° of flexion and hung free (Figure 3.6A). The authors explain that in this position, the tibia rotates internally and sags into valgus. The examiner then pushed the fibular head anteriorly with his thumb to increase the anterior displacement and internal rotation of the tibia (Figure 3.6B). The anterior displacements of the tibia at the medial and lateral compartments were measured on the sagittal view of the knee.

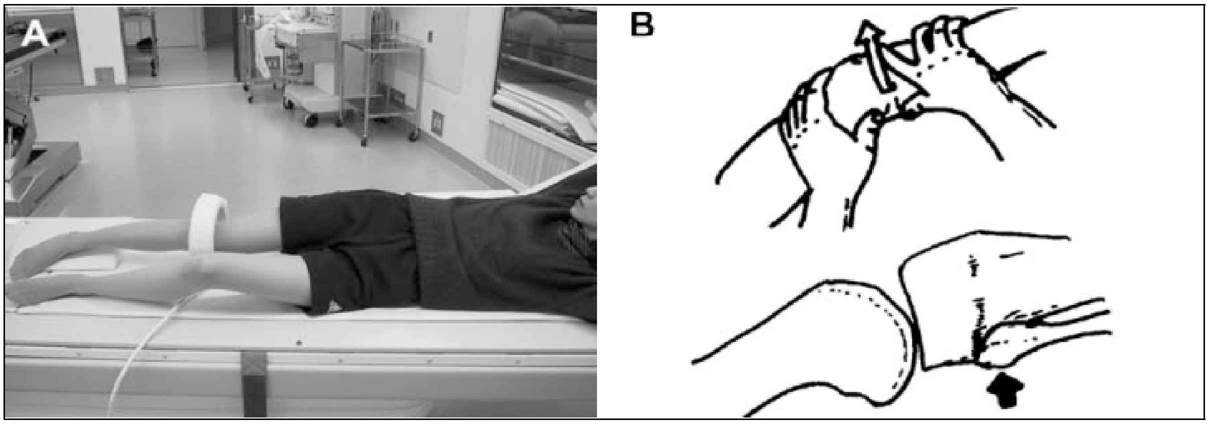

Figure 3.6 (A) The position of the subject in the open MRI system; (B) The pressure applied by the clinician to produce anterior displacement and internal rotation of the tibia.
Taken from Okazaki et al.[86]

The authors found that the displacements of both compartments were significantly reduced by ACL reconstructive surgery[86]. They also reported high intra- and inter-observer reliability. In a second study, they showed that side-to-side differences in anterolateral tibial translation have a positive correlation to the pivot shift grade. The method presented by the authors consists of a static laxity test designed to quantify both main components of the pre-reduction part of the pivot shift (anterior subluxation and internal tibial rotation) at once. The positive correlation to the pivot shift does not imply any correlation to the subjective criteria of knee joint function to which the pivot shift is correlated. Correlation of this measure to knee joint function will have to be verified as well as its sensitivity and specificity for the diagnosis of ACL rupture.

3.4 Skin movement artifacts

A major obstacle when going from the quantification of static tests to that of dynamic tests is skin displacement artifacts. There are a number of technologies available that allow for high spatial and temporal precision when recording the kinematics of the lower limb. As such, it is theoretically possible to quantify very subtle changes in kinematics. However, in practice, the displacement of the skin relative to the underlying bones introduces significant measurement errors. Many authors have raised this issue and quantified the effect of skin displacement artifacts[54, 88-93]. This effect is such that for movements of smaller amplitude, e.g. tibial rotation, the error has been shown to surpass the actual motion of the bones[89].

In an attempt to overcome this obstacle, different strategies have been proposed for the fixation of motion capture devices or markers to the lower limb. These solutions can be separated into four categories: the optimization of skin mounted markers; the use of percutaneous pins; bone embedded attachments and external attachment systems. Different proposed solutions in each of these categories will be presented as well as a summary of the strengths and weaknesses each.

3.4.1 Skin mounted marker optimization

The first solution is an optimization of the simplest method for attaching motion capture devices: fixing them directly to the skin. This is usually done using a double-sided tape and obviously does nothing to reduce skin displacement artifacts. The optimization consists in fixing a large number of markers over the thigh and shank. Algorithms are then used to approximate the true bone movements based on the fact that in the absence of skin displacement, there should be no relative movement between the different markers.

Many different methodologies and algorithms have been proposed to exploit this concept. Some studies have shown important reductions in skin displacement artifacts[88, 94, 95], while others found these artifacts to remain substantial after application of the algorithm[96-98]. Overall, this method has shown promise but results vary widely from one study to the next. The main challenge for these algorithms stems from the fact that the source of movement of the skin is the same as that of the bones; frequencies are thus similar[91]. Furthermore, it is possible for all the skin-mounted markers to move without actual bone movement.

Moreover, the larger number of markers used in such methodologies makes them impractical for short clinical evaluations and limits their use to optical markers.

3.4.2 Percutaneous pins

Percutaneous pins, or intra-cortical pins, are generally stainless steel cylinders with diameters that vary from 2.5 to 3.6 mm[99]. They are screwed into the cortical bone at depths up to 20 mm. Electromagnetic sensors or reflective markers are mounted on the pins using a fixation device. Figure 3.7 shows an example of reflective markers mounted on a percutaneous pin. The use of such pins is obviously the method that allows for the most precise measurement of bone movements. No study of their accuracy has been published, as this is the method that is considered to be the gold standard in evaluating knee joint kinematics. As such, many authors have conducted studies where knee joint kinematics were simultaneously recorded by percutaneous pins and by another attachment system to evaluate to precision of the latter[89, 93].

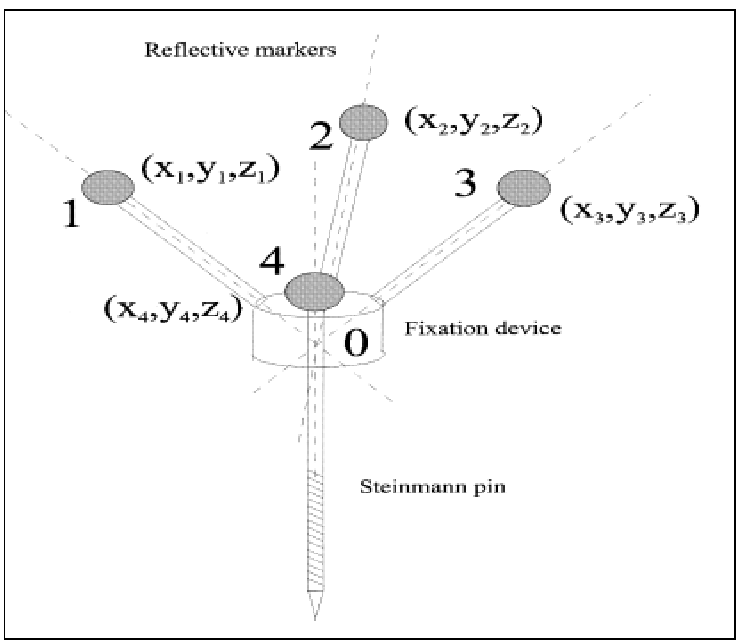

Figure 3.7 Illustration of a percutaneous pin with reflective markers attached.
Taken from Hubert et al.[75]

Despite being considered the gold standard, the use of percutaneous does not guarantee 100% accuracy. In addition to the error of the motion capture technology, the tendons and the skin surrounding the pins may, in some cases, cause the pins to bend or become dislodged. Some studies have reported the exclusion of up to 54% of their subjects because of such dislodgement[89, 93, 99]. In the absence of such complications, percutaneous pins remain the most accurate method for measuring bone movements. However, their use brings obvious drawbacks related to their invasive nature. Local or general anesthesia must be administered to the subjects and the fixation of the pins can be time consuming. As such, their use is restricted to research or per-operative evaluation.

3.4.3 External attachment systems

The final category for reduction of skin displacement artifacts is composed of several different non-invasive systems that attach to the lower limb and onto which reflective markers or electromagnetic sensors are mounted. They are said to be non-invasive because they only contact the skin and do not penetrate it. There are many examples of such systems in the literature; some have been used by a number of different authors but several were only used by their developers.

The most popular system consists of reflective markers (or an electromagnetic sensor), mounted on a rigid plastic plate that is fixed to the shank and thigh, usually at mid-segment. This method is commonly referred to as the Cleveland Clinic method (Figure 3.8B). When one of the markers is fixed to a pin that is perpendicular to the rigid plate, it is called the Helen Hayes method[92] (Figure 3.8E).

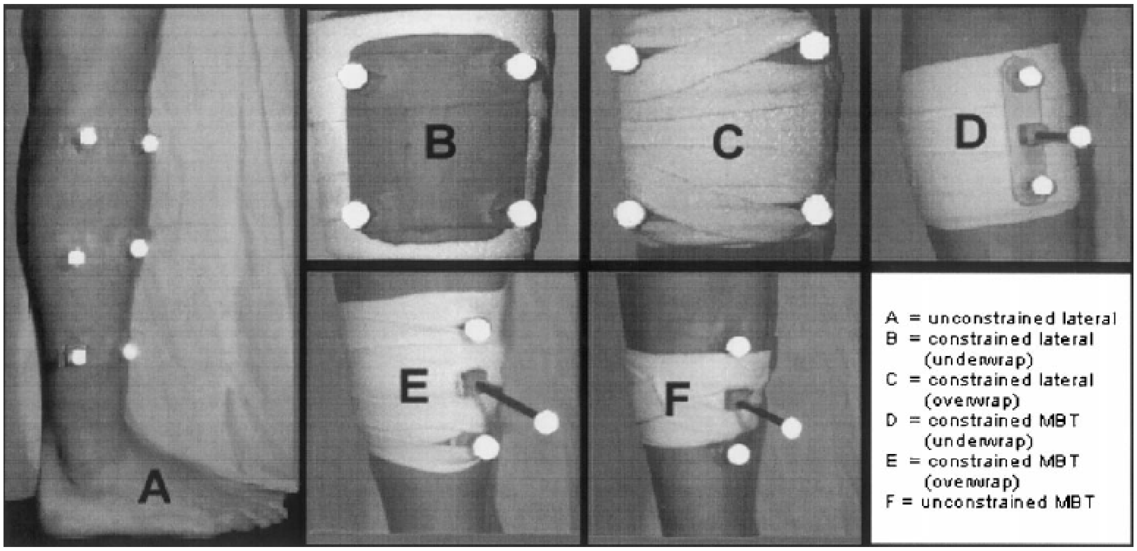

Figure 3.8 Different variations of the Cleveland Clinic and Helen Hayes methods, compared by Manal et al.
Taken from Manel et al.[92]

In 2000, Manal et al.[92] evaluated the accuracy of 6 variations of such attachment systems (Figure 3.8) on 7 subjects during gait. They varied the proximodistal position of each plate, resulting in 11 different combinations for each variation of the attachment system. The main objective of this study was to determine their accuracy in measuring tibial rotations. They found the position of each plate to have a statistically significant impact on the accuracy but even with the best setup, the accuracy for tibial rotation was about ±4°. Given the relatively small amplitude of tibial rotations, this is a significant error. In 2002, Ferber et al.[100] used the variation of the attachment system which was described by Manal as being optimal (Figure 3.9). Their objective was to evaluate the test-retest reliability of this attachment system to record knee joint kinematics during running. With the participation of 20 subjects they found that for many kinematic parameters, intra-class correlation coefficients (ICCs) below 0.75, which is considered to be the limit of acceptability[101]. The authors conclude that this method is not sufficiently reliable and that this is due to small errors in placing the different plates and markers.

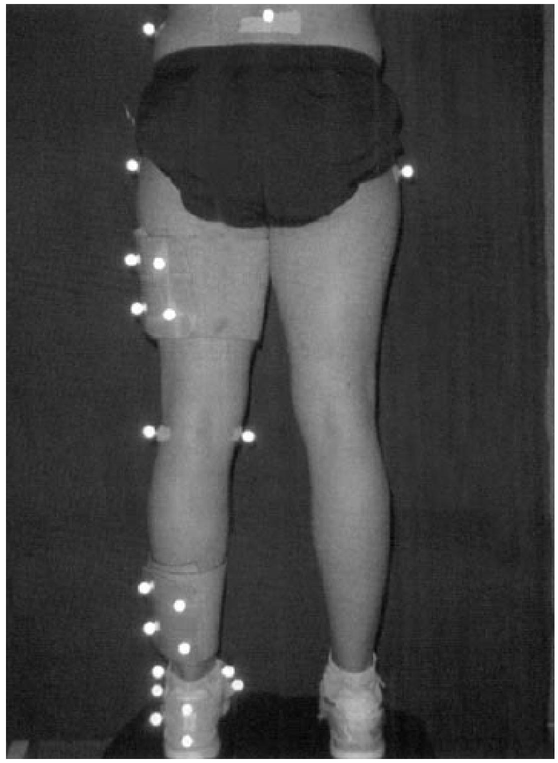

Figure 3.9 The marker placement used by Ferber et al.
Taken from Ferber et al.[100]

Other authors have developed more elaborate attachment systems in an effort to improve accuracy and reliability. Sati et al.[102] proposed an attachment system, called exoskeleton, that includes a femoral and a tibial component (Figure 3.10). The design of the femoral component was inspired by a fluoroscopic study that showed that the amplitude of skin displacement about the knee varies greatly depending on the exact location[54]. The study identified two locations where the displacement is minimal. At these anatomical locations, there are cavities that are used to attach the femoral component. This component consists of a rigid arch with an orthoplast at each extremity. The medial orthoplast inserts between the vast medialis and the sartorius muscle tendon; the lateral orthoplast inserts between the femoral biceps and the ilio-tibial (IT) band. These orthoplasts rest atop the femoral condyles. A pad on the medial side as well as a stabilizing rod which is attached to a Velcro strap, placed around the thigh, prevent rotation of the system about the orthoplasts.

The accuracy of the exoskeleton was validated by a fluoroscopic study. Radiopaque beads were fixed to the femoral component, which was installed on three different subjects who performed active flexion/extension under fluoroscopy. Average errors were found to be -0.4° in abduction/adduction and -2.3° in tibial rotation. A subsequent study of five subjects, with a similar methodology, found that the quadratic error is diminished by a factor of 4.3 for abduction/adduction when compared with skin mounted markers and by a factor 0f 6.2 for tibial rotation[103]. The intra- and inter-observer reliability of the exoskeleton has also been shown to be high[104].

Figure 3.10 The exoskeleton installed on the lower limb of a subject.

Taken from Ganjikia et al.[103]

In 2004, Houck et al.[105] presented the *femoral tracking device* (FTD). The FTD is composed of U-shaped aluminum rod with cushioning at the extremities. These cushioned extremities apply inward pressure against the femoral condyles (Figure 3.11). A spring-loaded mechanism on the medial side allows the examiner to adjust the pressure on the condyles.

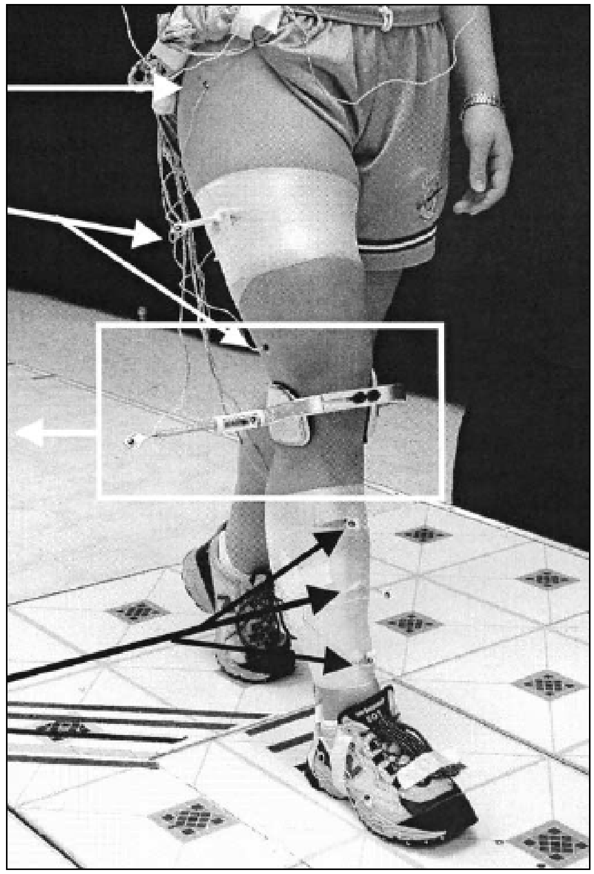

Figure 3.11 The FTD and *Helen Hayes* plaques installed on a lower limb.
Taken from Houck et al.[105]

The authors installed the FTD and percutaneous pins simultaneously on a single subject to evaluate accuracy. They found maximum errors of ±3° for all rotation angles up until 85% of the stance phase of the gait cycle. Errors were much higher after this point and the authors believe this is related to deeper flexion angles of the knee. As such, it appears the FTD may be appropriate only when the knee is near full extension, which is not the case when the pivot shift occurs.

Marin et al. [106] proposed an attachment system composed of two flat monoblocs made of plastic (Figure 3.12A). These monoblocs are strapped to the shank and thigh with Velcro straps and small blocks of foam limit the contact area with the skin. A study of the system's reliability found it to be good for flexion/extension but poor for other knee rotations. No study of the system's precision has been published. Goujon et al. [107] proposed a similar attachment system where additional markers are apposed to the skin and metallic tripods protrude from the plastics plates (Figure 3.12B). The authors used the system to quantify the gait kinematics of amputees but never published results showing its validation.

Figure 3.12 (A) Attachment system proposed by Marin et al. (B) Attachment system proposed by Goujon et al.
Taken from Südhoff et al.[108]

In 2006, , Südhoff et al.[108] published a study comparing the attachment systems proposed by Sati, Goujon and Marin. They evaluated their accuracy by installing one of the systems on 18 subjects and taking low-dose radiographic images in 5 different positions. These static images were taken in the frontal and sagittal planes. They concluded that the attachment system proposed by Sati et al. was the most accurate and that proposed by Marin, the least. They did however note that Sati's system caused discomfort for some of the subjects. The limitations of this study are mainly related to the static nature of the radiographic images. In these conditions, not only is the knee not in motion but there is no muscle activation, which could hypothetically have an important impact of the displacement of the attachment systems.

3.5 The instrumented pivot shift test

The need for an objective quantitative measure of the pivot shift has been underlined many times in the literature[5, 21]. There were a few early studies that attempted to quantify the pivot shift, with little success. More recently, with the availability of better technology and a better understanding of the importance of the pivot shift, a number of studies have investigated the pivot shift and have attempted to develop a method for quantifying it using electromagnetic devices or optical systems. A summary of the methodologies used and the results obtained by these studies will be presented here.

3.5.1 Early methods

Electrogoniometer

An electrogoniometer uses potentiometers and measures voltage changes to measure angular changes. The typical electrogoniometer uses three potentiometers, allowing for the measure of rotations in 3 axes. Such a system was used by Allum et al.[109] in an early attempt to quantify the pivot shift. The authors recorded rotations in the three anatomical axes of the knee: flexion/extension, internal/external tibial rotation and abduction/adduction. They recorded these rotations during the pivot shift test, performed on 10 subjects.

Their results were disappointing: pivot shifts that were visible to the naked eye were not observed in their kinematic data. Moreover, the output of their system had no numeric values; only the shape of the curves was used to analyze the kinematics. Such a system would therefore not render the pivot shift more objective. Their poor results are to be expected as the pivot shift is described in large part as a posterior translation[5, 21] and their system only measured rotations.

Genucom

The Genucom is a system that was developed to measure knee bone movements and that was once commercially available. The system is composed of a chair, a computer, an electrogoniometer and a dynamometer[110]. It records the relative motion between the tibia and the femur with 6 DOF. In this system, the patient's thigh is tightly strapped to the chair and it is the movement of the tibia relative to the chair that is recorded[111].

Andersen et al.[110] conducted a study to evaluate the sensitivity and reliability of the Genucom, on 147 subjects. For the pivot shift test, they found an average AP displacement of 27 mm for ACL-deficient subjects versus 24 mm for healthy subjects. The sensitivity in distinguishing healthy from symptomatic subjects was 30% and repeatability was found to be poor. The authors concluded that the Genucom's clinical use was not justified. Wroble et al.[111] found reliability to be good when tests were repeated during a same day. Nonetheless, the Genucom did not allow the clinician to freely manipulate the limb and its clinical relevance was never demonstrated. As such, its use was never widespread and it is no longer available.

3.5.2 ***In vivo* analysis of the pivot shift kinematics**

The recent *in vivo* studies that quantified the pivot shift can be separated into two groups: those that were aimed at developing a methodology for pivot shift quantification and those that merely employed a quantification method with the objective of comparing surgical techniques. Both will be presented but a special emphasis will be put on the first group, as their aim is similar to ours. **Table 3.2** presents a summary of the methodologies and results of several of these studies.

In 2002, Bull et al.[50] published one of the first studies to investigate the kinematics of the pivot shift using electromagnetic devices. The objective of their study was to assess the alteration of knee kinematics following reconstruction of the ACL. To do so, they recruited 10 ACL-deficient subjects that were undergoing reconstructive surgery. The tracking devices were fixed directly to the tibia and femur using intra-cortical threaded wires (Figure 3.13). A single orthopaedic surgeon performed the pivot shift test under anesthesia, before and after fixation of the ACL graft.

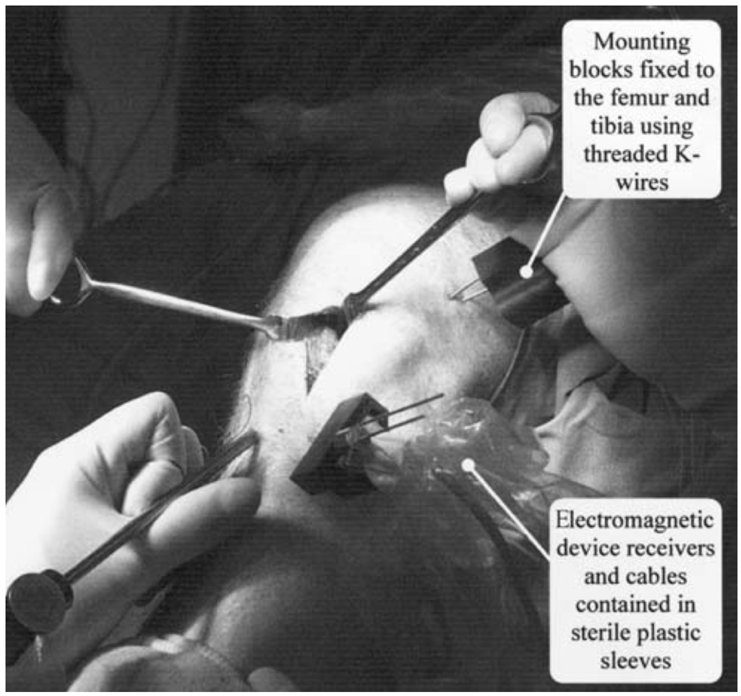

Figure 3.13 Fixation of the motion-capture sensors to the bone in the study by Bull et al.
Taken from Bull et al.[50]

They found that the pivot shift occurred around a mean position of 36 ± 9° of knee flexion and was an external tibial rotation of 13 ± 8° combined with a posterior tibial translation of 12 ± 8 mm. The authors noted that tibial rotation was very variable and even absent in some knees and that as such, the pivot shift is most consistently described as a tibial translation. There was a weak correlation between the amplitude of this tibial translation and the grade of pivot shift given by the surgeon. Figure 3.14 shows the translation of the center of the tibia during the pivot shift for a typical subject, before and after graft fixation.

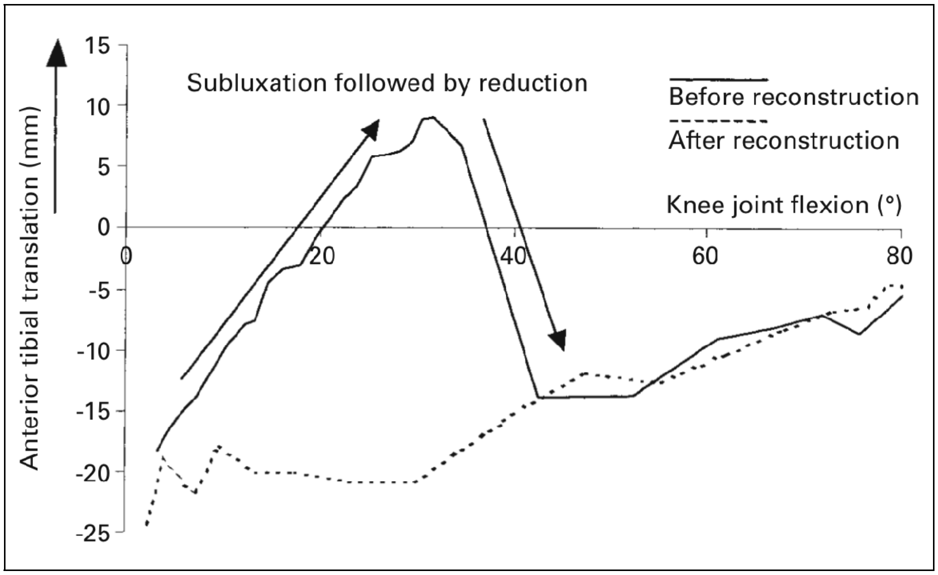

Figure 3.14 Translation of the center of the tibia relative to the femur during the pivot shift test before and after ACL reconstruction
Taken from Bull et al.[50]

More recently, Lane et al.[112] published results of a similar study. The objective of this study was also to analyze the *in vivo* kinematics of the pivot shift and how these were changed by reconstructive surgery. Twelve subjects had rigid bodies fixed to their tibia and femur using percutaneous pins. Reflective markers, which were tracked by an infrared optical localizer, were attached to these rigid bodies (Figure 3.15). One of two different surgeons performed passive knee flexion and the pivot shift test, before and after ACL reconstruction, and attributed the subjective grades.

Figure 3.15 Experimental setup of the Lane et al. study.
Taken from Lane et al.[112]

The authors found good correlation between the grades and tibial rotation, maximum anterior tibial translation (this is the subluxation before the actual pivot shift) and acceleration of posterior translation. They also describe a new measure, which they call the "angle of *p*". The so-called angle of *p* is measured at the intersection of the arc of motion of the pivot shift and the arc of motion of the reference passive knee flexion, in the sagittal plane (Figure 3.16). This new measure was found to have excellent correlation to the subjective pivot shift grade and significant differences were found between each pair of grades. While this result is certainly promising, the study has a major shortcoming that must be considered along with these results and that is that only 12 subjects were evaluated. Before reconstruction, all of these subjects were graded 1 (3 subjects) or 2 (9 subjects). After surgery, all 12 were graded

0. Therefore, there were no recordings of grade 3 kinematics and only 3 of grade 1. Larger populations of each of the grades would be necessary to confirm these results.

