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Review Article

The Current Knowledge in Tibial Translatory Movements in ACL-Deficient Knees: A Review of the Literature

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Abstract: The anterior cruciate ligament (ACL) is known as the main restraint of anterior tibial translation of the knee joint during movements. Loss of the ACL disrupts the delicate balance of knee structures and may lead to knee joint instability. This, in turn, may cause further damage to the knee structures. Because of the complexity of the knee joint, the movements of the tibia relative to the femur is not a simple anterior-posterior motion and there is a serious controversy in literature in measurement of tibial translatory amounts relative to the femur. This is mainly due to the existence of a semi-circular locus (and not a simple trans-condylar axis) of the instant centre in the knee joint. Occurring tibial translatory movement simultaneously with its rotary movement is another issue that makes measurement of this motion very hard. This study aimed to review the current methods of measurements of tibial translatory motion in ACL-deficient and normal knees. It was concluded that finding an accurate and non-invasive method to analyse tibial movement relative to the femur *in vivo* situations is very difficult and all of the available procedures have their own inherent limitations. It was also recommended that some new non-invasive methods using optic/optoelectronic devices should be considered to provide the most accurate data during *in vivo* tasks.
Keywords: ACL-Deficient Knees, Tibial Translatory Movements, Optoelectronic device, Kinematics.

INTRODUCTION

The knee joint is complex and ranges from 0 to 145 (130-155) degrees and represents the largest joint in the body. Normal function requires the smooth articulation of the tibio-femoral and the patella-femoral joints, the menisci and an intact tibio-fibular syndesmosis. The anterior cruciate ligament (ACL) is considered to be one of the most important single ligaments for stabilisation of the knee joint particularly in bipedal athletes. This ligament has a primary role in prevention of excessive anterior tibial displacement providing about 86% of the restraining forces [1, 2] and on hyperextension of the knee joint [3]; and a secondary role in controlling varus/valgus and rotational stability at the knee [4]. It is believed that ACL-deficiency leads directly to progressive degeneration within the knee joint [5, 6].

ACL injury is now increasing in frequency in sports activities [7]. Rupture of the ACL before or in the early part of an athlete's season presents a treatment dilemma: should the surgeon repair the ligament and end the athlete's season, or should physiotherapy be prescribed progressing to rehabilitative exercise and bracing to quickly return the athlete to competition? [8]. In the ACL-deficient knee, altered joint mechanics occurs and a rotary instability exposes the adjacent supporting ligaments and menisci to further degeneration [9, 10]. Koga and colleagues (2011) have studied anterior tibial translation from model-based image-matching (MBIM) of a noncontact anterior cruciate ligament injury in professional football [11]. They studied a noncontact ACL injury situation in a male footballer recorded during a television broadcast using 4 high-definition cameras from different views, including 2 high-speed recordings. They compared anterior tibial translation at 20, 30, and 150 milliseconds after initial contact. They concluded that the MBIM technique could describe the detailed joint kinematics, including tibial translations of a noncontact ACL injury situation. In addition to valgus motion coupled with internal tibial rotation, substantial anterior tibial translation was observed at the time of injury. These three motions seem to be important components of the injury mechanism. This study provided additional evidence in support of the injury mechanism proposed in the previous study that valgus loading and lateral compression generate internal tibial rotatory motion and anterior tibial translation, resulting in ACL rupture [11]. Since there is a crucial controversy in the literature regarding the amounts of the translatory measurements of the tibia with respect to the femur in the knee joint, this study aimed to comprehensively review the current methods of measuring tibial translatory motion in the normal and ACL-deficient knees with expressing the advantages and disadvantageous of each method. It was also proposed to recommend new non-invasive *in vivo* methods to overcome the disadvantageous of the current methods to enable researchers to compare the normal and excessive tibial translations in knees.

Biomechanical Studies

The translation of the tibia relative to the femur usually occurs in normal tibio-femoral movement. Knee flexion is actually a combination of rolling or rotation of the femoral condyles over the tibial plateau, and posterior gliding of the condyles along the plateau, which is anterior tibial translation [12]. As the true flexion angle increases, this gliding or translational motion theoretically assumes an increasing proportion due to the shape of the femoral condyles. While the increased anterior translation seen in the ACL deficient knees might be expected to occur, during the stance phase it may minimise the amount of translation seen. In addition, when ligamentous instability exists, these translational components may become even larger and play a more important role in total knee motion. However, these results must be interpreted with caution due to the poor accuracy of the apparatus used to measure small displacements.