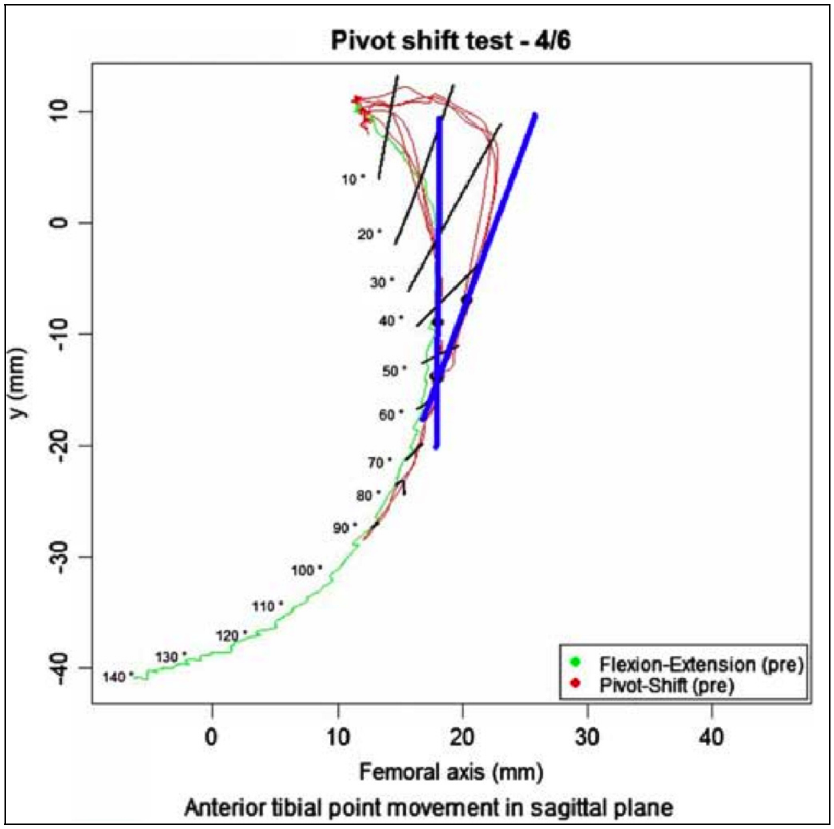

Figure 3.16 The angle of *p* created by the arc of motion of the pivot shift reduction and the arc of motion of the reference flexion, in the sagittal plane.
Taken from Lane et al.[112]

The previous two studies, although conducted on small populations, show promise for the quantitative measure of the pivot shift. On the other hand, because of the invasive nature of intra-cortical pins, their methodologies are not appropriate in a clinical setting. The use of such methods would be confined to the operating room and used during navigated ACL reconstruction. Three recent studies, published by two different research teams, have proposed similar methodologies but with non-invasive attachment of motion capture devices.

Kubo et al.[49] used plastic braces, strapped to the thigh and shank, on which electromagnetic sensors were mounted (Figure 3.17). They assessed the accuracy of this system on one subject by simultaneously recording the knee joint kinematics from the sensors attached to the braces and from two additional sensors, directly fixed to the bones. The authors report a maximum error of 0.85 mm between both approaches. This result suggests very good accuracy but the authors gave insufficient methodological details. For example, they do not elaborate on the technique used to fix the bone embedded markers. Using such markers to measure the precision of a non-invasive system may underestimate the effect of skin displacement. This is due to the fact that the percutaneous pins used to fix the markers to the bone effectively "staple" the skin to the bone, thereby reducing the relative displacement. Moreover, the authors fail to mention if accuracy was evaluated during a pivot shift manoeuver or a simple passive flexion. The importance of assessing the accuracy during a pivot shift test was recently highlighted by Amis et al.[48] who found their non-invasive attachment system did not follow bone movements during the reduction phase of the pivot shift (Figure 3.21).

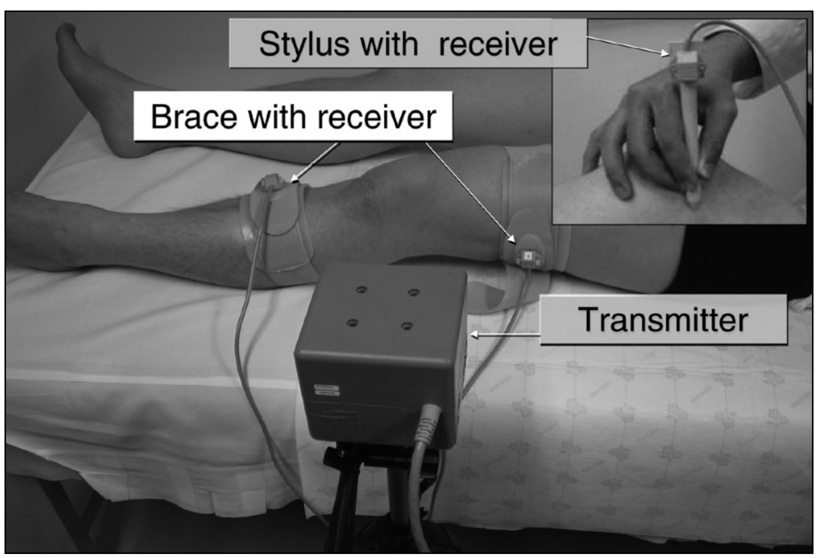

Figure 3.17 The experimental setup for the studies of Kubo et al. and Hoshino et al.
Taken from Hoshino et al.[51]

Contrary to the previous studies, the subjects in this study were awake and not under the effect of any anesthesia. A single examiner performed and graded the pivot shift test on 25 subjects with confirmed chronic ACL injury. To analyze the kinematics, the authors calculated the position of the tibial tubercle projected on the horizontal plane. This is in contrast with the majority of studies, which measured the kinematics at knee joint center. Three parameters were calculated and found to correlate to the grade of pivot shift: posterior translation, lateral translation and maximum posterolateral velocity. The latter had the highest correlation (Figure 3.18). The results were obtained on 13 recordings of a grade 0 pivot shift, 60 of grade 1, 58 of grade 2 and 15 of grade 3. Such a high number of recordings were acquired because the clinician induced the pivot shift five to eight times on each subject and each pivot shift was graded and recorded individually. This introduces a bias in the results as, for example, eight of the 15 grade 3 recordings may originate from eight consecutive pivot shifts on a single subject by a single clinician. This obviously diminishes the normal variability that exists between subjects.

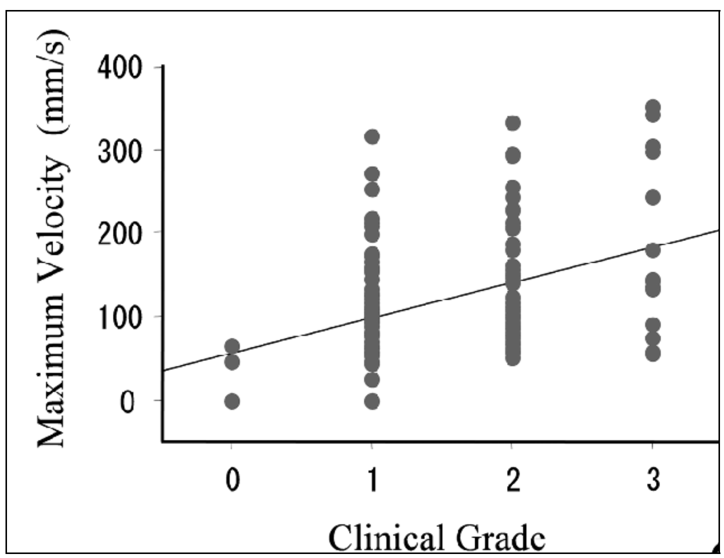

Figure 3.18 Correlation between the clinical grade of pivot shift and the measured maximum posterolateral velocity.
Taken from Kubo et al.[49]

In 2007, a group from the same research center published their own findings. Hoshino et al.[51] used the same attachment system as Kubo et al. used (Figure 3.17). In this study, the 30 subjects were evaluated under anesthesia, by one of three different orthopaedic surgeons. The kinematic parameters calculated were anterior tibial translation and acceleration of posterior translation. The contralateral, asymptomatic knees were also evaluated resulting in 30 grade 0 recordings, 11 of grade 1, 16 of grade 2 and 3 of grade 3. Significant differences were found between the group of intact knees and the group of contralateral knees for both calculated parameters. These parameters also showed positive correlations with grades 1, 2 and 3.

Amis et al.[48] recently put effort into developing a non-invasive attachment system for measurement of the pivot shift. They developed one system similar to that used by Kubo et al.[49] and Hoshino et al.[51], made of custom molded thermoplastic plates (Figure 3.19). They tested the accuracy of this system on 10 cadavers and found mean errors of ± 5.6° and ± 3.6 mm at the femur, which was judged to be unacceptable.

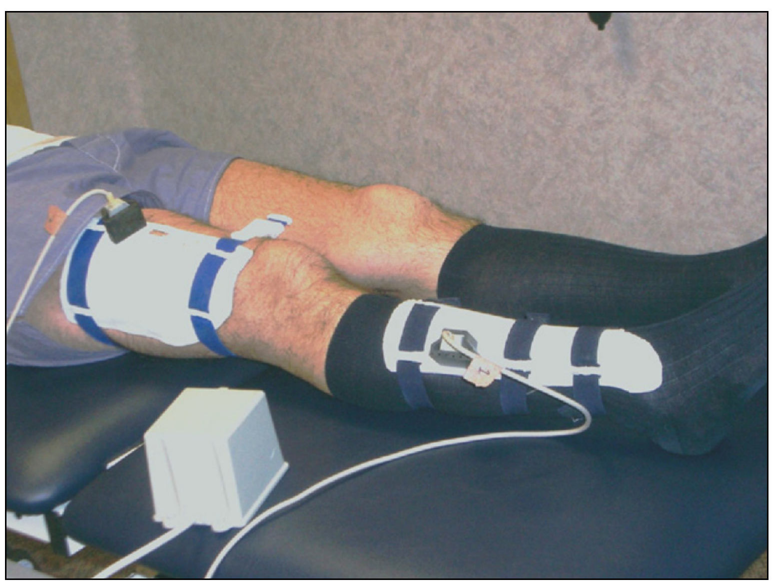

Figure 3.19 Attachment system made of custom molded thermoplastic plates.
Taken from Amis et al.[48]

They developed a second attachment system with a femoral component in the form of a clamp that secures to the medial femoral epicondyle and posterior to the lateral epicondyle (Figure 3.20). The clamp is attached to a stabilizing bar, similar to that of the harness, described by Sati et al.[102]. The accuracy of this clamp was evaluated on 10 anesthetized subjects by simultaneously recording kinematics with sensors attached to the bones. For normal, relatively slow motions, the system was found to be accurate to within 1 mm in translation and 1° in rotation.

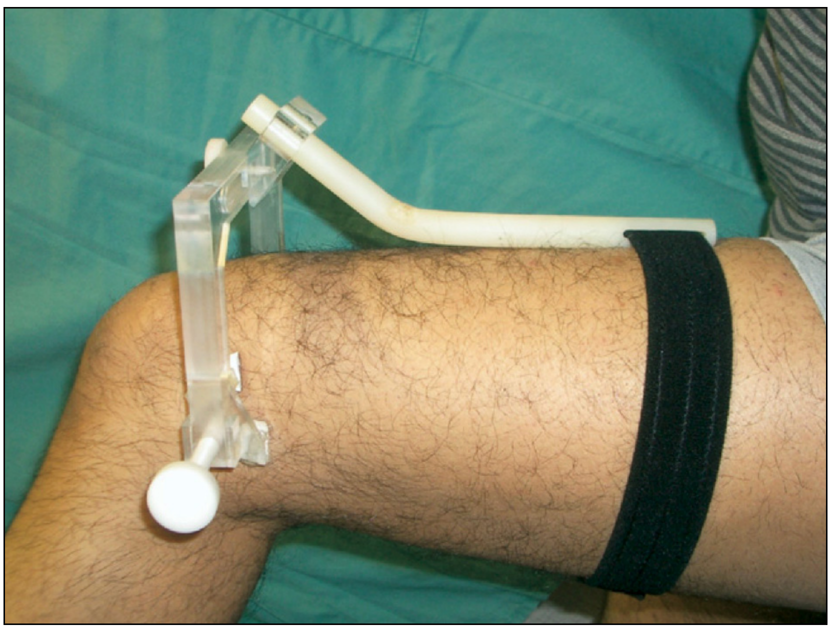

Figure 3.20 The femoral clamp and stabilizing bar developed by Amis et al.
Taken from Amis et al.[48]

However, when it was used to record a pivot shift, it was found that the skin-mounted attachment system greatly underestimated the motion of the bone during the sudden reduction phase (Figure 3.21). The authors concluded that this disparity was du to inertia of the large and relatively heavy femoral clamp. They decided to use the attachment system to measure the two main components of the pivot shift, anterior translation and internal tibial rotation, separately and under controlled loads. In doing so, they were able to establish personalized normal envelop of laxity limits for the subjects (Figure 3.22). They suggest that this will allow viewing of the pivot shift kinematics in the context of this normal envelop of laxity. A new, lighter version of the clamp is currently being developed for measurement of the pivot shift.

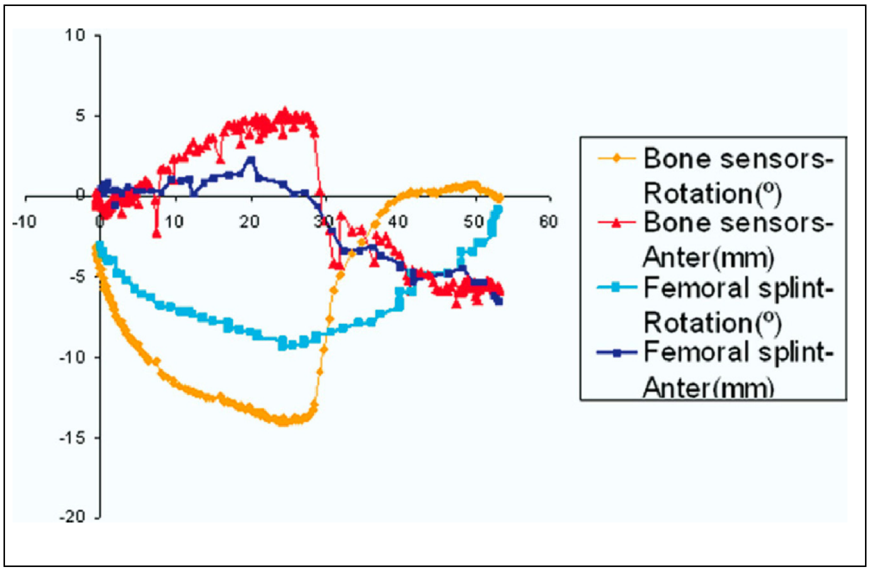

Figure 3.21 Simultaneous measurement of the translation and rotation components of the motion of the femur using bone- and skin-mounted attachment systems during a pivot shift test.
Taken from Amis et al.[48]

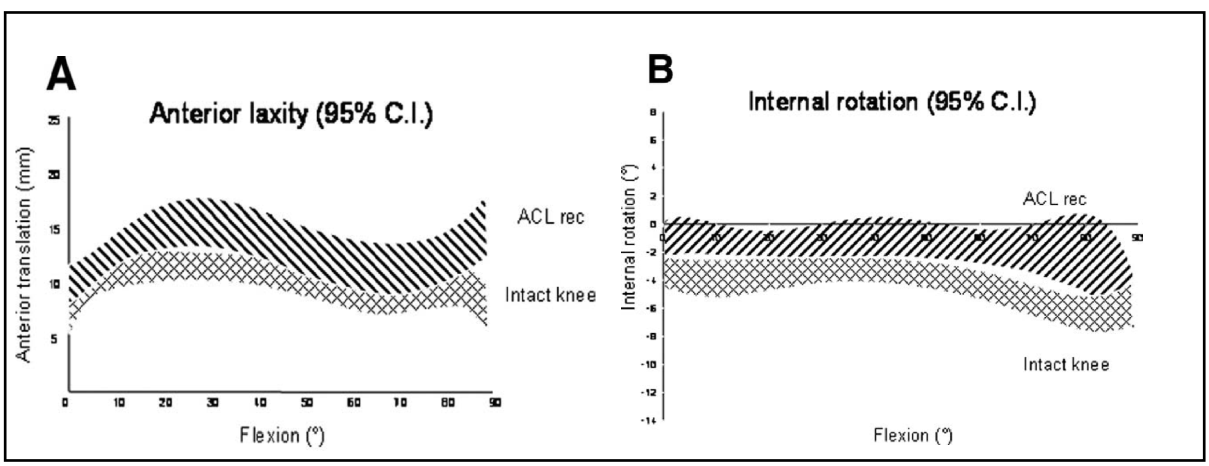

Figure 3.22 (A) Graph of anterior laxity versus knee flexion (B) Graph of internal rotation laxity versus knee flexion.
Taken from Amis et al.[48]

In 2009, Lopomo et al.[52] used an optical surgical navigation system to compare pre- and post-operative pivot shift kinematics of 18 subjects. Their aim was to identify new kinematic parameters and verify their clinical relevance. They found correlations between the pivot shift grade and the area of anteroposterior translation of the knee joint center, the area of anteroposterior translation at the lateral tibial compartment, the area of internal/external tibial rotation and the area of abduction/adduction. Areas were measured between the curves of motion during flexion and extension of the knee during the pivot shift test (Figure 3.23). These results were obtained on only 11 grade 2 and seven grade 3 pivot shifts. Nevertheless, they show potential for the use of the area as a kinematic parameter for quantification of the pivot shift.

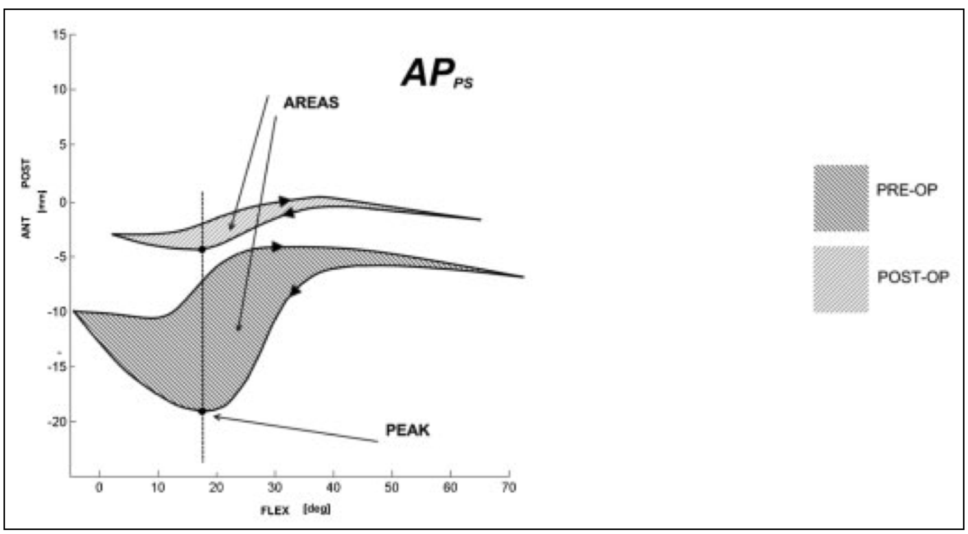

Figure 3.23 Area of anteroposterior translation of knee joint center during the pivot shift test.
Taken from Lopomo et al.[52]

Table 3.2 Summary of the *in vivo* studies that quantified the pivot shift

Study	**Fixation**	**Anesthesia**	**Subjects**	**Results**
Bull et al., 2002	Percutaneous pins	Yes	10	Weak correlation between posterior translation and subjective grade
Kubo et al. 2006	Plastic braces	No	25	Correlation between subjective grade and posterior translation, lateral translation and maximum posterolateral velocity.
Hoshino et al. 2007	Plastic braces	Yes	30	Anterior tibial translation and posterior acceleration higher in intact knee than symptomatic knee and correlates to subjective grade.
Amis et al. 2008	Clamp	Yes	10	Attachment system is accurate for slow motions but underestimates the knee joint kinematics during the reduction phase of the pivot shift.
Lane et al. 2008	Percutaneous pins	Yes	12	Excellent correlation between grade and angle of P. Good correlation between grade and tibial rotation and anterior tibial translation.

Table 3.3 Summary of the *in vivo* studies that quantified the pivot shift (continued)

Study	**Fixation**	**Anesthesia**	**Subjects**	**Results**
Lopomo et al. 2009	Percutaneous pins	Yes	18	Correlation between the pivot shift grade and the areas of AP translation of the knee joint center, AP translation at the lateral tibial compartment, internal/external tibial rotation and abduction/adduction.

Recently, different authors have used some of the kinematic parameters presented in **Table 3.2** to quantify the pivot shift. These authors did so to quantitatively compare different grafts or surgical techniques (e.g. single- versus double-bundle)[113-115].

3.6 Conclusion

The importance of the pivot shift grade has been established with regards to short and long term treatment outcome[38, 43, 58]. This grade, which is obviously a subjective one, has however been shown to not be very reliable: different clinicians attribute different grades to the same knee[48]. This can be at[47]tributed to differences of interpretation but it is also known that different clinicians actually produce very different kinematics when they induce the pivot shift.

Many issues have been raised concerning instrumented static tests such as the Lachman test, measured by the KT-1000. Nonetheless, in the absence of a validated measure of the pivot shift test, this has remained a widely used method for quantifying surgical outcome. In addition to the important variability inherent to the pivot shift test, skin displacement artifacts are a major obstacle in developing an objective measure. Several authors have used percutaneous pins to follow the motion of the bones, which all but eliminates these artifacts.

On the other hand, the invasive nature of this solution prohibits its use in a clinical setting and probably restricts its use to navigated reconstructions. There is no perfect solution to this problem at present time, the choice of marker attachment depends on the motion capture technology that is used and is a compromised between invasiveness and accuracy.

In previous studies of the kinematics of the pivot shift, there has been no agreement on which parameters should be considered. There is general consensus that AP translation is an important component of the pivot shift. Tibial rotation may also be of importance but is very variable between subjects. Many authors have proposed their own kinematic parameters and have shown some degree of correlation to the pivot shift grade. However, many studies included a small number of subjects and none have been able to establish a truly quantitative measure or automatic grading of the pivot shift test. These studies demonstrate the feasibility of measuring the pivot shift. Recent studies, where authors have used kinematic parameters that have yet to be validated as quantitative measure of the pivot shift to evaluate surgical outcome, demonstrate the need for such a validated measure.

CHAPTER 4

METHODOLOGICAL CHOICES AND SITUATION OF THE ARTICLES WITHIN THE THESIS

The data acquired for this study was collected in two separate sets of experimentations. The first involved 12 subjects and 3 orthopaedic surgeons. It was designed to establish which aspects of the clinician's gesture are related to inter-observer variability and then to reduce this variability. The second involved an additional 58 subjects and 8 orthopaedic surgeons, 2 oh whom had participated in the first set of experimentations (Appendix I shows the number of evaluations performed by each clinician). This second phase aimed to characterize and classify the grades of pivot shift on a larger population. This chapter will present a summary of the experimental methodology that was applied for both series of experimentations and will justify the key methodological choices that were made.

4.1 Summarized description of the experimentations

4.1.1 Inter-observer variability

In has been established that different clinicians produce different knee kinematics when they induce the pivot shift on a same knee[47]. The main objective of this first phase of the study was to develop a method for reducing this variability, thus paving the way for an objective measure of the pivot shift test that adjusts to the clinician's technique and not the other way around.

To do so, an inter-observer experimental protocol was conducted where 3 orthopaedic surgeons each performed the pivot shift test on one knee of 12 different subjects (Appendix II shows the main characteristics of each clinician's gesture). The kinematics of the pivot shift were recorded and used for two distinct purposes. They were used to compare the kinematics produced by each examiner, on each knee. These data, taken alone, were used in article 1. They were also added to the data collected in the broad phase to form a bank of as many pivot shift recordings as possible, for a larger analysis of the pivot shift phenomenon.

4.1.2 Characterization of the pivot shift

The second, larger phase of our study was conducted to obtain the pivot shift kinematics of a much larger population of subjects. This was important for several different reasons. First, we wanted to verify that the methodology developed with the data of the first phase of the study held true when applied to a larger population (see Appendix III for a summary of subject characteristics). Second, we wanted to study the kinematics of the pivot shift in relation to the grade attributed by an orthopaedic surgeon in order to establish which kinematic parameters account for most of the variability between recordings. The identification of these parameters would be a stepping-stone towards the development of an automated grade attribution method and, eventually, a quantitative measure of the pivot shift. The third and final objective of the second phase of experimentations was to gather the data necessary to develop a classifier that would automatically attribute the grade of pivot shift using the recorded kinematics. To do so, we needed a sufficiently large number of pivot shift recordings, distributed as equally as possible accross the four possible grades.

The experimentations for the broad phase were conducted over a period of 21 months, at six different hospitals. The experimentation sessions followed these step:

1 – The subject signed the consent form and filled out a form requiring him to provide contact information and anthropometric data.

2 – The subject changed into a pair of sports shorts that do not cover the distal thigh or hinder hip abduction. The attachment system (described later), with electromagnetic sensors mounted to it, was attached to the lower limb of the subject by an experimenter. A leather belt was also tightly apposed over the subject's iliac spines to follow the movements of the pelvis during the calibration phase.

3 – The subject lay on the examination table in a supine position. The examiner performed the calibration method, which consists of pointing at anatomical structures and applying passive movements to the knee and hip joints in order to define the axes according to the subject's functional anatomy.

4 – The custom software started the recording of positions and orientations of the thigh and shank electromagnetic sensors.

5 – An orthopaedic surgeon performed the pivot shift test. Typically, the pivot shift test was performed several times, in succession, until the surgeon felt he had properly induced the pivot shift, at which time he verbally attributed a grade to this pivot shift. This part of the evaluation was also recorded using a video recorder.

The subjects were evaluated by only one orthopaedic surgeon, who was not the same for each subject, and most had both knees evaluated. The pivot shift recordings that were obtained were added to those obtained during the inter-observer phase of experimentations, creating a data bank of 107 pivot shift recordings (Appendix IV shows typical knee joint kinematics for each grade of pivot shift). This data bank was used for all three articles; **Table 4.1** presents the analysis that was performed on the data for each of the articles.

Table 4.1 Utilization of pivot shift recordings for each article

Broad phase data analysis	**Article**
Reduction of inter-clinician variability	Article 1
Feature extraction	Article 2
Grade classification	Article 3

4.1.3 Attachment system

In chapter 3, the impact of skin displacement artifacts was exposed and different attachment systems were presented. Because of the small amplitude of some of the movements we wanted to quantify, e.g. translations and abduction/adduction, it was essential to utilize a fixation system that would follow the bones with higher accuracy than is possible with skin-mounted markers. The attachment system used by our lab for gait analysis, called exoskeleton, has been demonstrated to greatly reduce skin displacement artefacts[102] and to have high reliability[104]. However, the exoskeleton was designed for use on a standing subject and its femoral component, which rests atop the femoral condyles, falls out of place when a subject is placed in a supine position.

To overcome this obstacle, a new attachment system, inspired by the exoskeleton, was developed. The femoral component of this new attachment system is composed of two orthoplasts that are mounted on small rigid plates, held together by an elastic Velcro strap (Figure 4.1). This strap allows for inward pressure to be applied to the orthoplasts and it prevents them from falling out of place when the subject is supine. The purpose of the rigid plates is to stabilize the orthoplasts and to allow for fixation of the motion capture sensors.

Figure 4.1 The femoral component of the attachment system we developed for data acquisition.

The tibial component is composed of a rigid plate that is held over the tibia with an elastic Velcro strap, immediately distal to the tibial tuberosity (Figure 4.2). It is relatively short in length to allow a clinician to manipulate the lower limb without displacing it.

Figure 4.2 The tibial component of the attachment system we developed for data acquisition.

A preliminary study conducted with this newly developed attachment system, on 3 subjects, showed it to be as reliable as the exoskeleton for gait analysis. The results of this preliminary study are presented in the Supplementary Results section. Reliability was evaluated for gait analysis because gait is a highly repeatable movement. This is not the case for passive knee flexions such as those applied for the pivot shift test and it would have been impossible to distinguish the variability due to the attachment system from that due to actual kinematic variability.

4.1.4 Instrumentation

To obtain knee joint kinematics, it is necessary to record the movement of the tibia and femur with 6 degrees of freedom (DOF). To do so, two categories of motion capture devices are frequently used: electromagnetic devices and optical systems. For both phases of this study, we chose to use Fastrak electromagnetic sensors.

The main advantage of using electromagnetic sensors over optical systems is that they are much less cumbersome and more portable. Electromagnetic devices are easy to transport and to setup in a small clinical evaluation room. Moreover, they do not require extensive recalibration before each experimentation session, as opposed to optical motion tracking systems such as Vicon. Moreover, the clinician need not worry about his position interfering with the line of sight of the cameras. Finally, previous studies have had success recording pivot shift kinematics using electromagnetic sensors[48-51].

The main drawback of electromagnetic devices is conductive metal interference. That is to say that the presence of conductive metal objects within the source's electromagnetic field causes distortion errors. This is of particular concern for alternating current (AC) systems such as the Fastrak system. This issue was addressed by evaluating all subjects on a table containing no metallic components and with no metal objects in proximity. Before each session, the magnetic field was characterized using a calibration object with magnetic sensors at known relative positions[116]. Thus, we could insure that the field was free from distortions and apply corrections if this were not the case. No correction was necessary for our acquisitions.

4.1.5 Definition of the coordinate system

We chose to describe the movement of the tibia relative to the femur using the anatomical axes of the knee, as this description is easy to interpret clinically. Furthermore, all previous studies described the pivot shift with regards to the anatomical axes. Thus, the movement of the tibia relative to the femur is described as translations along the anteroposterior (AP), mediolateral (ML) and proximodistal (PD) axes. Rotations about these axes are: abduction/adduction, flexion/extension and internal/external tibial rotation, respectively.

The coordinate system we used is that proposed and validated by Hagemeister et al.[117]. To define the axes of this coordinate system, anatomical landmarks must be identified and the subject must perform different joint rotations. Because the pivot shift test is performed with the subject in a supine position, we adapted the latter part of the method to consist of passive joint rotations, applied by the examiner on the supine subject. The steps were as follows.

1 – The experimenter uses an electromagnetic stylus to point the subject's medial and lateral malleoli and his medial and lateral femoral epicondyles. This step allows for the identification of the ankle joint center, defined as the midpoint between the malleoli. It also allows for the identification of the midpoint between the femoral epicondyle, which is later used to define knee joint center.

2 – The experimenter lifts the subject's lower limb and applies a movement of hip circumduction for 15 seconds (Figure 4.3). The hip joint center, or center of the femoral head, is defined using a pivot algorithm, as proposed by Siston and Delph[118].

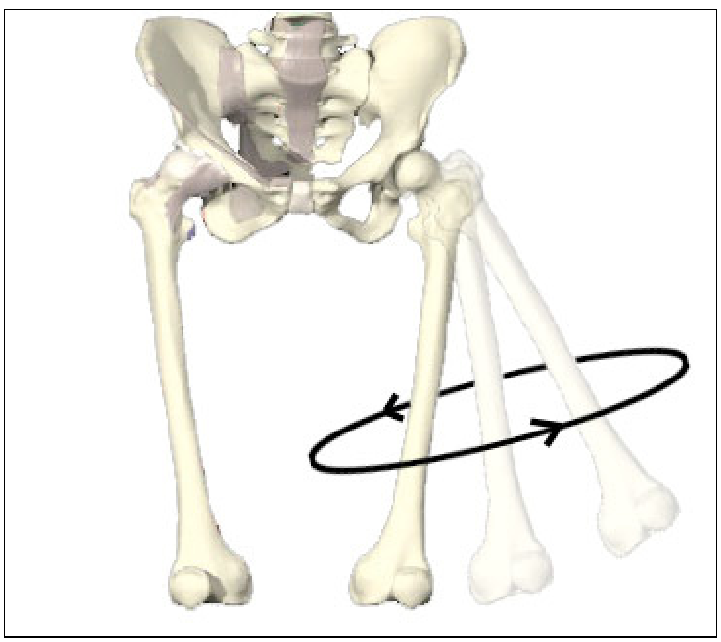

Figure 4.3 Illustration of the movement of hip circumduction, performed to identify the hip joint center.
Adapted from Primal Pictures Ltd

3 – The experimenter lifts the limb and holds it in full extension. He then flexes the knee to approximately 60° and then extends it to full extension (Figure 4.4). He repeats this flexion/extension several times consecutively. The mean axis of flexion is defined from this movement and the previously defined midpoint between the femoral epicondyles is projected onto this axis, defining the knee joint center.

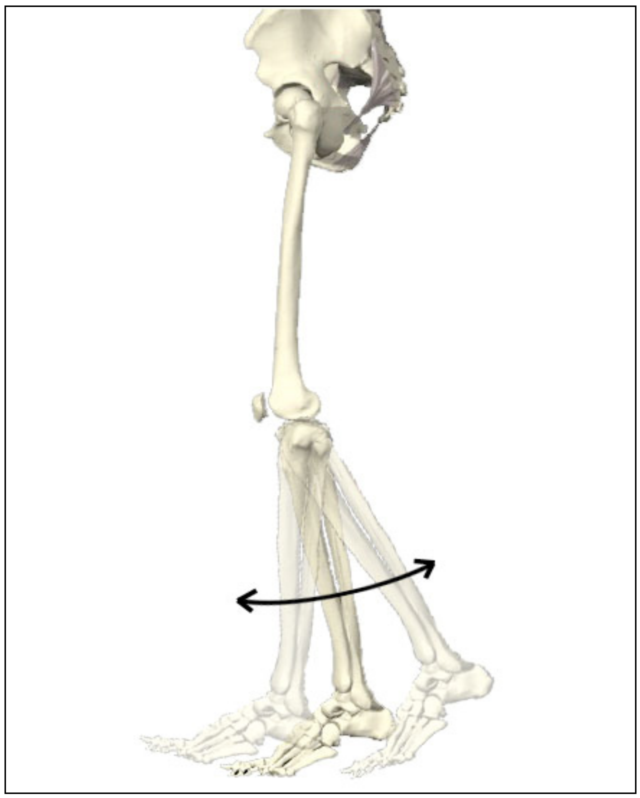

Figure 4.4 Illustration of the movement of flexion/extension, performed to define the mean axis of flexion.
Adapted from Primal Pictures Ltd

4 – The patient's legs are extended and his feet are placed in a calibration guide that maintains parallel to one another. The experimenter applies a movement of slight flexion/extension, alternating between approximately 10° of flexion and maximum extension (Figure 4.5). This step serves to establish the coordinate system with the limb in a predetermined position.

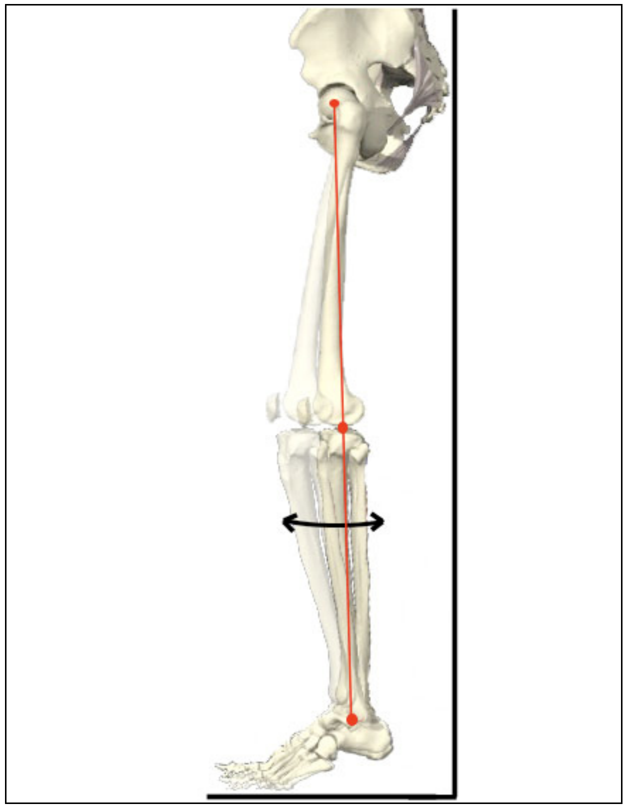

Figure 4.5 Illustration of the movement of slight flexion/maximum extension, performed to define the neutral position.
Adapted from Primal Pictures Ltd

The proximodistal (PD) axis of the tibia is defined by the vector joining the knee joint center and the ankle joint center. The mediolateral (ML) axis is perpendicular to this axis and to the X-axis of the electromagnetic source (equivalent to the vector normal to the surface of the examining table). The anteroposterior (AP) axis is perpendicular to the ML and PD axes.

The PD axis of the femur is defined by the vector joining the knee joint center to the hip joint center. The ML axis is perpendicular to this axis and to the X-axis of the electromagnetic source. The AP axis is perpendicular to the ML and PD axes.

The origins of the coordinate systems are situated at the knee joint center and are defined during the 4th step of the calibration method, when the PD axis of the femur is parallel to the PD axis of the tibial. In this position, tibial rotation is defined to be 0°.

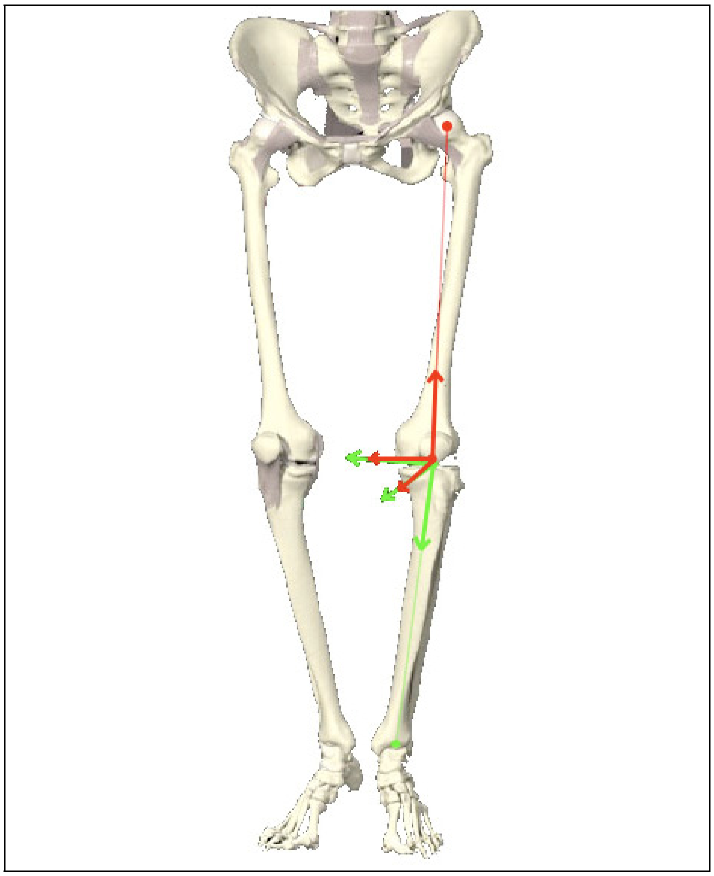

Figure 4.6 The coordinate systems of the tibia and femur as defined by the modified FP method.
Adapted from Primal Pictures Ltd

4.2 Computation of translations and rotations

The raw data acquired using the electromagnetic device consist of one matrix per sensor, for each of the iterations. Each of these matrices, $m_{tSensor}$ and $m_{fSensor}$, is of the form:

$$m = \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & t_x \\ r_{2,1} & r_{2,2} & r_{2,3} & t_y \\ r_{3,1} & r_{3,2} & r_{3,3} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where t_x, t_y and t_z are translations along the *x, y* and *z* axes respectively. Values represented by $r_{1..3,1..3}$ form a rotation matrix, which is an orthogonal matrix whose determinant is 1. Each matrix thus represents the position and orientation of one sensor in the global reference of the electromagnetic source (Figure 4.7).

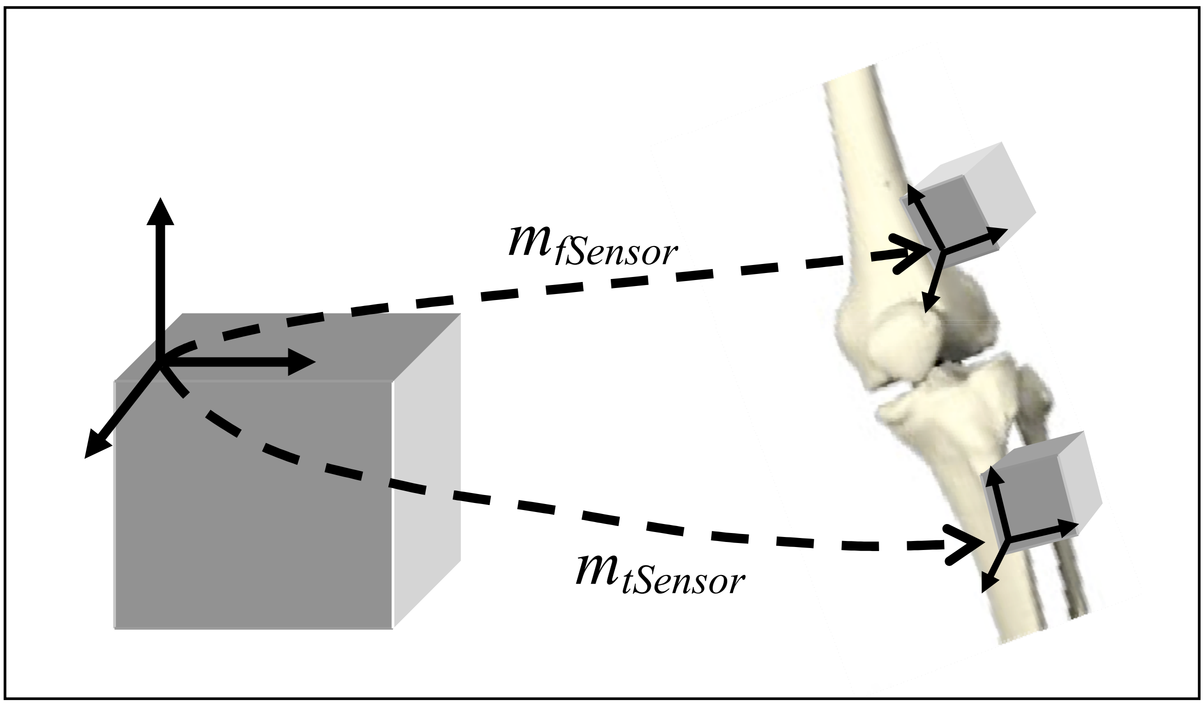

Figure 4.7 Representation of the matrices containing the position and orientation of the femoral and tibial sensors relative to the electromagnetic source.

To describe the knee joint kinematics in anatomical terms, this raw data were combined with the results of the calibration method, which was just described. This calibration method defines the anatomical axes, which means that it establishes the position and orientation of these anatomical axes relative to the tibial and femoral sensors. The calibration consists in two 4x4 matrices, $m_{tSensor \leftarrow tAxis}$, and $m_{fSensor \leftarrow fAxis}$ with the same format as the raw data matrices. The calibration matrices $m_{tSensor \leftarrow tAxis}$, and $m_{fSensor \leftarrow fAxis}$ are the transformation matrices that must be applied to the raw data matrices $m_{tSensor}$ and $m_{fSensor}$ to obtain the position and orientation of the tibial and femoral axes in global reference frame.

$$m_{axis} = m_{sensor} \text{ x } m_{sensor \leftarrow axis}$$

Because we wanted to calculate the kinematics of the knee joint, it is the relative movement between the axes of the femur and that of the tibia that was of interest. The representation of the movement of the tibia relative to the femur is in fact the transformation matrix from the femur to the tibia, $m_{tAxis \leftarrow fAxis}$. This can be obtained from matrices $m_{tSensor \leftarrow tAxis}$ and $m_{fSensor \leftarrow fAxis}$ with the following set of equations:

$$m_{tSensor \leftarrow tAxis} \text{ x } m_{tAxis \leftarrow fAxis} = m_{fSensor \leftarrow fAxis}$$
$$m_{tSensor \leftarrow tAxis}^{-1} \text{ x } m_{tSensor \leftarrow tAxis} \text{ x } m_{tAxis \leftarrow fAxis} = m_{tSensor \leftarrow tAxis}^{-1} \text{ x } m_{fSensor \leftarrow fAxis}$$
$$m_{tAxis \leftarrow fAxis} = m_{tSensor \leftarrow tAxis}^{-1} \text{ x } m_{fSensor \leftarrow fAxis}$$

The tibial rotations about the same three axes are defined in the rotation matrix ($r_{1,1}..r_{3,3}$) of $m_{fAxis \leftarrow tAxis}$. The angles of flexion/extension, abduction/adduction and internal/external tibial rotation were extracted from this rotation matrix using the method described by Grood and Suntay[119]. The pivot shift is an anterior subluxation and reduction of the tibia relative to the femur but this subluxation is along the AP axis of the tibia. As such, the transformation matrix from the tibia to the femur was calculated. The tibial translations along the ML, AP and PD axes are therefore equal to t_x, t_y, and t_z of $m_{fAxis \leftarrow tAxis}^{-1}$, respectively and are represented as the distance in mm between the origins of the coordinate systems.

4.3 Classification method

For each pivot shift recording, we have the clinical grade that was attributed by the evaluating clinician. We used this grade as a gold standard and we aimed to reproduce the grading done by experienced clinicians while rendering this grading more objective. As such, we chose to use a supervised learning method. We were looking for maximum agreement between our classifier and the clinicians, not for new sub-classes in our data.

Support Vector Machines (SVMs) are a set of supervised learning methods used for classification. A SVM constructs a hyperplane or set of hyperplanes in a high-dimensional space, which can be used for classification. It chooses the points that lie closest to the defined hyperplane as support vectors. This is well adapted to our study were the classes are predefined by the clinicians and where the different data points are easily confounded. Because we are dealing with continuous data, subjectively classified into discrete classes, the borders are not clear-cut and the biggest challenge is to limit errors along these borders; this is an area where SVMs generally excel.

Moreover, a SVM is a binary classifier. To distinguish multiple classes, the method must be applied iteratively. This also lends itself well to the grading of the pivot shift. In fact, the recordings can be first separated into that present a clunk (grade 2 and 3) and those that don't (grades 0 and 1). As a second step, the recordings with a glide (grade 1) can be distinguished from those with no glide (grade 0). Finally, those presenting a clunk (grade 2) can be distinguished from those presenting a more obvious, gross clunk (grade 3).

4.4 Situation of the articles within the scope of the thesis

The main objective of this thesis was to render the pivot shift test less subjective and more reliable. The three articles that follow make important contributions towards that end objective.

The first article presents the methodology for both the inter-observer and the broad phases of data acquisition. It presents the difference observed between clinicians in the first phase and the method developed to diminish it. The method is then applied to the data of the second phase in order to verify that similar improvement is observed.

The second and third article present results obtained from the knee recordings of both phases combined. The second presents the results of a principal component analysis (PCA) of the pivot shift kinematics in order to identify which parameters best explain the differences between the different pivot shift recordings. This information was then used to identify the parameters that are useful in classifying the recordings according to their grade. This classifier, based on a SVM algorithm is presented in the third article and is the culmination of the work presented in the previous two articles.

CHAPTER 5

ARTICLE I: ACCOUNTING FOR VELOCITY OF THE PIVOT SHIFT TEST MANOEUVRE DECREASES KINEMATIC VARIABILITY

Article submitted to the journal: The Knee

David R. Labbe[a,b], Jacques A de Guise [a,b], Neila Mezghani[a], Véronique Godbout[c], Guy Grimard[d], David Baillargeon[e], Patrick Lavigne[f], Julio Fernandes[g], Pierre Ranger[g], Nicola Hagemeister[a,b]

[a]Laboratoire de recherche en imagerie et orthopédie, Centre de recherche, Centre hospitalier de l'Université de Montréal (CHUM), Montréal, Canada

[b]École de technologie supérieure, Montréal, Canada

[c]Hôpital Notre-Dame, Montréal, Canada

[d]Hôpital Ste-Justine , Montréal, Canada

[e]Hôpital de la Cité-de-la-Santé, Laval, Canada

[f]Hôpital Maisonneuve-Rosemont, Montréal, Canada

[g]Hôpital du Sacré-Coeur, Montréal, Canada

Résumé

Contexte Le test du *pivot shift* est le seul test clinique qui corrèle à l'état fonctionnel du genou, suite à une rupture du ligament croisé antérieur. Un grade est attribué au *pivot shift* de façon subjective, ce qui a mené à diverses études ayant pour objectif de quantifier le déplacement entre les os du genou et le corréler avec le grade clinique. Cependant, la nature dynamique et non guidée de la manœuvre introduisent une variabilité importante dans les enregistrements cinématiques.

Objectif Notre objectif principal était de développer une méthode pour diminuer la variabilité attribuable à la technique utilisée par le clinicien pour ainsi augmenter les différences entre les grades.

Méthodes Trois chirurgiens orthopédiques différents ont chacun exécuté le test du *pivot shift* sur 12 sujets. La cinématique du genou a été enregistrée pendant les évaluations, à l'aide d'un appareil électromagnétique. La variabilité inter-clinicien a été quantifiée et une méthode a été développée pour la diminuer en utilisant la vitesse angulaire de flexion. Cette méthode a ensuite été appliquée sur une population de 127 genoux ayant divers degrés d'instabilité, évalués par un de huit chirurgiens orthopédistes différents.

Résultats La vitesse angulaire de flexion appliquée par les cliniciens avait une corrélation très significative avec la cinématique produite. La normalisation des paramètres cinématiques à l'aide de cette vitesse angulaire a réduit la variabilité inter-clinicien de 20% et a permis des différences plus significatives entre les grades de *pivot shift*.

Conclusions Une simple normalisation de la cinématique du *pivot shift* à l'aide de la vitesse angulaire de flexion réduit la variabilité liée au geste du clinicien et permet des différences significatives entre les grades. Ces résultats sont un pas important vers le développement d'une mesure objective du phénomène de *pivot shift*.

Abstract

Background The pivot shift test is the only clinical test that correlates to knee joint function, following rupture of the ACL. A grade is attributed to the pivot shift in a subjective manner, leading to efforts to quantify the bone movements and correlate them to the grade. However, the dynamic and unconstrained nature of the manoeuver introduces important kinematic variability.

Purpose Our main objective was to develop a method to lessen the variability attributable to clinician technique, therefore increasing inter-grade differences.

Methods Three different orthopaedic surgeons each performed the pivot shift test on 12 subjects. Knee joint kinematics were recorded during the evaluations using electromagnetic motion capture devices. Inter-clinician variability was quantified and a method was developed to diminish it, using the angular velocity of flexion. This method was then applied to a larger population composed of 127 knees with various degrees of instability, evaluated by one of eight different orthopaedic surgeons.

Results The angular velocity of knee joint flexion produced by the clinicians had a very significant correlation to the produced kinematics. Normalization of kinematic parameters using this parameter reduced the intra-clinician variability by 20% and allowed for more significant differences between the grades of pivot shift.

Conclusions Simple normalization of pivot shift kinematics using the angular velocity of flexion reduces clinician-related variability and allows for significant differences between the different grades. These results are an important step towards developing an objective measurement tool for the pivot shift phenomenon.

5.1 Introduction

Following rupture of the anterior cruciate ligament (ACL), different manual tests are used for diagnosis. The most widespread are Lachman's test[19], the anterior drawer test and the pivot shift test[23]. The pivot shift test, which reproduces the instability felt during episodes of giving way, is the only one which correlates with subjective knee function indicators such as patient satisfaction, giving way, participation in sport activities, Lysholm test score, etc.[38, 43]. It is widely accepted that the pivot shift test is the best indicator of knee joint stability and that the aim of treatments should be to eliminate the pivot shift[38, 43-45].

Objective measurement tools exist for the anterior drawer test and Lachman's test[71, 80] but the pivot shift is a more complex, dynamic displacement between the tibia and the femur and no such measurement tool is currently commercially available. Rather, the clinician must subjectively attribute a grade of 0 (none), 1 (glide), 2 (clunk) or 3 (gross) to the shift on the basis of his experience. It is this grade that gives an appreciation of knee function. However, it has been well documented that different examiners, especially less experienced ones, attribute different grades for a same knee[47, 120].

Efforts have been made to develop quantification tools for the pivot shift test[49-51, 112]. Different kinematic parameters have been found to correlate favorably with the clinical grade but finding significant differences between the individual grades has proven to be more difficult. Such differences would be of value for developing objective grading methods but have been limited due to large kinematic variability between pivot shifts of a same grade. This variability can be separated into that related to the subject's characteristics (specific injury, bony geometry[21, 66], muscular resistance, etc.) and that induced by the clinicians and the particularities of their techniques. In particular, preliminary data have shown that the angular velocity of flexion applied by a clinician during the execution of the pivot shift test has an important impact on the produced kinematics. We hypothesize that the aforementioned velocity of flexion can be used to apply a form of normalization of the pivot shift to diminish the variability associated with clinician technique.

The objectives of this study are therefore to identify kinematic parameters which vary between grades, to quantify the variability between clinicians amongst these parameters and to verify our hypothesis that it can be diminished, allowing for better distinction between the different grades of pivot shift.

5.2 Materials and methods

The study was conducted in two separate phases. In the first and main phase, twelve subjects were evaluated by three orthopaedic surgeons (inter-observer phase). The purpose of this phase was to evaluate inter-clinician variability in the produced kinematics and to establish a method for reducing it. A second phase was conducted to gather a larger bank of recordings of the pivot shift, induced by several different clinicians in order to verify if the results of the first phase hold true with a larger population and more clinicians (broad phase). Eight different orthopaedic surgeons participated in the broad phase of the study and together they evaluated 53 additional subjects.