Despite some advantages seen in cadaveric studies such as directed instrumentation for measurement of strain and/or displacement, some disadvantages have also been highlighted by these studies. The major disadvantage includes lack of the normal dynamic responses of living tissues in cadaveric models. In some dynamic *in vivo* studies an effort was made to duplicate physiological loading parameters other than tibial translation. A variety of methods are used to investigate the biomechanical changes, which occur following ACL injuries. These range from standard clinical evaluation to cadaveric models using a standard knee arthrometer, an electrogoniometer or a Roentgen stereo-photogrammetric and optic/optoelectronic gait analysis device. The early literature indicates that the kinematic assessments were often carried out by simple devices such as manual goniometers. Electrogoniometry, accelerometry, video analysis and optoelectronic scanning are different techniques for recording and analysing some dynamic activities. Use of videotaping and cameras and other advanced motion analysis apparatuses have simplified motion analysis and improved it so that it can be carried out in a more accurate manner.

In fact, because of the small amounts of tibial translatory motion relative to the femur and the existence of a semi-circular locus of the instant centre in the knee joint, finding an accurate and non-invasive method to analyse tibial movement relative to the femur *in vivo* situations is very difficult and all of the above-mentioned methods have their own inherent limitations. For instance, the arthrometer and electrogoniometer are operator-based devices and their directions can easily be changed during dynamic tests on limbs. In addition to the potential dangers of exposure to X-rays in Roentgen techniques, because of the need for simultaneous orthogonal views, it seems practically impossible during an analysis of true dynamic motion [13]. In brief, errors in some previous studies have occurred mainly due to the lack of advanced instrumentation [14]. Cawley *et al*. [14] suggested that as a consequence of the above-mentioned problems, the results of some studies are not reliable and must be further investigated with optoelectronic techniques even though they also have specific limitations.

Because of the limitations in most optoelectronic devices in directly measuring the small linear displacement of the tibia relative to the femur during a dynamic study, most efforts have been directed to analysing the differences in the angulatory kinematics, in conjunction with the other biomechanical parameters such as kinetic and EMG measurements between the normal and ACL-deficient knees.

Translatory Kinematic Analysis of the ACL-Deficient Knee Joint

As time went on, it became apparent that simple eye measurements were not enough in motion analysis. Any motion that happened faster than 1/12 of a second could not be measured by human eye [15]. Motion analyses is used for clinical and research purposes [16]. Automated tracking systems for motion analysis have received increasing clinical acceptance. These systems are multi-camera systems, and they track either passive reflective markers or actively illuminated markers.

An extensive search in the literature reveals that, generally two methods of analysis have been used in the study of ACL-deficient knees. These procedures are direct (invasive) and indirect (non-invasive) methods.

Direct (Invasive) Methods

In this method, an invasive approach is used to evaluate directly the biomechanics of the knee joint in different conditions. The aim of this approach is to find the pure strain on the ACL in intact knees or measurement of the tibial displacement in ACL-deficient knees. Intra-cortical pin insertion [17-20] and arthroscopic implantation of different strain transducers into the intact anterior cruciate ligament in normal knees, are usually used to study the biomechanical behaviour of the intact ACL in different weight bearing conditions [21-24]. In an invasive method, threaded stainless steels, which are called intra-cortical pins (2.5-mm diameter) are implanted into the cortices of the iliac crest, thigh and shank. Having recorded the trajectories of the reflective markers placed on the pins during the given tasks, the kinematics of the lower limb is found [25].