Injured subjects were required to have a positive pivot shift test caused by rupture of the ACL, as established by a prior clinical evaluation. Additional ligamentous or meniscal injury in the symptomatic subjects were not exclusion criteria as long as the pivot shift test could be performed without excessive pain or discomfort. The asymptomatic subjects were free of any knee pain or history of knee injury. All subjects gave their written consent by signing forms approved by the institutional ethics committees.

To record knee joint kinematics, electromagnetic motion capture sensors (Fastrak, Polhemus, Colchester, Vermont) were fixed to the shank and thigh of the subjects. These sensors recorded tibial and femoral kinematics with 6 degrees of freedom at a frequency of 60Hz. The manufacturer's specifications state that its static resolution is 0.8 mm RMS for position and 0.15° RMS for orientation when the sensor is within 75 cm of the transmitter, which it was for the entirety of our experimentations.

The motion capture sensors were attached using an attachment system that we developed (Figure 5.1) with the objective of following bone movements as precisely as possible (patent pending, 60/990,074). The femoral component (Figure 5.1a) is composed of orthoplasts which are held against the skin by an elastic Velcro band at anatomical locations where skin to bone displacement has been shown to be minimal[54, 103]. On the medial side, the orthoplast inserts between the vastus medialis and the sartorius muscle; on the lateral side, it inserts between the iliotibial band (ITB) band and the biceps femoris. These orthoplasts aim to stabilize the component on the thigh.

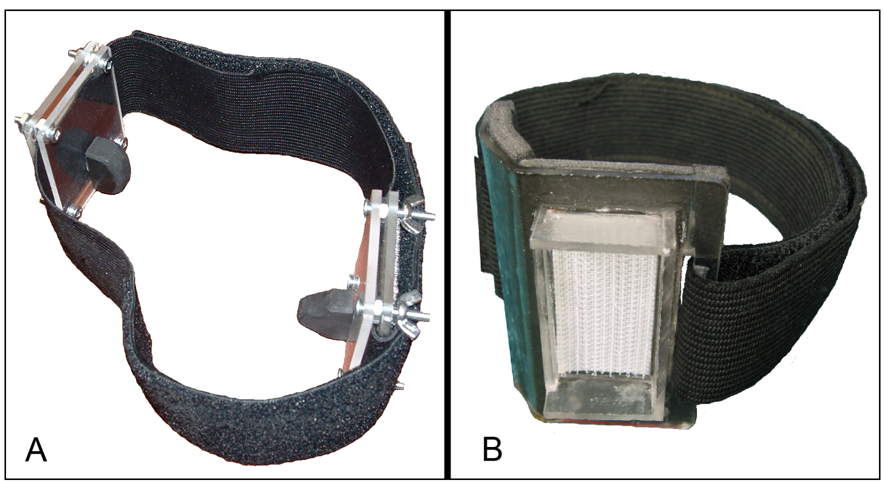

Figure 5.1: The attachment system used to fix motion capture devices to the lower limb. A) the femoral component, B) the tibial component.

The tibial component consists of a rigid plate, which is held against the medial face of the tibia by an elastic Velcro strap. It is placed immediately distal to the tibial tuberosity and is short in length (7 cm) to avoid interfering with the clinician's hand placement during the pivot shift test manoeuver.

5.2.1 Experimental protocol

Inter-observer phase

Four asymptomatic subjects and eight subjects presenting various degrees of knee joint instability following ACL rupture were each evaluated by all three clinicians during a single session. The objective was to obtain three recordings for each of the pivot shift grades. The subjects ranged from 18 to 57 years of age (mean 32.9) ; nine were male, three were female.

A single examiner, different from the clinicians, installed the attachment system on the injured limb for symptomatic subjects and on a randomly selected limb for asymptomatic subjects. He then performed the calibration method which consisted of the FP method [117] adapted so that it was done with the subject in a supine position and the movements were passively produced by the examiner. The method consists of digitalizing anatomical landmarks: the malleoli and the femoral epicondyles using a stylus. This is followed by passive hip circumduction and knee flexion/extension, which allows for the identification of hip and knee joint centers. Finally, the subject's knee is brought to maximum extension and slightly flexed to identify the position of the limb at 0° of flexion and 0° of tibial rotation.

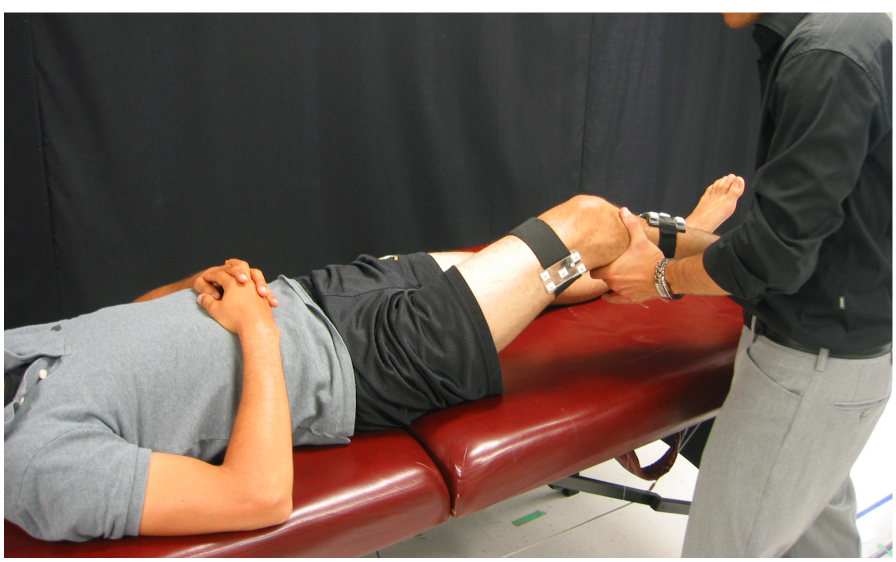

Figure 5.2 A clinician performing the pivot shift test on a subject.

Each of the three orthopaedic surgeons participating in the session then performed the pivot shift test in the manner in which he performs it in his practice (Figure 5.2) while kinematics were recorded. All three clinicians used similar techniques which were variations of the method originally described by Galway et al. [23]. This method consists of applying a valgus force to the knee while bringing it from an extended to a flexed position.

During the experimentation, the clinician would typically flex the knee many times until he felt the patient had sufficiently relaxed his muscle contraction and that he had correctly induced the pivot shift. He then subjectively attributed a grade of 0, 1, 2 or 3 to the pivot shift. Throughout the session, the surgeons were blinded to the grades attributed by their colleagues. However, in some instances, they had prior knowledge as to whether a subject was symptomatic or asymptomatic as they recognized them as patients of theirs.

Broad phase

Eight asymptomatic and 45 symptomatic subjects were evaluated by one or several of eight different orthopaedic surgeons. Symptomatic subjects included four post-operative cases with a lingering positive pivot shift. Subjects ranged from 13 to 54 years of age (mean 26.8); 32 were male, 26 were female. The evaluations were conducted in many sessions, at four different hospitals over the course of several months.

The protocol of each session was similar to that of inter-observer phase except that subjects were evaluated by a single clinician and that for most subjects, following the evaluation of the injured knee, the system was removed and installed on the controlateral limb. The calibration method and the pivot shift test were then repeated. This resulted in a total of 91 new knee recordings for a total of 127 when grouped with the 36 inter-observer phase recordings. The distribution of pivot shift grades is shown in **Table 5.1**.

Table 5.1 Number of knees evaluated for each grade

Clinical grade	*Number of recordings*
0	36
1	29
2	37
3	25

5.2.2 Data analysis

The raw kinematic data were combined with the calibration data, using the method described by Grood and Suntay[119], to obtain the kinematic values, which were: anterior/posterior, medial/lateral and proximal/distal translations as well and flexion/extension, abduction/adduction and internal/external tibial rotation angles at knee joint center. Relative linear and angular velocities and accelerations were obtained by derivative and second derivative of positional data. All parameters were expressed as movement of the tibia relative to the femur.

Inter-observer phase

For statistical analysis of the produced kinematics, the data from each recording were grouped with data of all other recordings to which the same clinical grade was attributed, regardless of the clinician. Spearman's rank correlation and one way ANOVA were computed for each kinematic parameter to determine the strength of the correlation between it and the grade attributed by the clinician. Tukey-Kramer's multiple comparison test was applied on the parameters with high correlation to the grade in order to identify which ones allow for significant differences between the individual grades.

To investigate the inter-clinician variability in produced kinematics, a standard deviation was computed for each subject from the values obtained by the three different clinicians. The techniques used by each clinician for eliciting the pivot shift were then analyzed: the relationship between the applied angular velocity and the pivot shift kinematics produced were quantified using Pearson's correlation coefficient. An optimal normalization of the data was established and then quantified by grouping the normalized kinematics according to their attributed grades and repeating the statistical analysis previously described.

Broad phase

All the data acquired during the broad phase were grouped by attributed grade and were analyzed in the same manner as they were in the inter-observer phase; Spearman's rank correlation, one-way ANOVA and Tukey-Kramer test were computed on both normalized and non-normalized data.

5.3 Results

Inter-observer phase

Statistical analysis of produced kinematics

A total of 36 knee kinematic recordings were analyzed resulting from the evaluation of the twelve subjects by three clinicians. For five of the 12 subjects, all three clinicians attributed the same grade of pivot shift. For the other seven subjects, one of the clinicians attributed a grade, which differed from that attributed by his peers. Attributed grades are presented in **Table 5.2**.

Table 5.2 Grades attributed by each clinician, for each subject

Subject ▸	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Clinician 1	3	2	2	1	2	0	2	1	3	1	0	1
Clinician 2	3	3	2	2	1	0	1	0	3	1	0	2
Clinician 3	3	2	2	1	2	0	2	0	2	1	0	1

Table 5.3 shows the results of Spearman's rank correlation coefficient between different kinematic parameters and the grade. P values resulting from ANOVA analysis are also

shown. Posterior translation and external tibial rotation, which are the parameters generally used to describe the pivot shift correlated poorly to the attributed grade. However, both were significantly different for grades 0 when compared to all other grades combined (P = 0.02 and P = 0.01). The velocity and acceleration of total linear translation were the parameters with highest correlation to the grade and will therefore be the focus for subsequent analysis.

Table 5.3 Spearman's rank coefficients and P values for different kinematic parameters with regards to the clinician-attributed pivot shift grade

Kinematic parameter	Correlation to grade (Spearman's rank coefficient)	ANOVA (P value)
Posterior translation	0.35	0.13
External tibial rotation	0.16	0.04
Velocity of tibial translation	0.44	0.01
Velocity of tibial rotation	0.20	0.30
Acceleration of tibial rotation	0.21	0.39
Acceleration of tibial translation	0.55	0.0009

Tukey-Kramer multiple comparison test using the maximum acceleration vector allowed for significant differences betweens grades 0 and 3, 1 and 3 and 2 and 3. Figure 5.3 shows that there exists great variability within each grade.

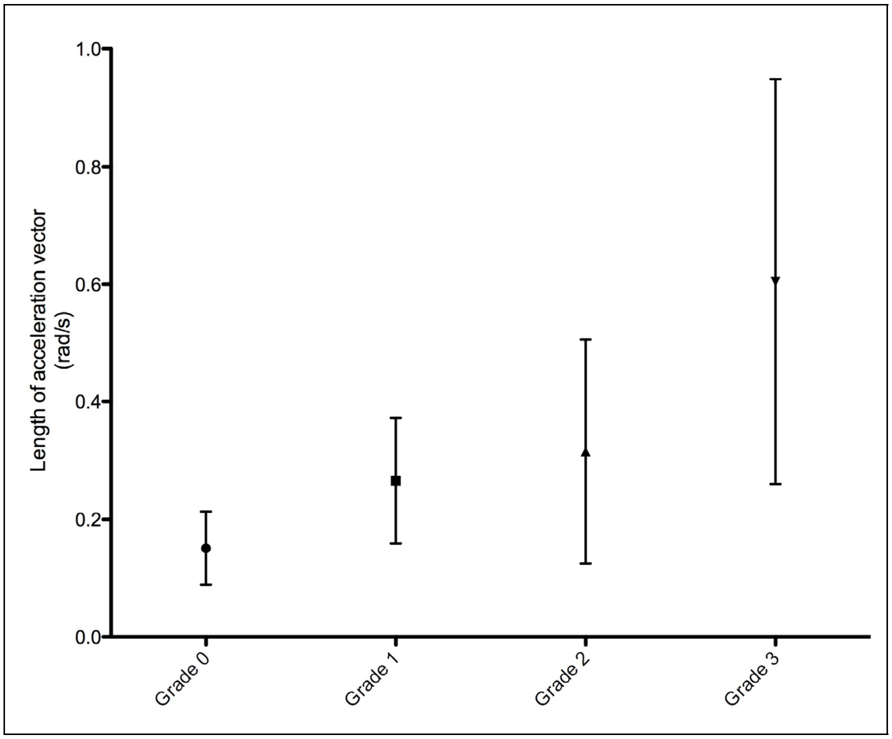

Figure 5.3 Mean and standard deviation values for length of acceleration vector according to the attributed grade.

<u>Investigation of inter-clinician variability</u>

Despite the fact that all three clinicians used similar techniques, there was considerable variability in the kinematics produced by the different clinicians for a same subject. Figure 5.4 shows the kinematics of two grade 3 pivot shifts produced by two different clinicians on a single knee. This was typical of what was observed across all acquisitions. On average, for a same subject, the maximum length of acceleration vector varied by 50% and the maximum linear velocity varied by 35%, depending on the clinician.

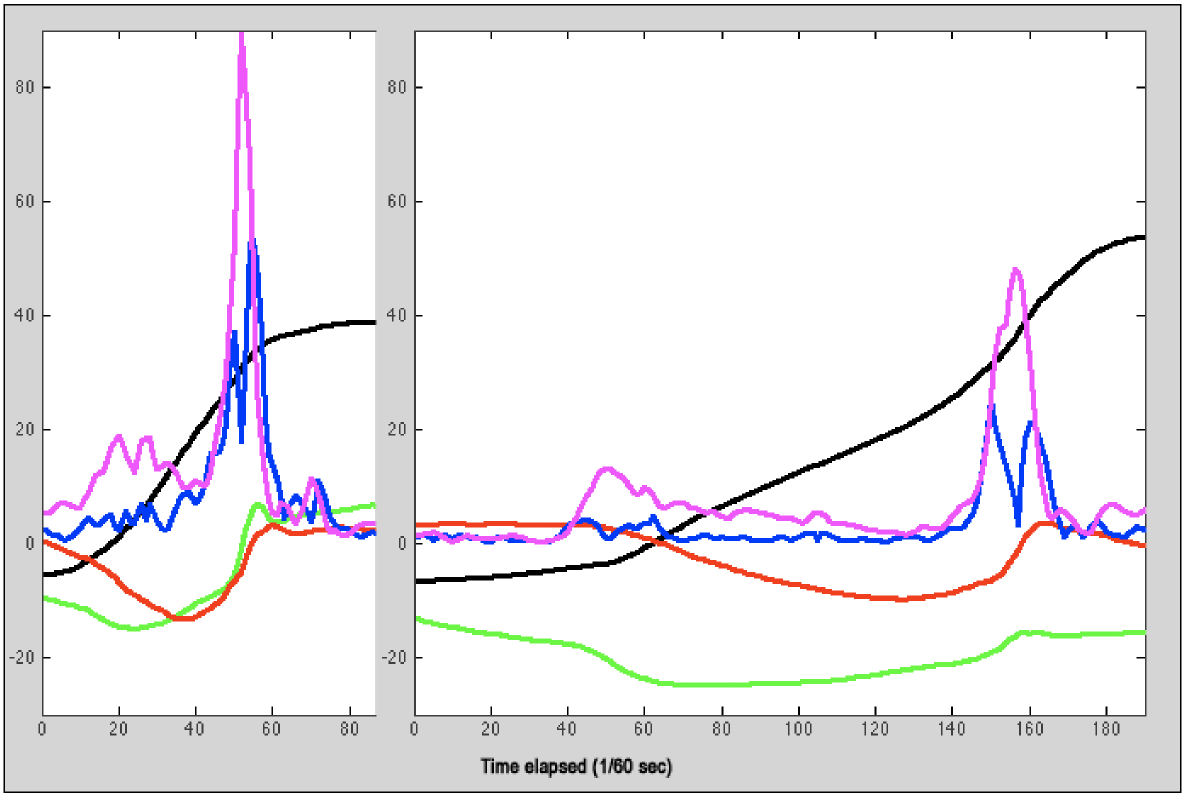

Figure 5.4 The kinematics of two grade 3 pivot shifts, produced by two different clinicians, on a single subject. Black: Flexion angle (°); red: posterior translation (mm); green: external tibial rotation angle (°); blue: velocity of linear translation (mm/sec); magenta: acceleration of linear translation (mm/sec^2). Acceleration values have been multiplied by a factor of 30 for visual representation.

Statistical analysis revealed a very significant linear correlation between the angular velocity of flexion used by the clinician to induce the pivot shift and the resulting linear acceleration vector. For example, amongst grade 2 recordings, which were the most numerous, the Pearson coefficient of the correlation was 0.7149 indicating that the clinician's gesture has an important effect on the kinematics of the pivot shift. To diminish this effect, kinematics were normalized for clinician's technique; all parameters were divided by 5 times the mean angular velocity of flexion produced by the clinician, resulting in scalar values which can only be used for distinguishing between grades and have no direct anatomical interpretation. The factor of 5 was established using a trial and error method aimed at reducing intra-subject standard deviations.

Normalization diminished the intra-subject standard deviations by 20 and 21% for maximum length of the acceleration vector and maximum amplitude of linear velocity, which are the parameters that best correlate to the given grade. The resulting kinematics no longer show any significant correlation to the angular velocity of flexion (r = 0.3121, P = 0.3) indicating a lessened effect of the clinician's gesture on these produced kinematics. **Table 5.4** shows the results of the statistical analysis of these normalized parameters and compares them to pre-normalization values.

Table 5.4 Comparison of statistical analysis of kinematic data with regards to attributed grade for normalized and non-normalized data

	Non-normalized	Normalized
Max velocity of translation		
P value[1]	0.01	0.005
Correlation to grades[2]	0.44	0.53
Max accel. of translation		
P value[1]	0.0009	< 0.0001
Correlation to grades[2]	0.55	0.65
Inter-grade differences[3]		0 vs 2, P < 0.005
	0 vs 3, P < 0.001	0 vs 3, P < 0.001
	1 vs 3, P < 0.01	1 vs 3, P < 0.001
	2 vs 3, P < 0.05	2 vs 3, P < 0.01

[1]ANOVA analysis, [2]Spearman's rank coefficient, [3]Tukey-Kramer test

Broad phase

<u>Kinematics of the pivot shift</u>

The pivot shift occurred at an average of 25.8° of flexion (17.5 to 40.9°). As seen in Figure 4, it generally consisted of a posterior translation of the tibial plateau relative to the femur coupled with an external tibial rotation. The amplitude of the posterior translation was 11.1

± 4.8 mm for grade 3 pivot shifts, external tibial rotation was 15.0 ± 9.0° and posterior acceleration was 0.46 ± 0.29 mm/sec^2. Tibial rotation was much more variable than posterior translation and was absent in some subjects, even amongst those with a grade 3 pivot shift.

Table 5.5 shows the result of statistical analysis of the normalized and non-normalized data, grouped according to the attributed grade.

Table 5.5 Spearman's rank correlation between kinematic parameters and the clinical grades attributed by an orthopedic surgeon

	Non-normalized	Normalized
Max velocity of translation		
Correlation to grades[1]	0.47	0.52
Max accel. of translation		
Correlation to grades[1]	0.53	0.62
Inter-grade differences[2]	0 vs 2, P < 0.05	0 vs 2, P < 0.05
	0 vs 3, P < 0.001	0 vs 3, P < 0.001
		1 vs 2, P < 0.05
	1 vs 3, P < 0.001	1 vs 3, P < 0.001
	2 vs 3, P < 0.001	2 vs 3, P < 0.001

[1]Spearman's rank correlation coefficient; [2]Tukey-Kramer multiple comparison test

5.4 Discussion

The pivot shift test is the only manual test which correlates with subjective knee function criteria such as giving way, activity limitation and patient satisfaction[38, 43]. As such, many different authors have suggested that the aim of reconstructive surgery should be to eliminate the presence of this pivot shift rather than to simply reduce anterior-posterior knee laxity [38, 43-45]. The lack of an objective method for grading the pivot shift is one of the reasons that anteroposterior laxity is still widely used, as instruments such as the KT-1000 allow for an objective measurement of this laxity [74]. The complexity and the dynamic nature of the pivot shift make it far more difficult to develop an equivalent tool for quantifying or grading the pivot shift test.

Perhaps the largest obstacle in developing an objective measurement of the pivot shift is related to the unconstrained nature of the test. Previous studies have shown that different clinicians produce very different knee joint kinematics while performing the pivot shift test on a same knee[47, 48]. Noyes et al. used an instrumented cadaveric lower limb to analyze the kinematics produced by 11 knee surgeons and reported great variability linked to their individual techniques[47]. For example, anterior translation varied from 10 to 18 mm between examiners. Other authors have shown that the position of the limb, particularly hip position and tibial rotation, affects the grade of pivot shift attributed by the clinician [56, 57, 59].

In previous studies of the kinematics of the pivot shift, inter-examiner variability was eliminated by including a single clinician in the experimental protocol[49, 50]. Other studies included 2 or 3 clinicians which were instructed to use the same technique, but inter-examiner variation was not quantified[51, 112]. Such practices are adequate when investigating the kinematics of the pivot shift but results are not readily transferrable to widespread clinical use where each clinician applies the test with his own particular technique and with different applied forces.

Our study is, to our knowledge, the first to quantify inter-examiner variability *in-vivo* in a clinical setting. We showed that the kinematics of the pivot shift vary greatly depending on the clinician performing the test. The maximum linear acceleration, which had the highest correlation to grade varied by an average of 50% between clinicians. Such high variability obviously hinders any efforts to develop an objective measurement of the pivot shift that is not designed for a single specific clinician. However, we found that this parameter had an extremely significant positive correlation to the speed at which the clinician flexed the knee during the test. This indicates that the angular velocity of knee flexion is one of the components that account for the high inter-clinician variability. Using this parameter to normalize the acceleration and velocity of the tibial translation, we were able to diminish inter-clinician variability by 20% for both parameters.

This normalization allowed for significant improvement in the correlation between the clinical grade and the kinematics of the pivot shift in the inter-observer phase. More importantly, similar improvement was achieved in the broad phase which involved nine different orthopaedic surgeons instructed to perform the pivot shift test in the manner in which they do in their practice. This improvement in turn yielded significant differences in linear acceleration between each pair of grades with the exception of the grade 0 – grade 1 pair. This makes sense as a grade 1 do not result in a clunk but in a glide, making the acceleration component of the motion very small. Grade 0 and grade 1 pivot shifts are best distinguished using the actual amplitudes of the tibial translation and of the tibial rotation.

Statistical analysis of our normalized data compares favourably with the results of previous studies which have attempted to identify which kinematic parameters best correlate with the grade of pivot shift attributed by an orthopaedic surgeon [49-51, 112]. Bull et al. [50] used intra-cortical pins on 10 anaesthetized subjects to measure the kinematics of the pivot shift. They found, as did we, that tibial rotation was highly variable between individuals presenting a pivot shift and some times even absent. They concluded that the pivot shift is most consistently described as a posterior translation but found only a weak correlation between posterior translation and the grade of pivot shift.

Kubo et al. [49] fixed electromagnetic sensors to the limbs of 25 non-anesthetised subjects using Velcro straps. They verified the relationship between the grade and different kinematic parameters using Spearman’s correlation. They found significant but weak correlations for maximum velocity, lateral translation and posterior translation. Hoshino et al. [51] used a similar methodology on 30 non-anesthetised subjects and found that the grade has a significant correlation with the acceleration of tibial posterior translation (APT) and with peak coupled anterior tibial translation (c-ATT). However, APT did not show significant differences between a grade 3 pivot shift and the healthy controlateral knee. The c-ATT did show a significant difference between healthy and injured knees ($P<0.05$) but not between individual grades of the injured knees.

Recently, Lane et al. [112] used percutaneous pins on 12 anaesthetized subjects and measured posterior acceleration, tibial rotation, anterior translation and the so-called “angle of P” during the pivot shift manoeuvre. All four parameters correlated with the grade and produced significant differences between grades 0 and 2. The “angle of P” was significantly different between grades 0, 1 and 2. None of the subjects had a grade 3 pivot shift.

The normalization technique we propose is a simple one that only takes into account the produced kinematics and improves the correlation between most parameters and the grade to values higher than those previously reported by studies not using percutaneous pins. Although measurement of the forces and moments produced by the clinician would provide valuable information that could be used to further normalize the kinematic data, such a setup would be costly and complex. The present study has shown that it is possible to diminish the variability of the pivot shift by normalizing with the produced kinematics. Such an approach makes for simpler, less costly clinical tools.

The subjective grading system that many pivot shift studies such as this one aim to improve is, in of itself, a limitation of these studies. In order to establish the kinematics of the different grades of pivot shift, we use the aforementioned subjective grades as a golden standard. In the inter-observer phase of our study, for 7 of the 12 subjects, the three clinicians failed to reach a consensus as to the grade. This could indicate that the clinicians actually produced different grades of pivot shift, that they have different interpretations of what constitutes a given grade or, more likely, some combination of both these factors. For our statistical analysis, we considered each recording individually so that if two clinicians graded a same knee differently, we considered each recording to be of the grade attributed by the performing clinician. If, instead, we considered all recordings for a same knee to be of the grade attributed by two or more clinicians, none of the correlations to the grades remained and differences between grades were no longer significant. This supports the notion that the differences in grading were more attributable to different grades being produced than to differences of interpretation. This is consistent with previous literature showing different produced kinematics[47] and is less problematic for use as a golden standard as we aim to grade the pivot shift which was actually produced.

Inter-clinician (and presumably intra-clinician) variability remains high after normalization. Part of this variability may be related to skin displacement artefacts in the recording the bone movements. Despite the use of an attachment system designed to follow bone movement as precisely as possible, skin to bone displacement artefacts cannot be considered to be negligible. Moreover, the angular velocity of flexion is obviously only one component of how a clinician executes the test. A more constrained gesture where the applied forces and moments are controlled would hypothetically greatly diminish the variability. Recent studies have proposed instruments capable of doing this for measurement of rotational knee laxity[48, 84, 85]. In developing an objective measure of the pivot shift, subject-specific kinematics are also an obstacle but could potentially be overcome by establishing a normal "envelop of laxity" specific to each subject as has been proposed by Amis et al.[48]

In conclusion, we have shown that the velocity of tibial translation, when normalized using the velocity of knee flexion applied by the clinician has a strong correlation to the pivot shift grade. This parameter is thus important for future development of quantitative measures of the pivot shift or of automated grade attribution algorithms.