Direct and invasive *in vivo* measurement of the tibia relative to the femur has an advantage of excluding skin movement artefacts, and is a very useful method in gait research using an electrogoniometer. In 1997, Ishii *et al*. three-dimensionally measured the kinematics of the knee joint directly from inserted intra-cortical pin fixation [26]. To exclude the effect of skin movement relative to the bone, and to exclude the effect of changing muscle volume, they implanted some Kirschner wires into the bone of five healthy male volunteers and determined an accurate description of the relative angular and linear movements between the tibia and femur. The clinical motions were determined as: abduction/adduction (3.4±1.2), internal/external rotation (10.6±2.8 degrees) representing screw home motion, and three translation measures which were: anterior-posterior displacement (5.2±1.7 mm) representing roll back phenomenon, proximal-distal (1.2± 2.7 mm) and medial-lateral (1.1±2.6 mm). An identical study was conducted by Lafortune *et al*. in order to gain a better understanding of the kinematics of the knee joint during walking on level ground [18]. They investigated five normal subjects *in vivo*, and obtained the three coordinate axes of knee motion by inserting special metal-covered wooden spheres. Four high-speed cine cameras recorded 3-D coordinates of the target marker data at a speed of 1.2 m/sec. They measured all six degrees of freedom of the tibia and concluded that external rotation of the tibia, which is so called "Screw home movement", did not occur during the last swing phase of normal walking.

Although the invasive method seems to be the best way to avoid surface marker artefacts, very few subjects would agree to undertake such an aggressive study. The knowledge about skeletal tibio-femoral kinematics is, thus, very limited, particularly in abduction/adduction and in internal/external rotation of the knee. In addition, preparation an invasive test is time consuming and needs local surgery. It can be identified from the literature that Lafortune *et al*. and Reinschmidt *et al*. have carried out many studies to assess directly the behaviour of the ACL-deficient knee [18, 19, 20]. Reinschmidt *et al*. also tried to compare the results of the studies with surface markers with those using intra-cortical pins [19]. They found very good consistency in only flexion/extension between skin and skeletal-based kinematics as the shape of the flexion/extension patterns were in general agreement across the subjects. However, poor agreement was found in the shape of skin and skeletal based abduction/adduction and the internal/external rotation curves across subjects. Nowadays, only sagittal plane data (flexion/ extension) is mostly studied in experiments with surface markers.

Indirect (Non - Invasive) Methods

Due to limitations in running invasive studies, most gait analysis studies are carried out using an indirect method, and some surface markers are used instead of intra-cortical pins. In these conservative methods, surface markers (active or passive) are attached to the specific parts of the limb. The markers can be directly mounted on the skin, or indirectly placed on the stick wands or special frames. Using a reconstruction algorithm, the coordinates of the markers are thereafter estimated in the laboratory system of the reference (Laboratory Coordinate System) in each sampled instant of time. From there, using constructed coordinates of a marker cluster, and a suitable mathematical procedure, a rigid body pose estimator, and the bone embedded frame (Local Coordinate System), six degrees of freedom are estimated versus time [27].

Each direct and indirect method has its individual advantages and disadvantages. The greatest advantage of the non-invasive method is the easy of use and availability of the instruments in most gait clinics. However, some disadvantages are associated with this method. Based on rigid body mechanics, three-dimensional analysis assumes that markers placed on the body represent the position of anatomical landmarks for the segment. However, surface markers may not represent the true anatomical locations, resulting in relative and absolute errors [28]. Relative errors are movements between markers with respect to each other, and are caused by skin movement relative to bone. An absolute error is movement of a marker with respect to a specific body landmark [26]. The above mentioned errors are of a particular concern during high dynamic activities [19]. Consequently, considerable questions remain regarding what constitutes normal motion of the knee [26]. In conclusion, despite the disadvantages mentioned above, the non-invasive method is currently the most common and relatively reliable gait analysis system.

Most *in vivo* kinematic studies have been conducted in ACL-deficient knees to compare the tibial translation in the ACL-deficient knee subjects with that of the normal knee subjects. Electrogoniometer has frequently been used to measure the anterior-Posterior (A-P) translation of the tibia relative to the femur in the ACL-deficient knees. Marans *et al*. used an electrogoniometer and measured the A-P translation of the tibia in 20 ACL-deficient limbs, and compared them with those in 30 normal subjects during walking on level ground [29]. They found a mean of 15.8-mm A-P translation in ACL-deficient subjects, which was significantly different from 7.6 mm A-P translation in normal subjects. The mean inter-limb difference between the injured and non-injured knee in ACL-deficient subjects was 4.7 mm, as statistically significant. These amplitude differences in anterior translation were noted to occur during the swing phase.

Vergis and Gillquist used an advanced electrogoniometer system and measured the tibial translation during ascending and descending stair climbing [30]. The purpose of this study was to compare the sagittal translation of the knee in the patients with ACL-deficient injury with that in the control subjects during concentric and eccentric quadriceps muscle activity during stair walking. The test was carried out in both straight and side ascent and descent walking. As a result, in both groups during the ascent cycle the tibia moved anteriorly in relation to the femur, whereas during the descent cycle it moved posteriorly. The maximum tibial movement was in a very wide range, between 1 to 12 mm (mean 7mm), in both groups. Although the maximal translation in both groups was similar, in the ACL-deficient group it occurred at a significantly smaller flexion angle (38°±8 relative to 44°±8). There was no difference between the translation during step ascent and descent in the groups. They concluded that during normal activity, the ACL-deficient patients were able to control abnormal anterior translation.

Using a six-DOF goniometer**,** Zhang *et al*. measured the six-degree of freedom of the knee joint in ACL-deficient, ACL-injured and healthy subjects during walking on level ground [31]. They used a 50 Hz frequency to capture their data. Six rotations (knee flexion/extension, adduction/abduction, internal/external rotation,) and six translatory movements (lateral/medial, posterior/anterior and proximal/distal directions) of the tibia relative to the femur were measured. The ACL-deficient subjects showed more tibial external rotation, more abducted tibia, significantly more anterior tibial displacement (mostly in swing phase) in translatory movements. The flexion/extension patterns of the deficient and normal control groups were similar to each other. However, the ACL-deficient patients flexed their knee significantly less than the normal control subjects did within the swing phase.

Lafortune *et al*. and Karrholm measured the translatory kinematics of the tibia and found different results [18, 32]. Karrholm *et al*. used a Roentgen stereo-photographommetry to measure 3D movements of the knee during A-P laxity test in ACL-deficient subjects and cadaver knees. Thirty-three ACL-deficient subjects and three cadaver knees at 30 degrees flexion were studied, and the translatory kinematics was recorded. In intact cadaveric knees, the anterior laxity (1.3 and 5.6 mm) was greater than the posterior (-0.2 and -0.9 mm). When the ACL ligament was cut, anterior displacement increased to slightly more than 9 mm in the two knees, and the posterior displacement to -0.7 and 2.5 mm. The A-P translation increased from 2.6 and 6.1 mm to 9.8 and 11.8 mm after the ligament had been sectioned. The ACL-deficient patients had at least 3.1-mm anterior displacement (mean 7.7 mm), while the posterior displacements were equal on the injured and the intact side. All ACL-deficient subjects displayed an increased anterior laxity of at least 4 mm (average 8.1 mm), and the average difference between the injured and the intact knee was 2.1±1 mm greater in the group of patients with associated injuries ($P<0.05$) [32]. However, Lafortune *et al*. discovered a distinct relationship between knee flexion-extension and tibial translations along all three femoral orthogonal axes [18]. Regarding anterior-posterior drawer movement along the floating axis, the tibia was drawn posteriorly when the knee was flexed, and it moved anteriorly during extension. Posterior drawer amounted to 3.6 mm during the first half of stance, while knee extension was associated with a maximum anterior displacement of 1.3 mm past the neutral position, defined as 0.0 mm.

In a study which attempts to directly assess the anterior tibial draw in patients with an ACL-deficiency, Beard *et al*. (2000) introduced a new *in vivo* method by measuring the patella tendon angle (α) [33]. They measured the acute α angle by using special marker positions and VICON gait analysis equipment in 20 ACL-deficient subjects during walking on level ground. The angle was measured of both the injured and apparently healthy side as the control group in both stance and complete gait cycle. They also divided the patients into patients with severe symptoms of knee instability (frequent giving way), and moderate symptoms of instability (rarely or no giving way). They found that the mean patella angle for both the injured and healthy side was less than the mean patella angle during quiet standing ($P=0.005$) and reported that all patients reduced their anterior tibial translation to some extent during walking. No significant difference was found in both limbs. However, patients with severe symptoms had significantly increased anterior tibial translation on their injured side (6.7°±2.3) compared to non-injured (10.1°±4.6) in both quiet standing and walking. Conversely, patients who were less symptomatic were found to have less anterior tibial translation on their injured side (7.9°±5.8) when walking. They concluded that ACL-deficient patients are able to control tibial translation during walking, and some patients are better able to control the pathological translation during activity than others. This ability to control translation appears to directly impact on their symptoms of instability. They emphasised on the important role of the hamstring muscles for excessive tibial translation and pointed out that patients with less symptoms may be able to activate their hamstrings muscles more efficiently to control tibial movement during locomotion [33].