5.5 Acknowledgements

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CHAPTER 6

ARTICLE II: FEATURE SELECTION USING A PRINCIPLE COMPONENT ANALYSIS OF THE KINEMATICS OF THE PIVOT SHIFT PHENOMENON IN THE KNEE

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David R. Labbe[a,b], Jacques A de Guise [a,b], Neila Mezghani[a], Véronique Godbout[c], Guy Grimard[d], David Baillargeon[e], Patrick Lavigne[f], Julio Fernandes[g], Pierre Ranger[g], Nicola Hagemeister[a,b]

[a]Laboratoire de recherche en imagerie et orthopédie, Centre de recherche, Centre hospitalier de l'Université de Montréal (CHUM), Montréal, Canada
[b]École de technologie supérieure, Montréal, Canada
[c]Hôpital Notre-Dame, Montréal, Canada
[d]Hôpital Ste-Justine , Montréal, Canada
[e]Hôpital de la Cité-de-la-Santé, Laval, Canada
[f]Hôpital Maisonneuve-Rosemont, Montréal, Canada
[g]Hôpital du Sacré-Coeur, Montréal, Canada

Résumé

Le test du *pivot shift* reproduit une instabilité complexe de l'articulation du genou suivant une rupture du ligament croisé antérieur. Il a été montré que la sévérité du *pivot shift* corrèle avec des critères subjectifs de l'état fonctionnel du genou, tels que le retour à l'activité physique et le résultat à long terme. Cette sévérité est représentée par le grade qui est attribué par un clinicien de manière subjective, ce qui rend le test du *pivot shift* peu fidèle.

L'objectif de cette étude était de faire ressortir les paramètres cinématiques qui sont interprétés par les cliniciens quand ils attribuent un grade au *pivot shift*. Pour ce faire, un de huit chirurgiens orthopédistes a exécuté le test du *pivot shift* sur un total de 127 genoux ayant divers degrés d'instabilité du genou. La cinématique de l'articulation a été enregistrée à l'aide de capteurs électromagnétiques et l'analyse par composantes principales a été utilisée pour identifier quelles caractéristiques du *pivot shift* expliquent la majeure partie de la variabilité entre les enregistrements. Il a été trouvé que quatre composantes principales sont responsables de la majorité de cette variabilité. L'accélération et la vitesse de la translation tibiale sont les caractéristiques qui corrèlent le mieux à la première composante principale, ce qui indique qu'elles sont les plus importantes pour différencier les enregistrements. Les amplitudes de translation et rotation tibiales ont été parmi les caractéristiques qui expliquent le moins la variabilité. Ces résultats indiquent que les études futures portant sur la quantification du *pivot shift* devraient s'attarder davantage à la vitesse et l'accélération de la translation tibiale et moins sur les amplitudes de translation postérieure et de rotation externe, qui sont traditionnellement utilisés pour décrire le phénomène du *pivot shift*.

Abstract

The pivot shift test reproduces a complex instability of the knee joint following rupture of the anterior cruciate ligament. The severity of the pivot shift test has been shown to correlate to subjective criteria of knee joint function, return to physical activity and long-term outcome. This severity is represented by a grade that is attributed by a clinician in a subjective manner, rendering the pivot shift test poorly reliable.

The purpose of this study was to unveil the kinematic parameters that are evaluated by clinicians when they attribute a pivot shift grade. To do so, one of eight orthopaedic surgeons performed the pivot shift test on 127 knees with various degrees of knee joint instability. The knee joint kinematics were recorded using electromagnetic sensors and principal component analysis was used to determine which features explain most of the variability between recordings. Four principal components were found to account for most of this variability. Acceleration and velocity of tibial translation were found to be the features that best correlate to the first principal component, meaning they are the most meaningful in distinguishing different recordings. The amplitudes of the tibial translation and rotation were amongst those that accounted for the least variability. These results indicate that future efforts to quantify the pivot shift should focus more on the velocity and

acceleration of tibial translation and less on the traditionally accepted parameters that are the amplitudes of posterior translation and external tibial rotation.

6.1 Introduction

The pivot shift test reproduces the complex rotational and translational instability of the tibiofemoral joint, which is associated with the episodes of giving way that are often reported by ACL-deficient patients. It is the only clinical test which correlates to subjective criteria of knee joint function following rupture of the anterior cruciate ligament (ACL) [38, 43]. As such, it is widely accepted that the objective of reconstructive surgery should be to eliminate or limit the pivot shift, which is graded subjectively by the clinician as being a grade 0 (none), grade 1 (glide), grade 2 (clunk) or grade 3 (gross clunk).

During the pivot shift test, the clinician flexes the evaluated knee while applying onto it a valgus moment. As the ACL-deficient knee flexes, the tibial plateau gradually subluxates anteriorly and rotates internally. At approximately 30° of flexion, the tibia suddenly returns to it's reduced position. In other words, the pivot shift is said to be a combination of posterior tibial translation and external tibial rotation[5, 21, 66].

Different studies have attempted to measure the precise kinematics of the pivot shift in an effort to establish a more objective and quantitative measurement[48-52, 112]. Several studies have indeed confirmed a correlation between posterior tibial translation and the grade of pivot shift whereas external tibial rotation has been shown to vary greatly between subjects and to have a weak correlation to the grade[49, 50].

The pivot shift is a complex, dynamic bone displacement. Posterior translation and external rotation have been insufficient in defining a quantitative measure of the pivot shift or a classification algorithm that would attribute the grade in a manner similar to that of an experienced clinician. If in fact the clinicians aren't solely evaluating the amplitude of posterior translation and of external tibial rotation when they attribute a grade, some other features must be involved. The elevated number of kinematic features that can be extracted from the kinematic data of pivot shift test recordings makes it difficult to study the correlation between these features and the pivot shift grade.

In this study, we use principal component analysis (PCA) as a dimension reduction method, which allows us to gain insight into which elements of the pivot shift kinematics explain most of their variability. We hypothesize that less obvious kinematic features are key to explaining the variability between pivot shift recordings and that these parameters will offer a better understanding of what a clinician is feeling when he attributes a grade. These features can then serve as the basis for a quantitative measure or an automatic grade classifier.

6.2 Methods

6.2.1 Experimental protocol

Twelve asymptomatic subjects and 58 symptomatic subjects presenting various degrees of knee joint instability following ACL rupture were evaluated by one of eight different orthopaedic surgeons. The subjects all had chronic ACL injury and were on a waiting list for reconstructive surgery. Most subjects had both knees evaluated and twelve were evaluated by more than one surgeon, resulting in 127 pivot shift tests. **Table 6.1** shows the distribution of the pivot shift grades for these evaluations.

Table 6.1 Number of knees evaluated for each grade

Clinical grade	*Number of recordings*
0	36
1	29
2	37
3	25

For each evaluation, the subject had electromagnetic motion capture sensors (Fastrak, Polhemus, Colchester, VT) fixed to his thigh and shank using an attachment system. A functional calibration method was performed to identify hip, knee and ankle joint centers and establish anatomical axes[117]. The clinician then performed the pivot shift test on the instrumented knee in the same manner as he does in his clinical practice. He attributed a grade of 0, 1, 2 or 3 to the pivot shift he produced.

6.2.2 Data analysis

The raw data acquired from the recordings were combined with the results of the functional calibration to be expressed as kinematics in the anatomical axes of the knee, as described by Grood and Suntay[119]. This resulted in translations and rotations in three axes, expressed as relative motion of the tibia with respect to the femur. Velocities and accelerations were calculated by derivative and double derivative of positional data.

Custom software developed in Matlab (Mathworks, Natick, MA) presented the user with the kinematic curves for an entire recording for one subject. The user manually indicated the knee flexion during which the clinician indicated having successfully induced the pivot shift. For the range of this flexion, the translations and rotations in all three axes were calculated. Total translation was also calculated as, in some knees, the reduction component of the pivot shift has been shown to be in the posterolateral direction rather than only posterior. Flexion was not included for further analysis as the flexion is controlled by the clinician and is not a possible component of the pivot shift. Similarly, proximodistal translation was also excluded. The velocities and accelerations of all the retained parameters were calculated by derivative and double derivative. This resulted in the list of features presented in **Table 6.2**.

Table 6.2 The list of kinematic features included in the principal component analysis

Kinematic parameter	**Extracted features**		
Anteroposterior translation	Amplitude	Velocity	Acceleration
Mediolateral translation	Amplitude	Velocity	Acceleration
Total translation	Amplitude	Velocity	Acceleration
Internal/external tibial rotation	Amplitude	Angular velocity	Angular acceleration
Abduction/adduction	Amplitude	Angular velocity	Angular acceleration

6.2.3 Principal component analysis

Principal component analysis (PCA) was performed on this set of 15 features across all 127 recordings. The objective of PCA is to perform dimensionality reduction while retaining as much of the variation present in the original dataset as possible. Consider M (n × m), the matrix containing the dataset. *n* is the number of recorded data and *m* the number of variables (the pivot shift parameters).

$$M = \begin{pmatrix} m_{1,1} & . & . & m_{1,m} \\ . & . & . & . \\ m_{n,1} & . & . & m_{n,m} \end{pmatrix}$$

The eigenvalues and eigenvectors of the covariance matrix M are obtained by eigenvalue decomposition. The eigenvalues are ranked in decreasing order because the largest values indicate the most variance of the data in the matrix M. The eigenvector associated with the largest eigenvalue constitutes the first principal component, PC_1. The second PC, PC_2, corresponds to the second highest eigenvalue and so on.

A powerful property of PCA is that the majority of the variation is explained by the first few principal components, $\{PC_1, PC_2, ..., PC_k\}$ where $k < m$. Components corresponding to the small eigenvalues can be dropped and the reduction in dimension is achieved. The number of principal components to retain can be determined using the scree test[121] and insuring that eigenvalues are greater than 1[122].

The loading factors are the correlation coefficients between the variables and the PCs. As a general rule, variables with large loading factors are representative of the component, while small loading factors suggest that they are not[123]. In deciding what is large or small, a rule of thumb suggests that factor loadings greater than 0.4 are considered to meet the bare minimal level of practical significance[124]. In this study we fixed the factor loading threshold at 0.5.

6.3 Results

The scree plot (Figure 6.1) of the 15 first eigenvalues shows that the first break occurs at the fifth PC, indicating that the first five PCs should be retained. However, only the first four PCs have an eigenvalue greater than 1; the fifth eigenvalue is thus discarded, resulting in four PCs.

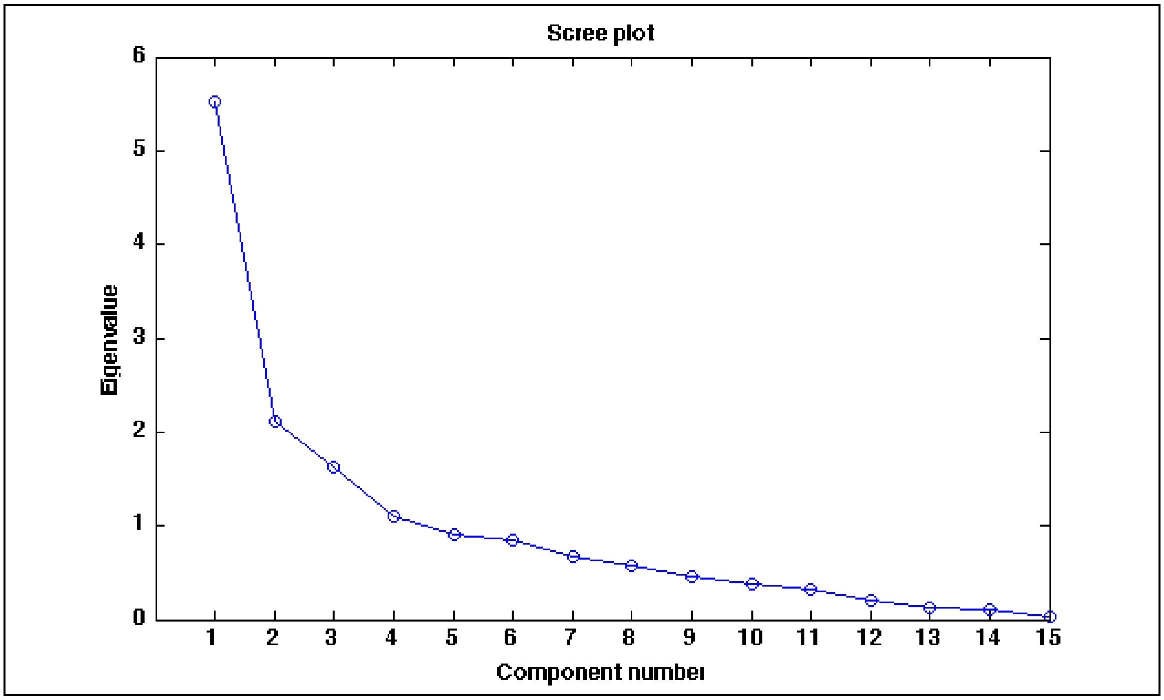

Figure 6.1 The scree plot of the 15 principal components (PCs).

Figure 6.2 shows cumulative percentage of total variance that is explained by each PC. The first components account for the majority of the variance and the first four PCs explain 69% of the total variance, combined.

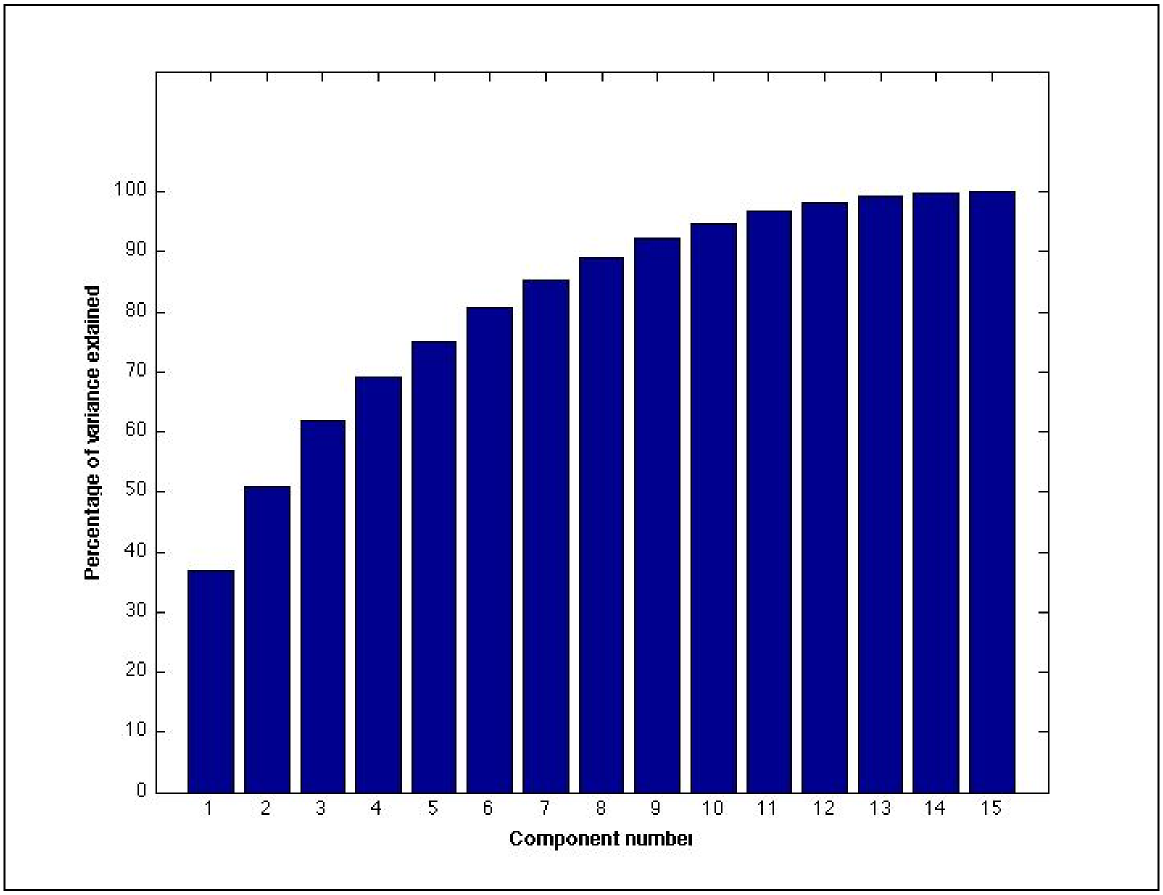

Figure 6.2 Cumulative percentage of total variance explained by the principal components.

Table 6.3 contains the loading factor of each variable on the retained PCs. The variables are listed in increasing order of their loading factor values. To simplify the interpretation, the loading factors lower than 0.5 are suppressed and are represented by blank spaces.

Table 6.3 Loading factors of the pivot shift parameters

	Component			
	PC_1	PC_2	PC_3	PC_4
Total translation acceleration	0.840			
AP translation velocity	0.809			
Total translation velocity	0.799			
ML translation acceleration	0.758			
AP translation acceleration	0.693			
Abduction acceleration	0.669			
Tibial rotation velocity		0.930		
Tibial rotation acceleration		0.823		
Tibial rotation amplitude		0.670	0.526	
Abduction amplitude			0.828	
Total translation amplitude			0.726	
ML translation amplitude			0.642	
Abduction velocity			0.501	
ML translation velocity				0.757
AP translation amplitude				0.516

6.4 Discussion

Different studies have recorded the kinematics of the knee during the pivot shift test and attempted to correlate these kinematics to the grades attributed by experienced clinicians in order to quantify the pivot shift test[48-52, 112]. In doing so, such studies aim to identify and measure what it is that the clinician feels and evaluates when he attributes a pivot shift grade. We have used ACP to establish which kinematic parameters account for most of the variability in the kinematics of the pivot shift and are therefore most important in developing an objective measure of this phenomenon.

The kinematic features of the pivot shift which load on the same PC correlate positively to each other. As such, it makes sense that we can distinguish different categories of parameters in **Table 6.3**, depending on which component they load on. The features that load on PC_1 are linear accelerations or velocities, with the exception of the angular acceleration of abduction, which is the least important. The group of features that load on PC_2 is composed only of tibial rotation and its derivatives. The features that load on PC_3 are amplitudes of movements rather than their derivatives except of the angular velocity of abduction, which is right at the threshold of 0.5. As for PC_4, only two features load on it, with one barely reaching the threshold, so it is difficult to find the common trait amongst these features.

Figure 6.1 shows that the eigenvalue of PC_1 is much higher than PC_2. Therefore, the parameters that load on PC_1 are more important in explaining the variability between recordings than the parameters that load on PC_2. In that sense, **Table 6.2** presents the features in an order that is related to their importance in describing the variations between the pivot shift recordings. Although the pivot shift has often been described as a sudden motion composed of an external tibial rotation and a posterior tibial translation, these features actually account for only a small amount of the differences between different pivot shift recordings. In fact, AP translation has only a weak loading on the fourth PC and tibial rotation has a weak loading on PC_2 and PC_3. The loading factors in **Table 6.2** give several important indications as what features are important in attributing the pivot shift grade. First, they confirm that the translational component of the pivot shift is more important than its rotational component. This is in agreement with previous studies that showed tibial rotation to vary greatly between subjects and to be completely absent in some subjects with a high grade of pivot shift [50,49]. However, it is the velocity and the acceleration of this translation that are important and not the actual amplitude. Even for the less important tibial rotation, the angular velocity and acceleration are more important than the amplitude. In addition, the acceleration in the ML axis is found to be important, indicating that the translation is not always in a purely posterior direction. Kubo et al.[49] also found that the pivot shift is often observed as a posterolateral translation rather than a posterior translation.

The subjective grading system that is currently used and which is a reference or gold standard in attempts to quantify the pivot shift describes the different grades as: *none*, *glide*, *clunk* or *gross clunk*. There is no real notion of amplitude of displacement in this description. While the difference between *none* and *glide* implies some displacement versus no displacement, the terms *clunk* and *gross clunk* are more related to a feeling of suddenness than to an amplitude of displacement. The current subjective grading system therefore distinguishes between no movement and some movement but then goes on to classify those knees with some movement based on suddenness of movement.

This is in agreement with our findings that the velocity and acceleration of the translation account for much more of the differences between the recordings than the actual amplitude of displacement between the tibia and femur. The exception may be in distinguishing grade 0 and 1 as there is no notion of acceleration involved in these grades. Based on the results of the current study, it would seem that a large part of what the clinician is feeling is how sudden the bone displacement is and that the actual amplitude of the displacement is less of a factor than previously believed. Previous studies that investigated the correlation between the grades and the kinematics of the pivot shift found some correlation between the pivot shift grade and velocity[49] and acceleration[51] of translation. However, to our knowledge, this is the first study to quantify the extent to which each kinematic feature of the pivot shift accounts for variability between pivot shift recordings. We have showed that the velocity and acceleration of translation are actually the most important features, much more so than the amplitude of this tibia translation.

Future attempts to develop a quantitative measure of the pivot shift or a method for objectively attributing the grade should focus more on velocity and acceleration of translation than on the traditional parameters that are the posterior translation and tibial rotation. The latter parameters may however be useful is distinguishing between grades 0 and 1. Moreover, translation should be considered along both the AP and ML axes.

6.5 Aknowledgements

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CHAPTER 7

ARTICLE III: A CLASSIFICATION METHOD FOR AN AUTOMATIC AND OBJECTIVE ATTRIBUTION OF THE PIVOT SHIFT GRADE

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David R. Labbe[a,b], Jacques A de Guise [a,b], Neila Mezghani[a], Véronique Godbout[c], Guy Grimard[d], David Baillargeon[e], Patrick Lavigne[f], Julio Fernandes[g], Pierre Ranger[g], Nicola Hagemeister[a,b]

[a]Laboratoire de recherche en imagerie et orthopédie, Centre de recherche, Centre hospitalier de l'Université de Montréal (CHUM), Montréal, Canada
[b]École de technologie supérieure, Montréal, Canada
[c]Hôpital Notre-Dame, Montréal, Canada
[d]Hôpital Ste-Justine , Montréal, Canada
[e]Hôpital de la Cité-de-la-Santé, Laval, Canada
[f]Hôpital Maisonneuve-Rosemont, Montréal, Canada
[g]Hôpital du Sacré-Coeur, Montréal, Canada

Résumé

Contexte Le test du *pivot shift* est le seul test clinique pour lequel il y a une corrélation démontrée avec des critères de l'état fonctionnel du genou. Le grade du *pivot shift* est important pour prédire le résultat à court et à long terme. Cependant, ce grade est attribué par un clinicien, de manière subjective et peu répétable.

Objectif L'objectif de cette étude était de développer une méthode objective pour automatiquement attribuer le grade du *pivot shift* à l'aide d'un enregistrement de la cinématique du genou.

Type d'étude Étude descriptive en laboratoire

Méthodes Soixante-cinq sujets ayant différents degrés d'instabilité de l'articulation du genou ont été évalués à l'aide du test du *pivot shift*, fait par un de huit chirurgiens orthopédistes. La cinématique du genou a été enregistrée pendant ce test. Un algorithme basé dur la méthode de la machine à vecteurs de support a été utilisé pour automatiquement classifier les enregistrements selon leur grade clinique. Les grades attribués par les chirurgiens ont été utilisés comme *gold standard* pour le développement du classificateur.

Résultats Il y a eu une accordance substantielle entre notre classificateur et les chirurgiens dans l'attribution du grade (kappa pondéré = 0.68). Pour 95% des enregistrements, le grade attribué par notre classificateur était à un grade ou moins de celui attribué par les chirurgiens. De plus, les grades 0 et 1 ont été distingués des grades 2 et 3 avec une sensibilité de 86% et une spécificité de 90%.

Conclusion Nos résultats montrent la faisabilité de la classification automatique du grade du *pivot shift*. Le grade attribué est semblable à celui attribué par un clinicien d'expérience et est basé sur la cinématique du genou.

Pertinence clinique La classification automatique du grade rend le test du *pivot shift* moins subjectif et permet aux cliniciens moins expérimentés d'attribuer un grade. Plus important encore, il permet de faire ressortir les paramètres cinématiques qui sont interprétés par les cliniciens lorsqu'ils attribuent un grade, ce qui est une étape importante dans le développement d'une mesure quantitative du *pivot shift*.

Abstract

Background The pivot shift test is the only clinical test that has been shown to correlate favorably with subjective criteria of knee joint function following ACL rupture. The grade of the pivot shift is important in predicting short and long-term outcome. However, this grade is attributed by the clinician in a subjective and poorly repeatable manner.

Purpose The purpose of this study was to develop an objective method to automatically grade the pivot shift test based on recorded knee joint kinematics.

Study design Descriptive laboratory study

Methods Sixty-five subjects with different degrees of knee joint instability had the pivot shift test performed by one of eight different orthopaedic surgeons while their knee joint kinematics were recorded. A support vector machine (SVM) based algorithm was used to automatically classify these recordings according a clinical grade. The grades attributed by the surgeons were used as a gold standard for the development of the classifier.

Results There was substantial agreement between our classifier and the surgeons in attributing the grade (weighted kappa = 0.68). Seventy-one of 107 recordings were given the same grade and 96% of the time our classifier was within one grade of that given by the surgeons. Moreover, grades 0 and 1 were distinguished from grade 2 and 3 with 84% sensitivity and 90% specificity.

Conclusions Our results show the feasibility of automatically classifying the pivot shift grade in a manner similar to that of an experienced clinician, based on knee joint kinematics.

Clinical Relevance Automatic classification of the grade eliminates the subjectivity from the pivot shift test and allows less experienced clinicians to attribute the pivot shift grade. More importantly, it unveils which kinematics parameters are subjectively evaluated by the clinicians, thus paving the way for the development of a quantitative measure.

7.1 Introduction

Rupture of the anterior cruciate ligament (ACL) typically leads to increased anteroposterior (AP) and rotational laxity, resulting in a functional instability of the knee joint. The AP laxity can be evaluated using the Lachman test[19] or the anterior drawer test[20]. These tests, particularly the Lachman test, have been shown to be useful in establishing a diagnosis of ACL rupture but they are not related to subjective criteria of knee function[38-42]. On the other hand, the pivot shift test, which reproduces the functional instability, correlates with several subjective criteria such as patient satisfaction, giving way and activity limitation amongst others[38, 43]. It is now widely accepted that ACL reconstruction should aim to eliminate the presence of a pivot shift to maximize patient outcome[38, 43-45, 58].

During the pivot shift test, the knee is flexed while a valgus moment is applied to it. In an ACL-deficient knee, the tibial plateau gradually subluxates and internally rotates. At approximately 30° of flexion, there is a sudden reduction or return to normal position, called the pivot shift. This pivot shift is graded subjectively as 0 (absent), 1 (presence of a glide), 2 (clunk) and 3 (gross). Such a grading system is poorly repeatable, especially in the hands of a less experienced clinician[21]. However, the grade is critical in establishing which type of treatment to pursue[21] and has been directly correlated to the ability to return to normal sports participation[58]. Different studies have established a link between the lingering post-operative pivot shift grade and long-term outcome following ACL reconstruction[44, 58].

Because of the lack of an objective and reliable grading system for the pivot shift, it is difficult to compare pre- and post-treatment evaluations in order to quantify improvement. It also makes difficult the comparison of outcomes for different treatments and it is difficult to compare the populations of different studies. The Lachman test, which can be reliably quantified using the KT1000, is thus still used for this purpose despite extensive literature showing the pivot shift to be the best predictor of short- and long-term outcome.

Previous studies have attempted to quantify the pivot shift test. These studies have focused on recording knee joint kinematics during the pivot shift test and established which parameters favorably correlated with the pivot shift grade[48-52, 112, 113]. Some relatively strong correlations to the grade were found but such variability exists between recordings of a same grade that no single kinematic parameter or simple coupling of parameters has been established as a possible quantitative measure of the pivot shift.

The objective of this study was therefore to develop a method to automatically and objectively grade the pivot shift using knee joint kinematics recorded during an instrumented pivot shift test. This method would therefore eliminate subjectivity as an important source of variability in the pivot shift grading. We hypothesized that a support vector machine (SVM) algorithm could be used to automatically attribute the pivot shift grade in high agreement with the grades attributed by experienced orthopaedic surgeons, while removing the subjectivity.

7.2 Materials and methods

7.2.1 Population

Fifty-six subjects, 35 male and 21 female, participated in this study (Figure 7.1). Of these subjects, 8 were ACL-intact and asymptomatic (26.7 years old ± 6.0) and 48 presented various degrees of knee joint instability (26.6 years old ± 11.4) caused by ACL rupture. These 48 symptomatic subjects were recruited from ACL reconstruction surgery waiting lists; most had undergone an MRI examination to confirm the ACL-rupture diagnosis. Every subject had their knee examined by one of 8 orthopaedic surgeons. Twenty-seven subjects also had their controlateral, ACL-intact knee evaluated. Twelve other subjects had only their ACL-deficient knee evaluated three times by three different clinicians. This resulted in 107 knee evaluations; the grade distribution is shown in **Table 7.1**.

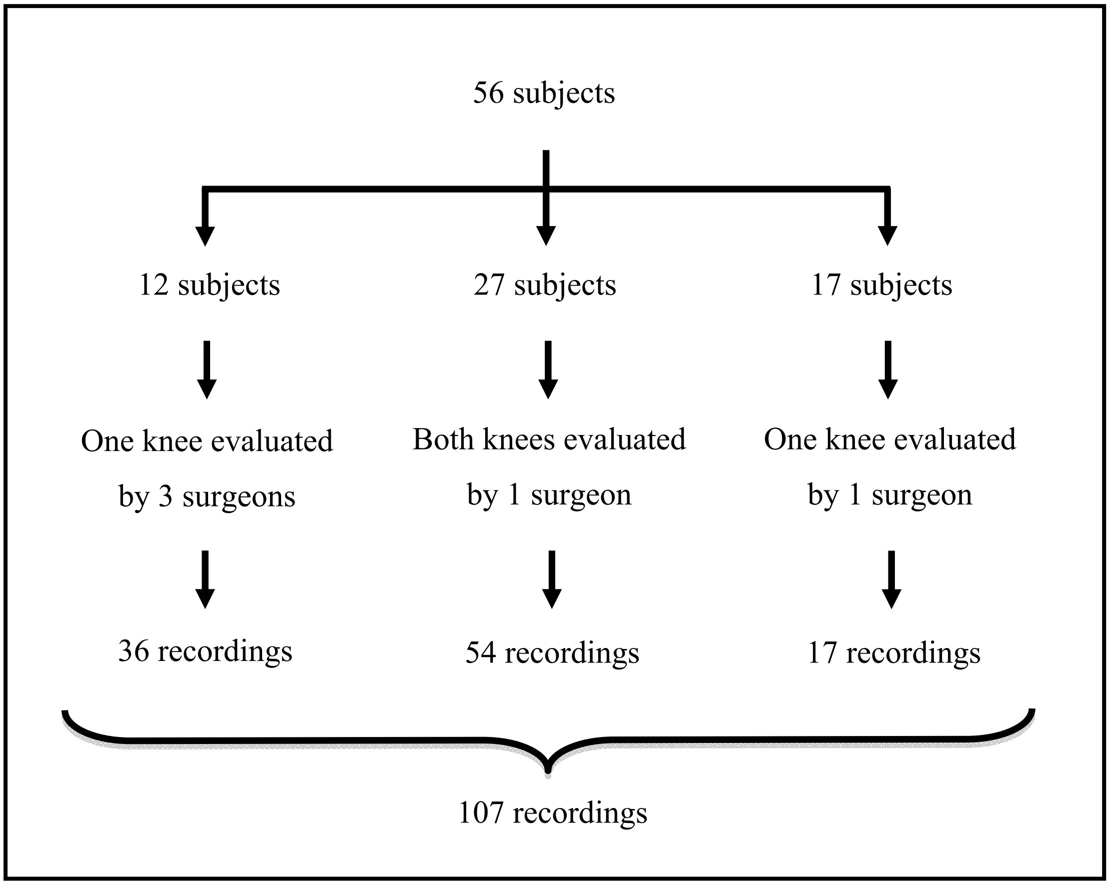


Figure 7.1 Representation of the distribution of the pivot shift recordings obtained from 56 subjects and 8 orthopaedic surgeons.

Any history of knee injury or current knee joint pain was exclusion criteria for asymptomatic subjects. For ACL-deficient subjects, additional soft tissue injuries (i.e. meniscal and/or MCL tears) were not exclusion criteria as long as they did not cause excessive discomfort. All subjects signed consent forms approved by the institutional ethics committees.

Table 7.1 Grade distribution of the pivot shift recordings

Grade	Number of knee recordings
0	28
1	24
2	33
3	22

7.2.2 Experimental protocol

Each subject had electromagnetic motion sensors (Fastrak, Polhemus, Colchester, VT) attached to his tibia and femur using an attachment system we developed with the objective of diminishing skin to bone movement artifacts (Figure 7.2). The femoral component of this attachment system consists of two orthoplasts mounted on separate rigid plates and held together using an elastic Velcro strap. The orthoplasts apply pressure on the medial and lateral aspects of the knee, at anatomical locations were skin to bone movement artifacts have been shown to be minimal[54]. On the medial side, the orthoplast inserts between the adductor magnus and the sartorius tendons. The lateral orthoplast applies pressure between the ilio-tibial band and the biceps femoris.

A third motion capture sensor was attached to a belt that was tightly apposed over the iliac crest and was used for anatomical calibration. With the patient in supine position, a passive functional calibration method was applied to identify hip, knee and ankle joint centers and align the anatomical axes through these joint centers. This calibration method was an adaptation of the FP method[117], which is usually performed actively by the subject in a standing position.

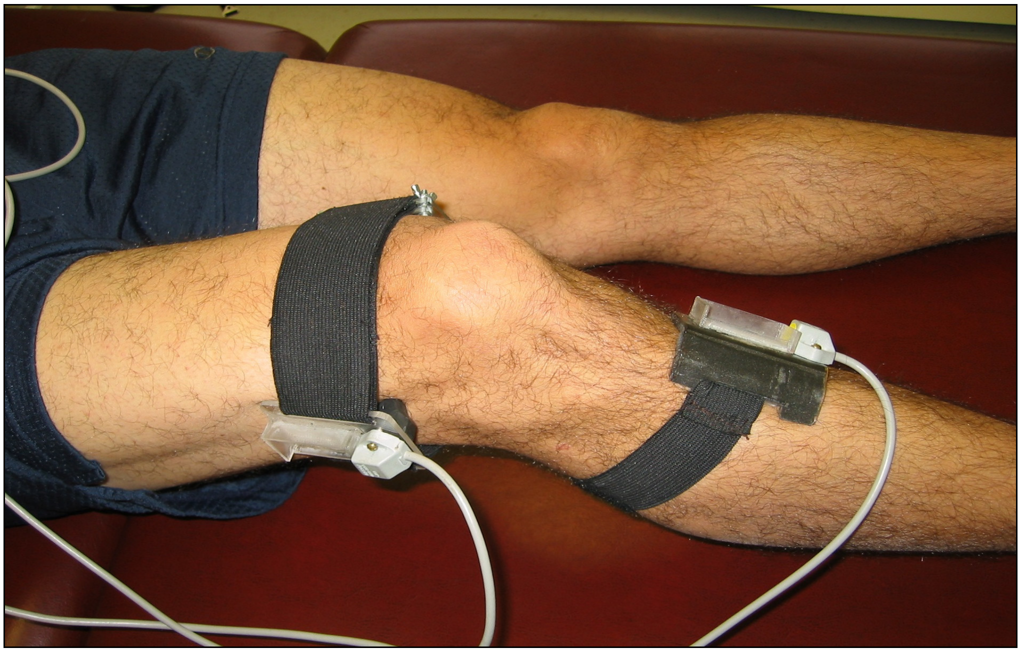


Figure 7.2: Electromagnetic motion capture device attached to a subject's lower limb using an attachment system developed with the objective of diminishing skin to bone movement artifacts.

An experienced orthopaedic surgeon then performed the pivot shift test while knee joint kinematics were recorded. The induced pivot shift was then graded from 0 to 3 by the orthopaedist. This grade was used as a gold standard for further analysis. For subjects that were evaluated by 3 different clinicians, these clinicians were blinded to the grades attributed by their colleagues. The evaluations were conducted at 5 different hospitals.

7.2.3 Data classification

The raw kinematic data obtained during the pivot shift recordings were combined with the data from the calibration method to be expressed in the anatomical axes, as described by Grood and Suntay[119]. This resulted in rotations (flexion/extension, internal/external tibial rotation and abduction/adduction) and translations in all three axes (anteroposterior, mediolateral and proximodistal). Velocities and accelerations were obtained by derivative and double-derivative of positional data.

To account for subtle differences in clinician technique, the obtained kinematics were all divided by 5 times the mean velocity of knee flexion applied by the clinician. This has been shown to reduce inter-clinician variability by an average of 20% and allow for better distinction between the kinematics of different grades[125].

A second degree polynomial support vector machine (SVM) algorithm implemented in Matlab (Mathworks, Natick, MA) was used for classification of the knee recordings according to grade. Because we aimed to replicate the grading of experienced clinicians, a supervised learning method such as a SVM was appropriate. The kinematic parameters used as dimensions for the SVM classifier were identified using principal component analysis (PCA). Parameters were added one at a time in order of their correlation to the principal components, as long as classification sensitivity was improving. The grades attributed by the clinicians were taken to be the gold standard for training the SVM.

Following a phase of supervised learning, a SVM constructs a hyperplane in n-dimensional space that separates a dataset into two subsets, representing different classes. As a first step, a SVM was trained to classify the recordings as being of grades 0, 1 or 2, 3 (SVM_1). This makes sense in the case of the pivot shift, as there is a clear distinction between these pairs of grades (absence vs presence of a clunk). Two additional SVMs were then trained to separate grades 0 from grades 1 (SVM_2) and grades 2 from grades 3 (SVM_3). All three SVMs were then validated, independently and as a whole, using leave-one-out validation.

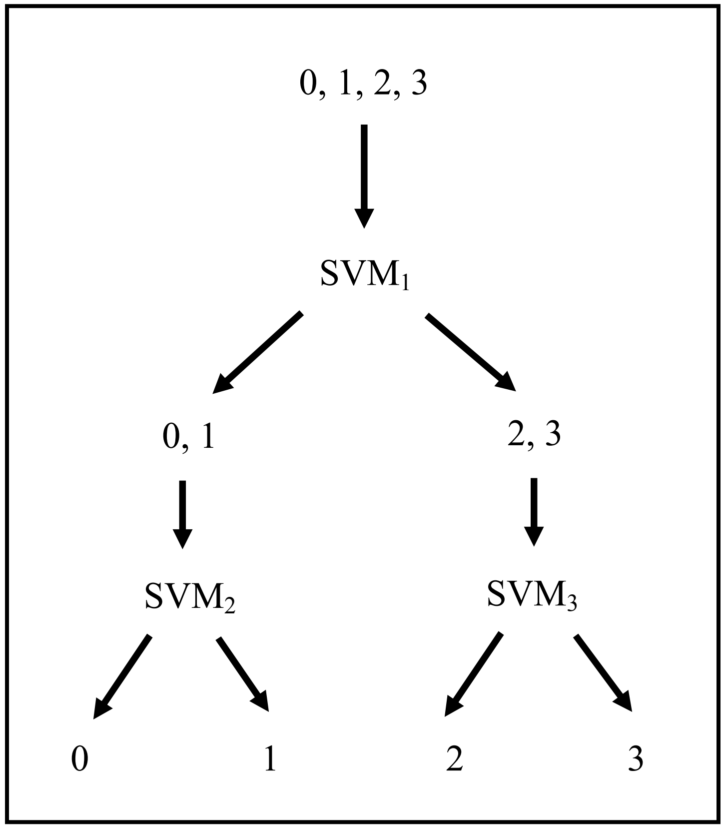


Figure 7.3 Classification of the pivot shit recordings according to their clinical grade, using three SVMs.

A weighted Cohen's Kappa coefficient[126] with quadratic weights was calculated to obtain the inter-rater agreement between the clinicians and our multiclass SVM-based classification algorithm. Moreover, the sensitivity and specificity of the intermediary step, which separates grades 0 and 1 from 2 and 3, were calculated.

7.3 Results

Principal component analysis revealed that the components that explain most of the variability between recordings are the acceleration and velocity of tibial translation. Success rates for SVM_1 and SVM_3 were best when using the amplitude of anteroposterior translation and the five parameters that had the highest correlation to the two principal components (these kinematic parameters are shown for all subjects in Appendix VI). These parameters were, in order: the total linear acceleration, anteroposterior velocity, total linear velocity, mediolateral linear acceleration and anteroposterior linear acceleration. SVM_2, which separated grades 0 and 1 had the highest success rate using only the amplitudes of tibial translation and rotation as well as the velocity of tibial rotation.

Table 7.2 shows the classification of the pivot shift recordings by the clinicians and the multiclass SVM, trained to distinguish grades 0 from 1 and 2 from 3 respectively. The clinicians and the classifier were in agreement in 66% of cases. Overwhelmingly, when the classifier was in disagreement with the clinicians, the difference was of only one grade. In fact, the classifier and the clinicians were in agreement to within one grade in 95% of cases. The kinematic curves of the 5 recordings were there was a disagreement of more than one grade are presented in Appendix V.

Table 7.2 Grading of the pivot shift recordings by clinicians (lines) and a SVM-based classifier (columns)

Clinicians ↓ Classifier →	Grade 0	Grade 1	Grade 2	Grade 3
Grade 0	**22**	5	0	1
Grade 1	8	**12**	4	0
Grade 2	4	5	**23**	1
Grade 3	0	0	8	**14**

Agreement between the clinicians and the classifiers, as defined by a Cohen's weighted Kappa, was $\kappa = 0.68$, considered to be substantial agreement[127].

The first step, consisting of a SVM trained to distinguish grades 0 and 1 from grades 2 and 3, also yielded noteworthy results. This SVM achieved a sensitivity of 86% and a specificity of 90%, using leave-one-out validation. Agreement with the clinicians was also found to be substantial as indicated by the Kappa coefficient of $\kappa = 0.74$. **Table 7.3** shows the results of this classification versus the grades attributed by the clinicians. Of the 5 recordings wrongly classified as grades 2 or 3 by our classifier, in disagreement with the clinicians, 4 had been given a grade 1 by the evaluating clinician and 1 had been graded as a 0. All 9 of the recordings classified as being of grades 0 or 1, in disagreement with the clinicians, had been given a grade 2 by the evaluating clinician.

Table 7.3 Classification of the pivot shift recordings by clinicians (columns) and a SVM-based classifier (lines), into groups formed by grades 0, 1 and 2,3

Clinicians ↓ Classifier →	Grades 0 and 1	Grades 2 and 3
Grades 0 and 1	**47**	5
Grades 2 and 3	9	**46**

7.4 Discussion

Establishing the grade of pivot shift in an ACL-deficient knee is important in determining appropriate treatment[21]. Kocher et al.[38], in a study of 202 subjects, found that the pivot shift grade correlates with many subjective criteria of knee joint function such as giving way, patient satisfaction and Lysholm score. Leitze et al.[43] also found that a positive pivot shift correlates with patient dissatisfaction and lower subjective outcome scores at 9-year follow-up. Kaplan et al.[58] established a direct correlation between the grade of pivot shift and the ability to return to stressful sports.

Despite its demonstrated clinical relevance, pivot shift grading remains highly subjective and poorly reliable[5, 21]. In a study of the kinematics produced by 10 different examiners, Noyes et al.[47] found that tibial rotations and translations induced on a single cadaver knee varied drastically.

Much effort has been put into quantifying the kinematics of the pivot shift[48-52, 112, 113] but to date, there hasn't been a method proposed to attribute the grade in an objective manner. In this study we were able to automatically grade the pivot shift in the same manner as the surgeon performing the pivot shift test for 71 of the 107 recordings. When the classifier was not in agreement with the clinicians, in only 5 cases was there a difference of more than one grade. A weighted kappa was used to interpret the results because it accounts for partial agreement. It showed substantial agreement ($\kappa = 0.68$) between our SVM-based classifier and the interpretation of an orthopaedic surgeon, which we used as a gold standard.

The first step of our method is able to classify the pivot shift recordings as being of grade 0,1 or 2, 3 with high specificity (90%) and sensitivity (85%). These specificity and sensitivity values are calculated with regards to the agreement between our classification method and the grade attributed by experienced orthopaedic surgeons. This portion of the classifier cannot be said to distinguish symptomatic from asymptomatic subjects. In our study, 8 of the 24 grade 1 pivot shifts were produced on symptomatic knees. Nevertheless, it has the potential to distinguish between subjects that have good function from those with a true instability, susceptible to episodes of giving way.

In the literature, distinction has been made between grades 0,1 and 2,3. Leitze et al.[43] used the term pivot shift to describe grades 2 and 3 whereas they used the term pivot glide for grade 1. They showed that the correlation to subjective criteria of knee joint function was much lower for a pivot glide versus a pivot shift. Kaplan et al.[58] found that a grade 1 pivot shift does not correlate to clinical instability and that the majority of knees that exhibit this type of pivot shift do not demonstrate giving way despite a high level of sports participation. In their study of 52 patients, none of the subjects with a grade 2 or 3 pivot shift were able to return to unlimited sports participation. On the other hand, only 29% of those with a grade 0 or 1 were unable to do so. Furthermore, it has been documented that patients that have increased joint laxity often display a grade 1 pivot shift in the absence of trauma[5]. Therefore, although distinguishing between grades 0, 1 and 2, 3 does not yield sensitivity and specificity values that can be directly associated to clinical diagnosis, it is relevant with regards to the treatment option and the ultimate outcome.

The kinematic parameters that were used by our classifier give insight into what a clinician is interpreting when he attributes a clinical grade. They show that the translational component is much more important than the rotational component in grading the pivot shift. Moreover, it is essential to consider the velocity and acceleration of the translation, not solely its amplitude. This indicates that the pivot shift grade is more closely related to the suddenness of the tibial reduction than to its amplitude. This makes sense as the current subjective scale describes grades 2 and 3 as a “clunk” and a “gross clunk”. These terms imply suddenness but contain no notion of amplitude of displacement.

The parameters used for SVM_3 differed. For separating grade 0 and 1, tibial rotation is useful, as is the amplitude of tibial translation. The velocity and acceleration of the translation is not. This is also in accordance with the subjective scale as we are trying to distinguish between the presence or the absence of a “glide”. Here, there is no notion of suddenness, just of a small displacement.

Because there is no way to establish a true grade, our results are based on the grading of experienced clinicians. The subjective nature of this grading scale is what prompted efforts to quantify the pivot shift in the first place. Such an imperfect gold standard, coined a “fuzzy gold standard”[128], results in a paradox because we are attempting to reproduce the very scale which we aim to replace. However, the current grading scale has been shown to correlate to clinical outcome. Our aim is therefore to grade in a manner similar to that of experienced clinicians while eliminating subjectivity.

Moreover, the pivot shift grades are discrete but the actual kinematics that are produced are of a continuous nature. Therefore, in practice, there are grade 1 pivot shifts that are closer to grade 0 and others that are closer to grade 2 pivot shifts. No absolute limit can be defined between the different grades based upon the subjective grading. Consequently, it is to be expected that there will be some degree of disagreement at the frontiers separating the grades. In fact, using the first part of our classifier, 13 of the 14 recordings where there is disagreement were considered to be of grade 1 or 2 (the frontier grades) by the clinicians. In our full classifier, 31 of the 36 recordings where there is disagreement were assigned a grade adjacent to that given by the clinician.

By replicating the grading of an experienced clinician, two objectives are met. First, we are unveiling the kinematic parameters that they interpret when attributing a pivot shift grade as well as their relative importance. This is an important step in developing a quantitative measure for the pivot shift that would consist of a combination of several kinematic parameters. In this study we have found that several such parameters are important for grading the pivot shift but some are more so than others. Consequently, a good quantitative measure would probably be one that uses many weighted parameters. Simply quantifying posterior translation and external tibial rotation, which have traditionally been used to describe the pivot shift, has not been shown to result in a valid quantitative measure of the pivot shift.

Second, an automatic grade attribution based on produced kinematics that takes the clinician's technique into account offers a less subjective alternative to grading the pivot shift test. Clinicians with less experience, such as general practitioners are known to have more difficulty in attributing a grade[21]. Therefore, some clinicians could use a such tool to establish the grade of pivot shift. It is worth noting however that our method classifies kinematic recordings and not patients. This distinction is important in that the method remains dependant on the clinician's execution of the test. If a clinician only induces a low-grade pivot shift on an ACL-deficient knee, the recording will be classified as such. In that sense, our method could also be used as a tool for teaching the pivot shift maneuver and grade attribution.

The present study demonstrated the relevance and feasibility of an automatic classification of pivot shift recordings according to their grades. Before its transfer to clinical use, intra- and inter-observer reliability of the method will have to be assessed. A study aimed at quantifying the accuracy of our attachment system during the pivot shift test is currently under way although this is less of a concern as long as sensitivity is high and results are reliable. Future work will focus on the development of such a quantitative measure based on the results of this study. Such a measure would be valuable for comparing the outcomes of different ACL surgeries.

7.5 Aknowledgements

The authors would like to thanks NSERC and Canada Research Chair for funding. They also thank Laurence Mark and Gerald Parent for their help with data acquisition.

CHAPTER 8

SUPPLEMENTARY RESULTS

Before the beginning of the data acquisition phase of this study, a small preliminary study was conducted to verify the reliability of the attachment system we developed. Specifically, its reliability was compared to that of a simple Velcro strap as well as to that of the exoskeleton of Sati et al. [102] and to the molded plates described by Manal et al. [92].

The reliability was evaluated during gait because this is a much more reproducible movement than the pivot shift test and kinematics can be expected to be almost identical between acquisitions. All three attachment systems were installed three times each on three different subjects by a single observer. For each installation, the calibration method described in the Methodological Choices section was applied in a supine position. For the acquisitions using the exoskeleton, the original FP calibration method was applied because, as previously stated, the femoral component falls out of place when the subject is placed in supination. The subject then walked on a treadmill at a self-determined comfortable pace.

The three rotations and three translations of the knee joint were calculated for each recording and a mean coefficient of multiple correlation (CMC), as described by Kadaba[129], was computed for each feature and for each attachment system. **Table 8.1** shows the results of this analysis.

Table 8.1 The CMC coefficients of four attachment systems for the recording of knee joint kinematics during gait

	Our attachment system	Velcro strap	Exoskeleton	Molded plates
Flexion/extension	0.99	0.99	0.99	0.99
Abduction/adduction	0.96	0.93	0.89	0.76
Int./ext. tibial rotation	0.93	0.81	0.85	0.82
ML translation	0.67	0.51	0.50	0.74
AP translation	0.95	0.92	0.91	0.93
PD translation	0.92	0.97	0.89	0.91

These results, although preliminary, are an indication that the attachment system we developed can record knee joint kinematics with a reliability that is equal or better than that of the exoskeleton for all three rotations and translations. Moreover, for the two parameters traditionally considered to be the most important in the pivot shift, AP translation and internal/external tibial rotation, our system has higher CMC values than all the other tested systems.

CHAPTER 9

DISCUSSION

9.1 General aspects

The widespread acceptance of the benefits of evidence-based medicine as well as the availability of several different ACL grafts and surgical techniques have underlined the importance of developing an objective measure of knee joint function following ACL injury. The pivot shift test is the only test that has been shown to correlate to this knee joint function. As such, several studies have attempted to quantify the pivot shift in the past few years.

These studies measured the kinematics of knee during the pivot shift and either attempted to correlate these kinematics to the pivot shift grade or they compared pre- and post-operative kinematics. The technologies and methodologies that were used varied, but there has been relative resemblance in the results of most studies.

Many of them found that the kinematic parameters that had been used to describe the pivot shift, posterior tibial translation and external tibial translation, do in fact correlate positively to the pivot shift grade[49-52, 112]. The fact that these parameters increase as the grades increase indicates there is a strong trend and that these parameters are useful in describing the pivot shift but it does not indicate that they can be used as a direct measure of the pivot shift. The large standard deviations present in the values of a same grade have made it difficult to take the next step, which is to use the measured kinematics to attribute the grade and to develop a quantitative measure for the pivot shift.

This study has furthered the understanding of what defines the pivot shift and particularly of what aspects of the pivot shift characterize the different grades. It also proposes a method to take the aforementioned next step and attribute the grade automatically. This section discusses these results and how they bring us closer to a quantitative measure of the pivot shift. It also addresses the issues that have made it so difficult to develop such a quantitative measure. Finally, this study's limitations are discussed in detail.

9.1.1 Definition of the pivot shift

This study has shed some light on the parameters that are important in attributing a pivot shift grade. Our results are in agreement with previous literature that defines the pivot shift as a gradual anterior subluxation and internal rotation of the tibial plateau followed by a sudden reduction[22, 49-52, 66, 112]. Nevertheless, the translations observed in our subjects during the reduction phase were often times not directly inline with the AP axis, resulting in a posterolateral translation rather than a purely posterior translation. This is also reflected in the results of the second article, which found ML translation to be an important factor in explaining variability. Kubo et al.[49] also found the translation to be often times directed posterolaterally rather than posteriorly.

We concur with studies that found that the rotational component of the pivot shift is much more variable than the translational component and that some subjects display high-grade pivot shifts with no tibial rotation[50]. Furthermore, we find that the grade of the pivot shift is best characterized by the suddenness of the reduction rather than by amplitude of the subluxation. The results of the first article show that the acceleration and velocity of the tibial translation correlate better to the grade than do tibial translation and rotation. Our second article, which aimed at identifying the parameters that explain most of the variability between pivot shift recordings, supports these results. It shows that acceleration and velocity explain more of the variability between pivot shift recordings than does the amplitude of translation. The latter may be more related to knee laxity than to more functional symptoms such as episodes of giving way.

9.1.2 Progress accomplished toward quantitative measure

These new understandings of the kinematics of the pivot shift and of the parameters that explain the most variability between recordings are important in developing a quantitative measure of the pivot shift. It has become evident that the AP translation and tibial rotation are insufficient for such a measure as there values vary too much between pivot shifts of a same grade. Nevertheless, the fact that our classifier was able to achieve substantial agreement with the subjective grades given by clinicians indicates that information that characterizes the grades is contained within the kinematic recordings.

By identifying the features that explain most of the variability between pivot shift recordings, the PCA provided important insight into the kinematic parameters that should be explored in an effort to develop a continuous scale of pivot shift. The SVM classifier also adds to the understanding of the kinematics involved in attributing the pivot shift grade. To attain the level of agreement presented in the third article, 8 different kinematic parameters (or dimensions) were input into the SVM-based classifier. A combination of these parameters, weighted for importance, would hypothetically result in a continuous grading scale with high correlation to the current grading system.

9.1.3 Difficulty in quantifying the pivot shift

The obstacles to using these results to develop a quantitative measure of the pivot shift are many and are mainly related to the large variability in pivot shift kinematics. Our results, as well as those of previous studies, show that there exist several different kinematic patterns of pivot shifts for a given grade. Some authors have noted large variability, even in the simplest expression of the pivot shift, which is in terms of posterior translation coupled with external rotation. In fact, some subjects have a large translation with small tibial rotation while others have more rotation and less translation. Some grade 3 recordings show no tibial rotation at all. It is difficult to isolate the cause of such differences between recordings of a same grade. The specific injury and the bony geometry of the subject are known to affect the kinematics of the pivot shift. Moreover, muscle relaxation is critical in inducing the pivot shift correctly. Thus, even if the test were applied in the exact same manner, which is not possible, inter- and intra-subject variability would remain considerable. Our results show that when three different clinicians examine a knee consecutively, the recorded knee kinematics vary greatly. Furthermore, clinicians induce different kinematics on a same cadaveric knee, where muscle relaxation is obviously a non-factor[47]. This is probably due to subtle differences in hand placement, initial tibial rotation, applied forces and moments as well as flexion velocity. In the absence of a more constrained pivot shift test or of a means of measuring applied forces, there is no way to apply the test twice in exactly the same manner, even if both tests are performed by a single clinician.

This means that a pivot shift recording is dependant on the specific subject, the time of the evaluation, the clinician performing the test and the specific forces applied by the clinician during the specific evaluation. This variability, combined with the fact that our gold standard is in fact a subjective evaluation of the pivot shift, makes it very challenging to indentify a quantitative coefficient which would be a direct measure of the pivot shift phenomenon.

9.2 Limitations and specific aspects

9.2.1 Validation of the method

The validation of a new measurement device involves the assessment of validity, accuracy and reliability (also called precision)[101]. In this study, only validity has been assessed. The validity of a measure is the extent to which it measures what it is supposed to measure. We developed a method for grading the pivot shift but another method to do so already exists: the subjective grading of clinicians. In such situations, we assess criterion validity, which is the correlation of a scale with an existing gold standard. Because both grade attributions were based on a single evaluation, the form of criterion validity assessed is called concurrent validity[101].

Validity

The concurrent validity of our method was quantified by the weighted kappa coefficient, which is a measure of correlations between our grading method and that of experienced clinicians. This coefficient showed substantial agreement between both methods, indicating that validity is good and we are indeed measuring what we intend to measure (the grade of pivot shift). The assessment of criterion validity presents an interesting paradox in that the development of a scale aimed at improving the existing scale is then validated against this same imperfect scale. Moreover, when the correlation is less then perfect between both scales, it is difficult to establish which one is at fault. Such is the case with this study.

Reliability

The concept of reliability is a way to reflect the amount of error, both random and systematic, inherent to any measure[101]. Basically, it is a measure of the ratio of variability between subjects to the total variability of the measure. This ratio is critical in interpreting results as it indicates to what extend repeated measures on a same subject can be expected to yield similar results. This study has not assessed the reliability of the proposed method; a reliability study should be undertaken as the next step in the validation process.

The reliability has previously been shown to be high for gait analysis[117] using the FP calibration method combined with the attachment system proposed by Sati et al[102]. Because we use adaptations of both the calibration method and the attachment system, reliability will have to be reassessed. The intra- and inter-observer reliability as well as test retest reliability need to be quantified, especially given that reliability is a major concern when it comes to the pivot shift test.

The inter-observer phase of our study aimed to diminish the variability associated with variations in clinician technique. As such, the focus was not put on clearly establishing the inter-observer reliability. Because each clinician in our experimental protocol did not repeat the pivot shift evaluation more than once on each subject, we are unable to quantify intra-clinician variability. Without this, it is impossible to distinguish inter-clinician variability from intra-clinician variability. Our normalization method therefore reduces the kinematic variability that is introduced by repeated evaluations but one cannot quantify inter-observer reliability based on our results.

Accuracy

The final step of the validation process is the assessment of the accuracy of the measure. Accuracy is the degree of closeness of a measured quantity to its true value. In this study, accuracy can be measured between the recorded kinematics and the actual bone movements. This accuracy mostly pertains to the accuracy of the attachment system and that of the electromagnetic device. The Fastrak electromagnetic device's accuracy has been shown to be high. A previous study of the pivot shift reported its static error of position and orientation to be 0.8 mm RMS and 0.15° RMS, respectively[49].

The accuracy of the attachment system is related to its ability to reduce skin displacement artifacts. We chose to use an adaptation of an attachment system that was shown to be accurate during non weight-bearing knee flexions[103]. The accuracy of our adaptation in following the femur and tibia during the pivot shift test has yet to be quantified although a fluoroscopic study is currently underway. Quantifying the accuracy of our kinematic recordings is of lesser importance for the validation of our classifier. If reliability and validity are high, the actual accuracy is almost irrelevant. In fact, it is more important to have a measure that is representative of a symptom (e.g. knee instability) than the actual measure of the bone displacements. On the other hand, for the development of a quantitative measure, the accuracy will be important for interpretation of the physiological implications.

9.2.2 Use of multiple recordings from a single subject

The 107 pivot shift test recordings we analyzed in this study were obtained from 65 different patients, many of whom had both knees evaluated. Twelve of the subjects were evaluated by three different clinicians, resulting in three separate pivot shift recordings. These recordings were considered to be independent from one another and were individually grouped with other recordings to which the clinician attributed the same grade. As shown in **Table 5.2**, the attributed grades were not always the same across all three clinicians. A single recording per subject-clinician pairing was included for data analysis.

We considered each recording separately because the objective of our study was to characterize and classify individual pivot shift recordings, not patients. As such, if two clinicians attributed different grades of pivot shift, we aim to classify each recording in accordance with the particular clinician who produced the pivot shift.

In studying the pivot shift, previous studies have also included more than one recording for a single subject. Kubo et al.[49] correlated the pivot shift kinematics to the clinical grade using 146 recordings obtained from only 25 subjects and one examiner.

9.3 Fuzzy gold standard

Our study aimed to develop an objective classification of the pivot shift grade. This was necessary because the existing grading scale is flawed in that it is very subjective and poorly repeatable. There does not exist another scale for the pivot shift grade and as such, this scale was considered to be the gold standard for our study. It is obviously a paradox that we developed a classifier that aims to replicate the very scale we aim to replace.

It is therefore a limitation of our study that we have an imperfect gold standard, or fuzzy gold standard, as we cannot calculate the sensitivity of our classifier with a high degree of certainty. On the other hand, although imperfect, the existing scale has been shown to correlate positively with many criteria of knee joint function[38] and is thus a good starting point in developing an objective scale. We were able to attain substantial agreement with the existing scale, which indicates that our classifier attributes grades in a manner similar to that of experienced clinicians. It is impossible to reach perfect agreement with such a subjective scale but such is not the goal of our study. We aimed to develop a classifier that would attribute the grade objectively based on the recorded knee joint kinematics and that has maximum agreement with the grading of experienced clinicians.

CHAPTER 10

CONCLUSION AND OUTLOOK

The objective of this study was to develop an objective method for grading the pivot shift test. To do so, we acquired and analyzed 107 pivot shift recordings from 65 subjects and 9 orthopaedic surgeons. The original hypotheses were all verified by this study and the main objective, as well as the specific objectives were met.

The first article presented a method for reducing the variability in the kinematics of pivot shifts induced by different clinicians. To our knowledge, no other study has addressed the issue of the variability introduced by the differences in forces and moments applied by different clinicians. Previous studies have limited the number of clinicians performing the pivot shift to one and in a few instances two. We chose to include several clinicians thereby introducing additional variability as this reflects the reality of clinical evaluations. Our method does not eliminate this variability by any means but diminishes it sufficiently to allow for statistically significant differences between kinematics of the different grades.

The second article used ACP to determine which features of the pivot shift kinematics explain most of the differences between recordings. These features are those that are most important in characterizing the pivot shift. The results confirmed that tibial translation is a more important component of the pivot shift than is tibial rotation. It was also shown that the accelerations and velocities are more closely related to the grade than the actual amplitude of movements. This study is the first to apply feature reduction to the pivot shift kinematics and to establish the parameters that explain the variability between pivot shift recordings.

The third and final article proposed a method for objective attribution of the pivot shift grade. This method showed high specificity and sensitivity in distinguishing pivot shift recordings with a clunk (grades 2, 3) from those without (grades 0, 1). In attributing a specific grade to each grade, the classifier showed substantial agreement with the grades attributed by experienced clinicians. Disagreements overwhelmingly occurred along the borders separating the different grades. This study is the first to propose a method for objectively attributing the pivot shift grade based on recorded knee joint kinematics.

Overall, this study has demonstrated the feasibility of objectively attributing the pivot shift grade using a SVM-based classifier. It also underlines the large variability in pivot shift recordings and the resulting difficulty in defining borders between the different grades. One of the sources of variability between recordings was diminished, which increased the kinematics differences between the grades and allowed for better distinction. Finally, it confirmed the need to look beyond AP translation and tibial rotation when grading or quantifying the pivot shift. As such, this study is as much of a step towards a quantitative measure of the pivot shift as it is one towards a reliable, objective classification of the pivot shift grade. As stated in the discussion, a validation of this method will need to be done before it can be transferred to clinical use. Moreover, the following steps could further reduce variability therefore improving the accuracy of the classifier and contributing to a more reliable quantitative measure:

Development of a quantitative measure

The ultimate objective of quantifying the pivot shift kinematics is to develop a truly quantitative measure of the pivot shift. Such a measure, which would be continuous in nature, would make it possible to quantify improvement following treatment and therefore to compare improvements achieved by different treatments. A continuous coefficient of pivot shift would also better reflect reality as there are not only four possible outcomes; there are pivot shifts that are somewhere between two grades. This study identified the kinematic parameters that are important in characterizing the pivot shift; these are the parameters that would hypothetically be components of such a coefficient. The biggest challenge is to diminish variability sufficiently for this coefficient to have acceptable reliable.

Normalization for clinician technique

Our study was able to reduce the variability due to clinician technique by simply using the produced angular velocity of flexion. Nevertheless, this variability remains high and a more thorough normalization to account for clinician technique would presumably further reduce this variability. This could included to measuring of forces and moments applied to the knee by the clinician. However, in developing such a normalization method, which would require costly technology, the challenge is to find middle ground between reliable results and clinical practicality.

A more constrained pivot shift test manoeuver

Another way to diminish clinician-related variability would be to attempt to actually render the manoeuver more uniform. The KT-1000 accomplishes this by measuring the loads applied to the tibia. It is far more complex to do so for the pivot shift test. Some authors have developed mechanical apparatuses to apply a simulated pivot shift on cadaveric knees while always applying the same forces and moments. Although not easily transferable to a clinical setting, such an apparatus could be developed for in-vivo studies.

Establishment of the normal envelop of movement

Variability of the pivot shift kinematics related to the individual is another obstacle in quantifying the pivot shift. Some have suggested that the pivot shift kinematics be compared to that of the controlateral knee. While this has potential to somewhat reduce the variability, one study found that such a method was unable to distinguish between knees with a grade 3 and the asymptomatic controlateral knees[51]. Performing passive flexion/extension to establish the normal envelop of movement beforehand and then expressing the pivot shift kinematics with regards to this envelop may help in defining typical kinematic patterns for each of the grades. This recommendation is an extension of one recently made by Amis et al.[48]

APPENDIX I

NUMBER OF PIVOT SHIFT EVALUATIONS PER CLINICIAN

Clinician #	Number of knees evaluated
1	2
2	20
3	2
4	3
5	12
6	30
7	41
8	9
9	8

APPENDIX II

PARTICULARITIES OF CLINICIAN TECHNIQUE

Clinician # →	1	2	3	4	5	6	7	8	9
Primal hand	Mid	Mid	Mid	Prox	Prox	Prox	Mid	Prox	Mid
Distal hand	UA	Dist	UA	Ankle	Dist	Dist	Dist	Dist	Dist
Applied int. rot. (°)	17.7	11.9	7.5	17.1	10.0	20.1	19.7	11.3	12.4
Flexion velocity (°/sec)	166.7	65.3	103.7	145.5	118.0	133.5	153.6	119.2	88.9

Mid = mid-shank; prox = proximal region of the shank; dist = distal region of the shank; UA = the clinician placed the distal region of the subject's shank under his arm.

APPENDIX III

SUBJECT CHARACTERISTICS

Subject #	Sex	Age (years)	Height (cm)	Weight (kg)	Injury
001	F	25	168	54	Isolated ACL rupture
007	M	35	178	68	Post-op ACL reconstruction
008	F	18	168	57	Post-op ACL reconstruction
009	F	43	160	98	ACL rupture + meniscal tear
010	M	29	175	65	Isolated ACL rupture
011	M	22	196	118	Post-op ACL reconstruction
012	F	36	168	54	Isolated ACL rupture
013	F	31	173	58	Post-op ACL reconstruction
014	M	27	178	67	Healthy
015	F	18	163	60	Healthy
016	F	20	165	57	Healthy
017	M	16	163	60	Healthy
I01	M	57	173	77	ACL rupture + meniscal tear
I02	M	36	170	75	Isolated ACL rupture
I03	M	29	188	91	ACL rupture + meniscal tear
I05	M	27	163	60	Healthy
I06	F	24	173	54	Isolated ACL rupture
I07	M	36	171	83	Partial ACL rupture
I08	M	23	196	118	Post-op ACL reconstruction
I09	F	40	173	64	Healthy
I10	M	32	178	82	Failed ACL reconstruction
I11	M	26	185	82	Healthy
I12	F	31	173	75	Healthy
I13	M	34	191	102	Post-op ACL reconstruction
021	F	18	155	41	Isolated ACL rupture

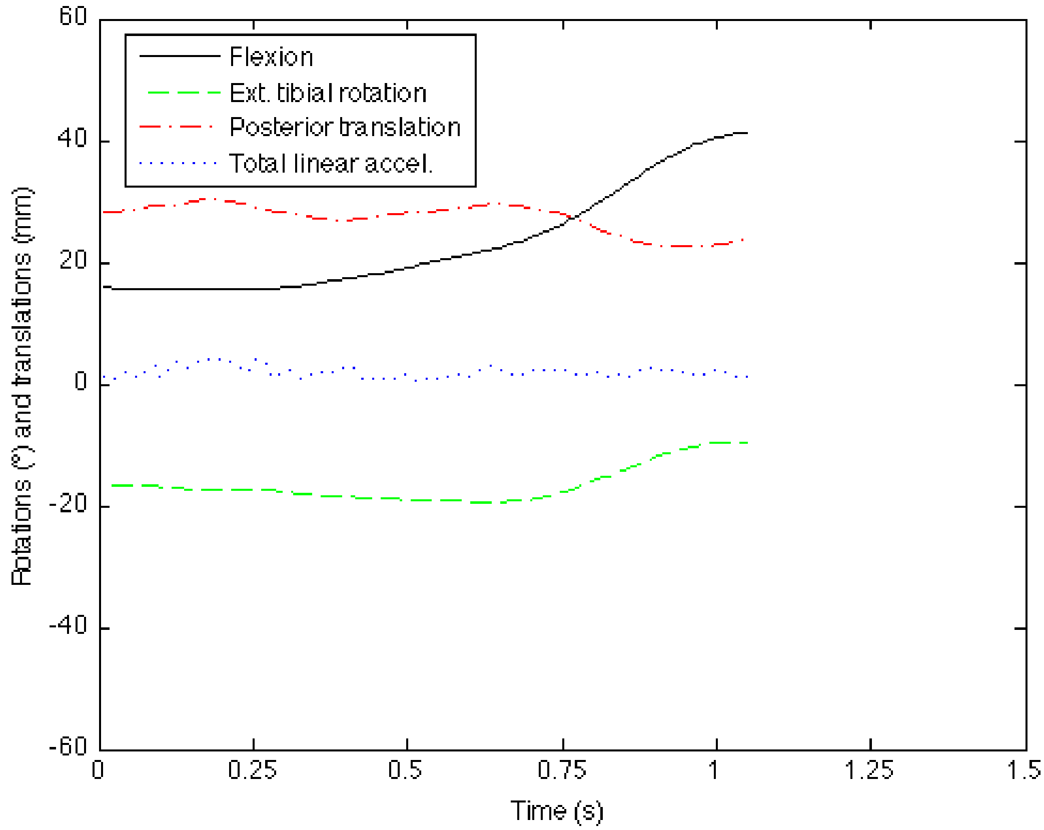
022	F	24	160	57	Healthy
023	M	28	175	68	Healthy
024	F	39	163	55	ACL rupture + meniscal tear
031	M	19	183	81	Isolated ACL rupture
032	F	45	160	70	ACL, MCL rupture + meniscal tear
033	M	30	163	86	Isolated ACL rupture
034	M	21	175	64	ACL rupture + meniscal tear
035	F	52	173	66	Isolated ACL rupture
036	M	28	178	109	Isolated ACL rupture
037	M	18	170	70	Partial ACL rupture
038	F	53	164	56	Isolated ACL rupture
039	M	24	178	71	Isolated ACL rupture
040	F	42	164	54	ACL rupture + meniscal tear
041	M	34	183	102	Isolated ACL rupture
042	M	31	185	88	Isolated ACL rupture
043	M	16	170	59	Isolated ACL rupture
044	M	43	175	91	ACL rupture + meniscal tear
045	M	32	178	93	ACL rupture + meniscal tear
046	F	36	160	74	Isolated ACL rupture
047	M	31	180	107	ACL rupture + meniscal tear
048	M	40	183	118	ACL rupture + meniscal tear
049	F	36	168	68	Isolated ACL rupture
050	M	35	188	78	Isolated ACL rupture
051	F	22	160	58	ACL, MCL, PCL rupture
052	M	18	185	79	Isolated ACL rupture
053	M	16	170	64	ACL rupture + meniscal tear
054	M	18	173	79	ACL rupture + meniscal tear
055	M	19	188	91	Isolated ACL rupture
056	F	17	158	59	ACL rupture + meniscal tear

057	F	17	168	54	Isolated ACL rupture
058	F	17	180	91	Isolated ACL rupture
059	M	17	168	70	ACL rupture + meniscal tear
060	M	12	166	50	ACL rupture + meniscal tear
061	M	17	168	82	Isolated ACL rupture
062	F	15	155	58	Isolated ACL rupture
063	F	13	155	41	ACL, MCL rupture + meniscal tear
064	F	17	163	60	Partial ACL rupture
065	F	16	160	57	Isolated ACL rupture
066	M	14	173	68	Isolated ACL rupture
067	M	15	168	41	Isolated ACL rupture
068	F	16	160	65	ACL rupture + meniscal tear

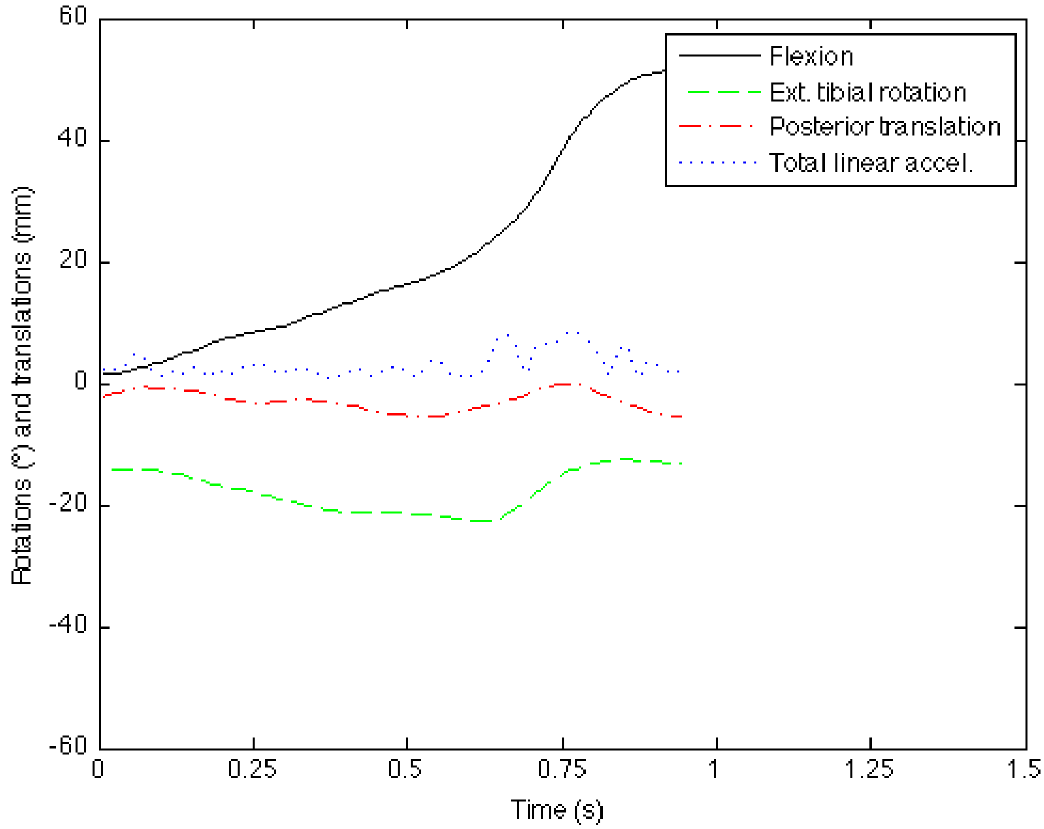
APPENDIX IV

TYPICAL KNEE JOINT KINEMATICS DURING THE PIVOT SHIFT TEST

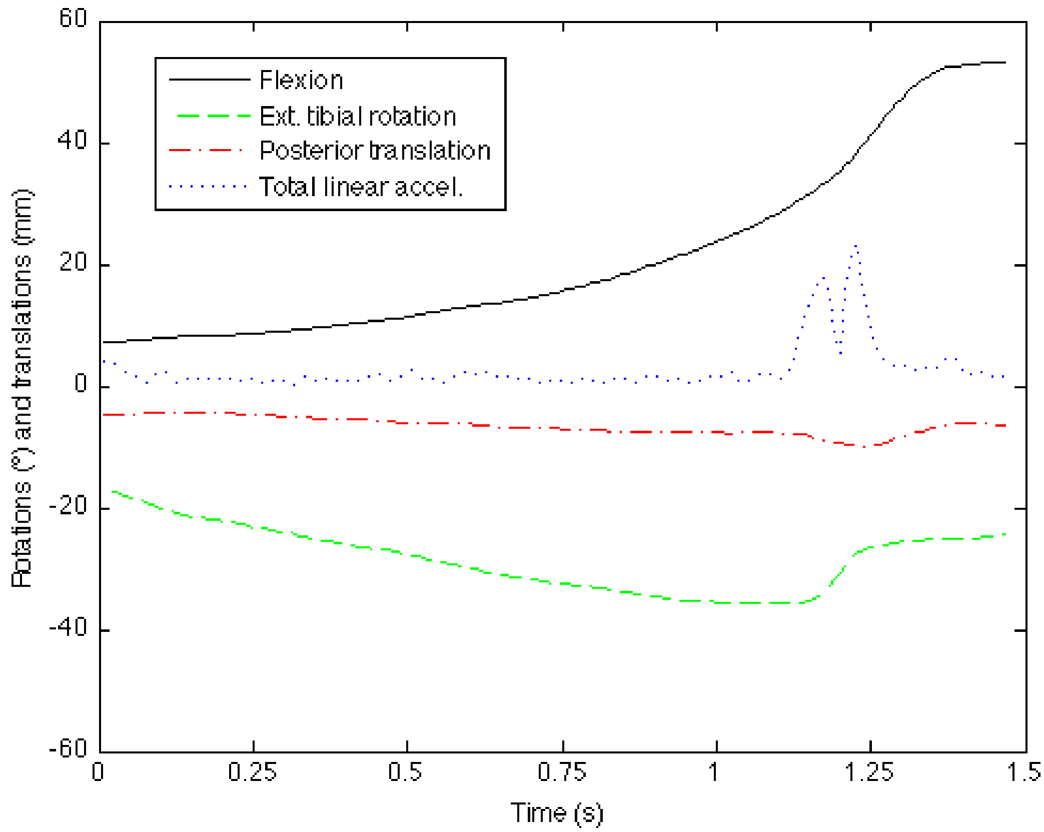
Typical knee joint kinematics in the absence of a pivot shift (grade 0)



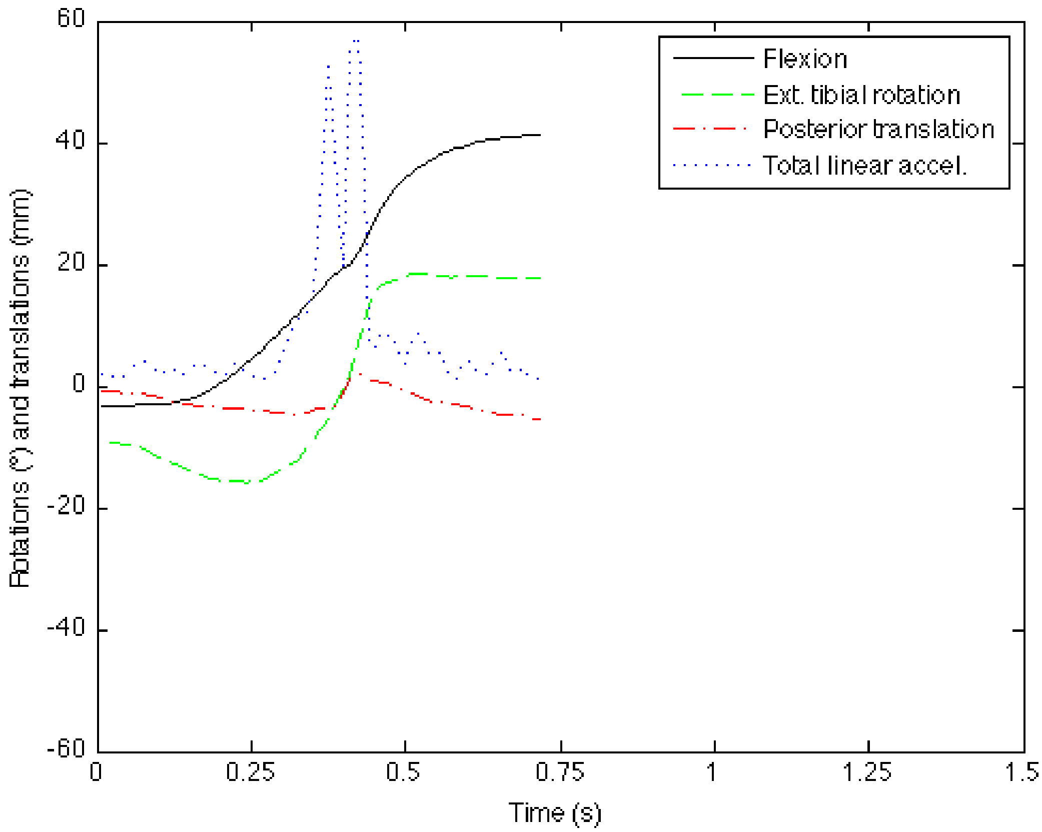
Typical knee joint kinematics of a grade 1 pivot shift



Typical knee joint kinematics of a grade 2 pivot shift



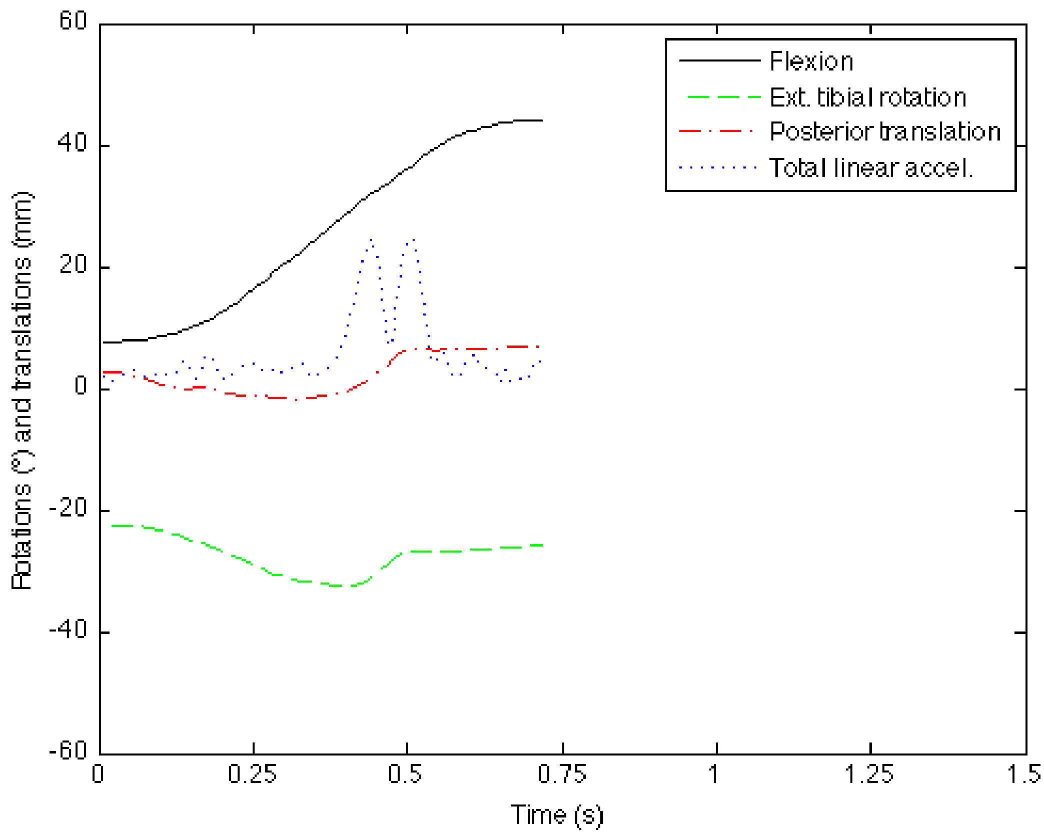
Typical knee joint kinematics of a grade 3 pivot shift



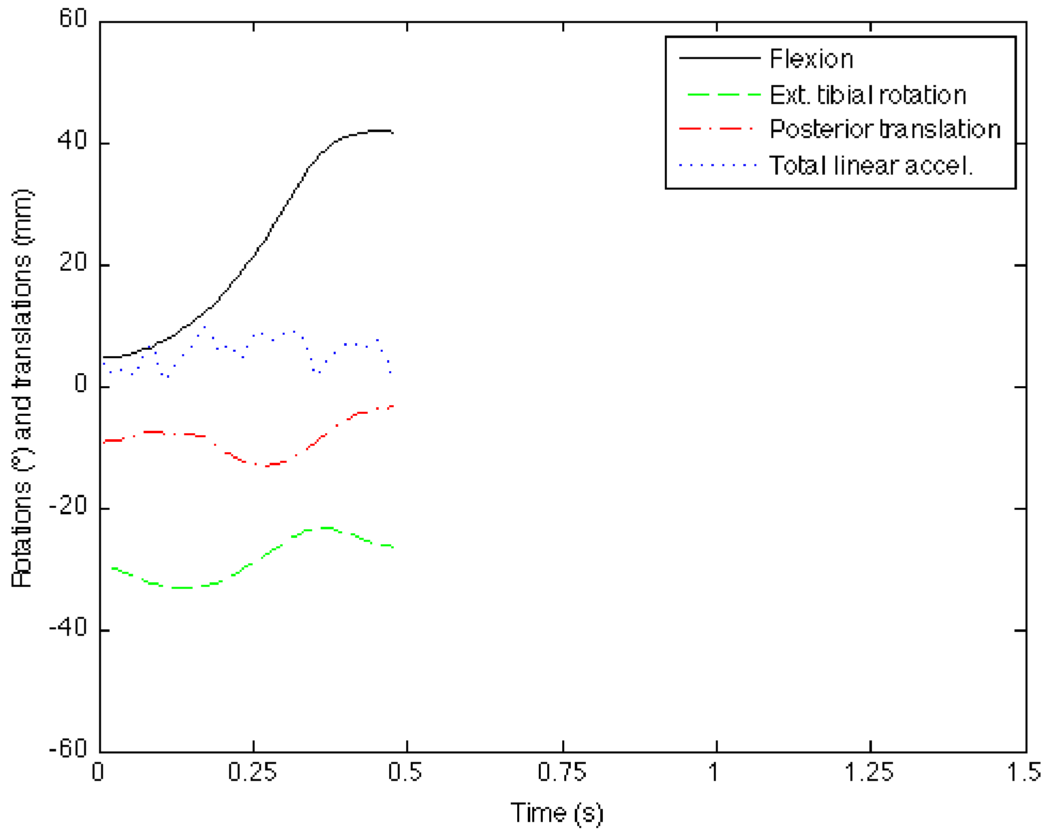
APPENDIX V

KNEE JOINT KINEMATICS OF THE PIVOT SHIFT RECORDINGS WHERE THERE IS A DISAGREEMENT OF MORE THAN ONE GRADE BETWEEN THE CLINICIAN AND CLASSIFIER

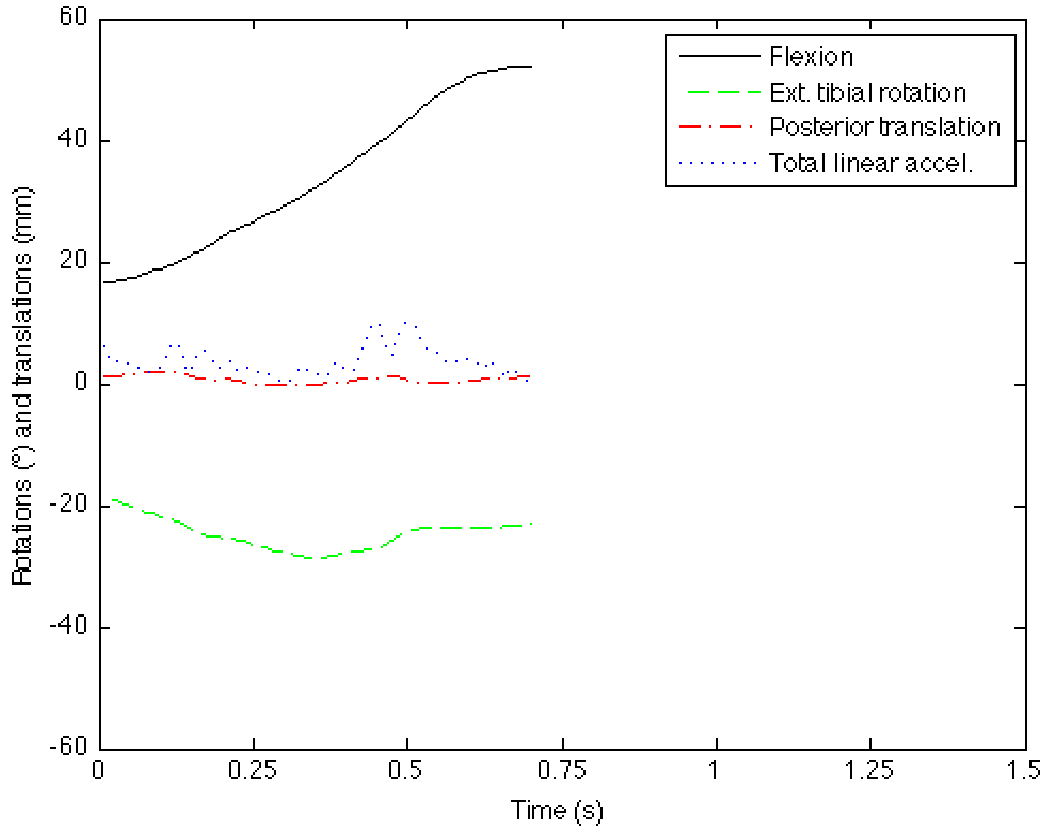
Recording graded as 0 by the clinician but as 3 by the classifier (subject #035)



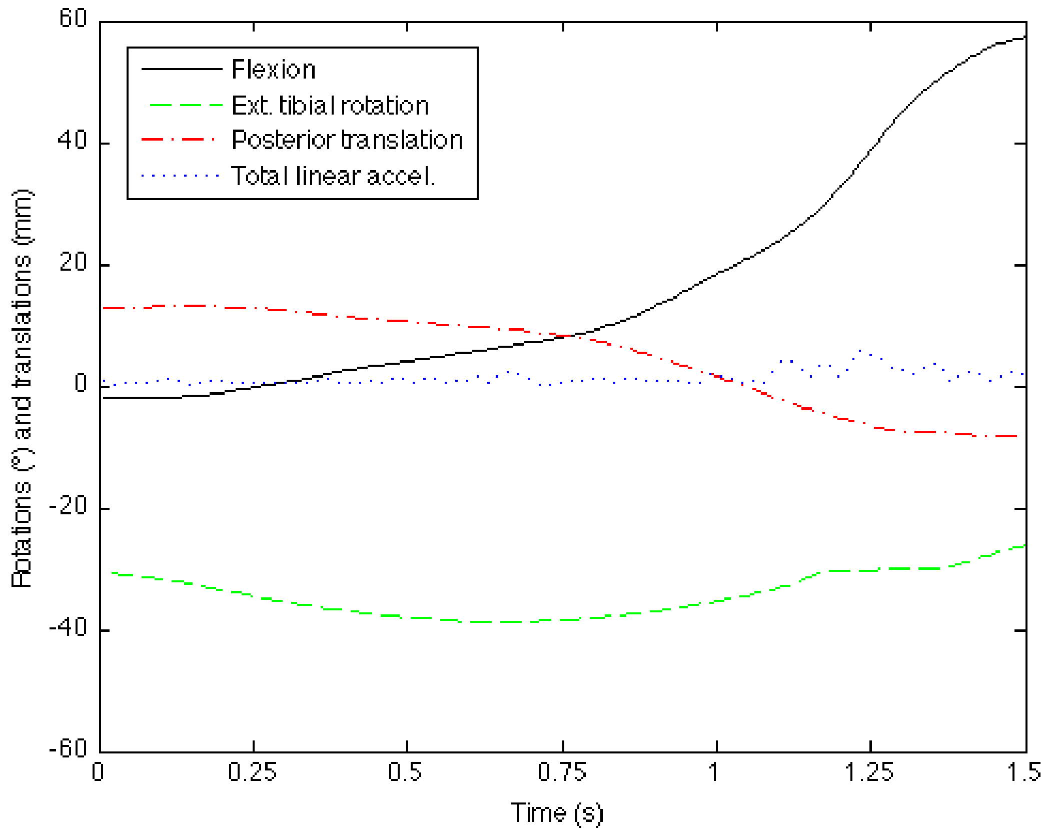
Recording graded as 2 by the clinician but as 0 by the classifier (subject #035)



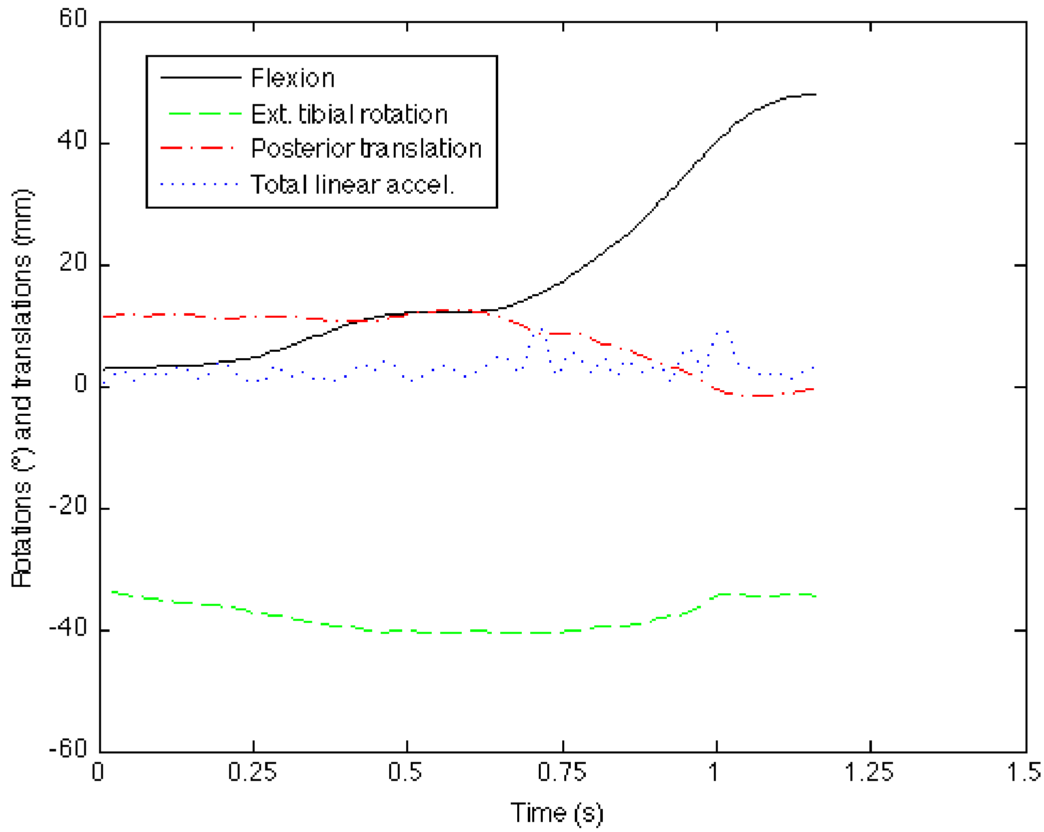
Recording graded as 2 by the clinician but as 0 by the classifier (subject #033)



Recording graded as 2 by the clinician but as 0 by the classifier (subject #I06)



Recording graded as 2 by the clinician but as 0 by the classifier (subject #I06)



APPENDIX VI

KINEMATICS OF THE PIVOT SHIFT THAT WERE USED BY THE SVM-BASED ALGORITHM

Subjects given a **grade 0** by the clinicians

Subject and knee	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
039L	0.020	5.11	9.89	0.028	0.007	0.20	0.01	0.029
043L	0.018	4.36	6.56	0.025	0.012	0.06	0.58	0.033
044L	0.013	2.75	5.79	-0.013	0.010	0.02	0.50	0.058
060R	0.030	3.38	7.74	0.032	0.018	-0.42	1.26	0.160
061R	0.025	4.21	7.69	0.021	0.023	0.06	-0.74	0.059
063L	0.020	3.64	5.52	0.033	0.014	0.03	0.75	0.155
I07R	0.016	4.11	8.99	0.007	0.014	0.41	-0.10	0.075
I07R	0.025	3.60	14.18	-0.027	0.019	-0.33	0.90	0.152
I07R	0.011	3.16	5.28	0.013	0.008	-0.72	0.99	0.045
I09R	0.017	3.09	5.13	0.013	0.017	0.21	0.39	0.069

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
I09R	0.006	2.55	3.93	0.007	0.004	0.01	0.67	0.016
I12R	0.015	2.59	6.59	-0.017	0.012	-1.02	-0.19	-0.002
I12R	0.021	3.79	11.73	0.027	0.015	-0.57	0.65	0.081
I12R	0.015	1.10	7.73	0.027	0.010	-0.17	0.54	0.011
001R	0.013	2.20	4.88	-0.017	0.008	0.06	0.56	0.030
022R	0.026	2.94	8.71	-0.027	0.011	0.23	-0.14	0.046
022L	0.008	0.93	3.98	-0.010	0.003	-0.20	1.88	0.054
023R	0.015	1.41	6.25	0.025	0.004	-0.37	-0.27	0.017
023L	0.030	11.59	15.18	-0.028	0.023	0.93	0.84	0.064
031L	0.015	5.14	5.42	-0.015	0.013	0.12	0.26	0.051
032L	0.010	1.67	4.14	0.014	0.008	0.03	0.25	0.011
033L	0.030	0.83	8.14	0.029	0.025	-0.70	0.47	0.114
034R	0.020	4.52	8.69	-0.018	0.018	-0.33	0.56	0.042
035R	0.064	10.91	31.84	-0.122	0.017	0.89	0.70	0.029
036R	0.024	2.59	8.09	0.033	0.014	-0.07	-0.35	0.025
042R	0.023	5.44	8.42	0.025	0.015	0.31	-0.03	0.011
054R	0.031	5.56	19.71	-0.054	0.014	0.35	0.61	0.040

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
056R	0.009	5.23	5.43	0.009	0.007	0.47	0.58	0.043
Mean	0.020	3.87	8.77	0.001	0.013	-0.02	0.43	0.054
Std dev	0.011	2.50	5.78	0.034	0.006	0.45	0.54	0.044

Subjects given a **grade 1** by the clinicians

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
I09R	0.036	6.99	7.10	0.015	0.035	0.30	-0.40	0.081
I11R	0.010	1.38	4.88	0.015	0.006	-0.28	1.48	0.057
I11R	0.023	2.65	9.14	-0.024	0.021	0.21	1.56	0.146
052L	0.014	5.29	7.39	-0.015	0.014	0.77	1.03	0.068
053L	0.017	2.39	4.60	0.027	0.006	-0.06	1.06	0.178
067R	0.029	7.76	8.55	0.024	0.026	0.22	0.36	0.195
041R	0.013	4.38	5.12	-0.018	0.011	-0.56	-0.25	0.027
043R	0.023	6.37	8.00	0.032	0.015	0.25	0.28	0.050
062L	0.031	4.50	12.97	-0.040	0.020	0.18	1.44	0.122
064R	0.020	4.14	8.54	0.038	0.015	-0.01	1.37	0.169
I05R	0.012	2.31	7.13	0.009	0.007	-0.66	1.13	0.033
I06R	0.030	1.80	10.05	0.037	0.025	-0.73	1.09	0.090
I08L	0.037	9.35	18.30	-0.036	0.029	0.93	3.90	0.311
I11R	0.016	3.44	8.74	-0.015	0.010	0.23	1.06	0.086
I13L	0.027	9.14	15.76	0.035	0.015	0.71	1.96	0.203

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
I13L	0.032	10.93	19.63	0.027	0.030	1.22	2.70	0.213
013R	0.020	6.22	10.56	-0.029	0.019	0.19	2.01	0.130
013L	0.011	3.54	4.78	0.015	0.005	0.56	0.36	0.042
031R	0.012	2.73	5.63	-0.018	0.004	0.36	0.53	0.063
058L	0.037	3.81	16.32	-0.049	0.011	-1.15	1.61	0.236
066L	0.025	1.60	8.54	0.028	0.022	0.05	0.29	0.138
068L	0.020	2.12	9.58	-0.028	0.014	-0.21	1.13	0.222
I05R	0.018	1.43	9.29	0.009	0.012	-0.03	0.43	0.033
057R	0.039	6.75	15.57	-0.069	0.015	0.49	0.92	0.237
Mean	0.023	4.63	9.84	-0.001	0.016	0.12	1.13	0.130
Std dev	0.009	2.75	4.36	0.031	0.009	0.55	0.93	0.080

Subjects given a **grade 2** by the clinicians

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
046L	0.035	3.79	14.09	-0.059	0.014	0.45	0.66	0.112
059R	0.025	5.80	7.48	-0.030	0.011	0.36	0.65	0.091
061L	0.051	11.78	23.49	-0.071	0.034	0.67	2.06	0.192
062R	0.057	5.12	16.81	0.087	0.010	0.38	1.33	0.240
064L	0.026	3.11	10.39	-0.033	0.025	-0.14	1.22	0.135
065L	0.034	3.46	9.63	-0.035	0.027	0.12	0.77	0.235
I05R	0.022	1.79	8.09	-0.032	0.020	0.02	2.54	0.198
I06R	0.021	2.19	7.79	0.025	0.013	-0.63	0.48	0.033
I06R	0.011	1.38	5.75	0.016	0.005	-1.32	0.73	0.052
I08L	0.036	6.65	22.35	-0.062	0.013	0.84	1.78	0.060
I08L	0.037	11.14	25.06	-0.055	0.017	1.40	3.37	0.196
I13L	0.038	7.26	16.42	0.061	0.022	0.64	1.75	0.266
017R	0.021	1.13	4.91	-0.028	0.005	-0.26	1.24	0.067
017L	0.008	2.10	2.66	0.006	0.004	0.21	1.20	0.022
I02R	0.029	2.71	10.29	-0.052	0.010	0.37	-0.09	0.011

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
I02R	0.034	9.52	15.42	-0.054	0.018	0.78	0.40	0.036
I02R	0.047	6.77	18.67	-0.087	0.017	0.41	0.83	0.107
I03L	0.041	9.33	12.90	0.026	0.023	0.88	0.93	0.053
I03L	0.039	11.36	11.57	-0.035	0.030	0.63	0.94	0.206
I03L	0.017	3.85	9.44	-0.026	0.009	0.60	1.04	0.008
I03L	0.056	7.60	11.69	-0.041	0.027	0.40	1.30	0.364
032R	0.041	6.51	10.99	-0.047	0.025	0.52	0.61	0.075
033R	0.026	2.46	11.31	-0.042	0.013	0.17	0.10	0.028
037L	0.033	5.12	14.92	0.031	0.005	0.70	0.27	0.075
039R	0.042	3.03	18.33	-0.070	0.008	0.26	0.70	0.068
054L	0.039	10.64	19.61	-0.056	0.039	1.50	1.58	0.087
059L	0.032	6.18	9.35	-0.046	0.018	0.24	0.88	0.119
068R	0.025	3.86	6.87	-0.022	0.015	0.50	0.95	0.186
I10L	0.015	3.67	7.75	-0.023	0.007	0.35	1.52	0.066
024R	0.021	4.15	6.39	-0.022	0.018	0.10	0.18	0.193
035L	0.015	6.02	9.88	0.015	0.011	0.51	0.39	0.029
036L	0.029	8.21	12.24	-0.052	0.014	1.43	-0.13	0.023

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
052R	0.035	8.19	9.85	-0.048	0.028	0.38	0.43	0.120
Mean	0.031	5.63	12.19	-0.026	0.017	0.41	0.99	0.114
Std dev	0.012	3.10	5.48	0.039	0.009	0.54	0.74	0.087

Subjects given a **grade 3** by the clinicians

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
040L	0.034	4.88	9.73	-0.036	0.013	-0.09	0.44	0.047
060L	0.065	9.79	21.39	-0.113	0.025	0.95	1.63	0.289
063R	0.059	5.73	23.81	-0.094	0.013	0.07	2.07	0.159
I10L	0.025	7.25	10.61	0.029	0.016	0.43	0.68	0.034
I10L	0.055	10.67	16.07	-0.068	0.028	0.66	0.70	0.083
001L	0.046	7.82	10.32	-0.074	0.023	1.08	1.47	0.159
I01L	0.036	9.52	13.45	-0.055	0.023	-0.12	0.76	0.080
I01L	0.052	8.67	15.88	-0.070	0.050	0.02	1.11	0.114
I01L	0.050	3.54	16.92	-0.072	0.022	-0.06	0.25	0.025
I01L	0.094	5.89	26.54	-0.160	0.057	-0.77	2.25	0.384
I02R	0.106	23.33	34.46	-0.158	0.040	1.27	1.04	0.112
I04L	0.092	16.45	38.87	-0.129	0.026	1.33	1.56	0.109
I04L	0.044	11.61	21.01	-0.053	0.023	1.14	0.60	0.020
034L	0.064	18.96	27.82	-0.076	0.049	0.78	0.58	0.075
038R	0.014	2.92	4.28	-0.026	0.004	0.39	0.51	0.045

Subject	Total transl. acceleration (mm/sec^2)	AP transl. velocity (mm/sec)	Total transl. velocity (mm/sec)	ML transl. acceleration (mm/sec^2)	AP transl. acceleration (mm/sec^2)	AP transl. amplitude (mm)	Tibial rot. amplitude (°)	Tibial rot. Velocity (°/sec)
053R	0.027	7.14	8.58	-0.033	0.021	0.72	0.88	0.113
055R	0.064	4.77	27.69	-0.121	0.028	0.24	1.90	0.249
056L	0.030	2.93	6.41	-0.042	0.012	0.32	1.52	0.225
057L	0.118	5.90	38.45	-0.200	0.027	-0.17	3.05	0.058
058R	0.067	11.78	14.50	-0.090	0.045	-0.15	2.22	0.285
066R	0.079	11.06	29.58	-0.123	0.029	0.28	2.24	0.305
067L	0.078	5.31	20.10	-0.109	0.026	-0.27	2.49	0.608
Mean	0.059	8.91	19.84	-0.085	0.027	0.37	1.36	0.163
Std dev	0.027	5.10	9.87	0.051	0.013	0.55	0.77	0.141

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