The ACL-deficient knees also demonstrate different patterns of tibiofemoral kinematics during gait. Current ACL-reconstruction techniques will restore some functions of the ACL; however, some studies have suggested that anatomical ACL-reconstruction may better restore normal tibiofemoral kinematics. Although in vitro studies have contributed much to our knowledge of knee kinematics, increasingly accurate in vivo measurement techniques now offer new insight on rotational stability. The methodologies of in vivo kinematics include radiological techniques, video-based motion analysis electromagnetic tracking devices, and ultrasound-based systems. As management of knee pathologies continue to evolve, development of reliable measures of rotational stability may be the next challenging clinical and functional outcome assessment. Video-based motion analysis systems have been widely used to study the tibiofemoral joint kinematics because it is non-invasive, easy to operate, and able to assess various movements such as gait, landing, jumping, and cutting. However, because of soft tissue movement artefacts (mainly from skin), it has limited applications. To minimize errors associated with soft-tissue artefact, Andriacchi et al have combined the "point cluster technique", in which clusters of skin markers were placed on each segment, with the "interval deformation technique, "which uses a model of skin deformation during daily activity to minimize skin artefacts. They minimized the errors up to 0.25 mm in location and 0.37° in orientation [34].

Electromagnetic Tracking Device (ETD) allows for in vivo tracking of knee kinematics in 6 DOF simultaneously and can operate up to a radius of 0.7 mm from the transmitter, with an accuracy of :to.5 mm in translation and :t 1° in rotation, collecting data at 100 Hz [35]. Another advantage of ETD is the capability to assign any anatomical points to obtain 6 DOF data (Fig.1).

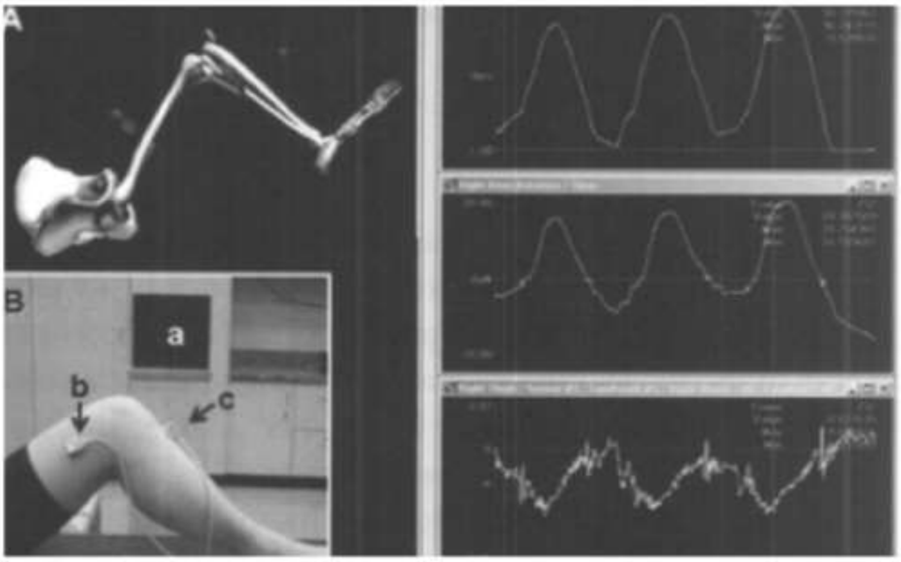

Fig.1: Electromagnetic Tracking Device (ETD)

Although ETD can collect surface points noninvasively with a high frequency, the main drawback lies in their poor precision (mainly due to skin artefacts) and lack of methods to compensate for this inaccuracy. The root mean square (RMS) error was previously reported to be 1.5 mm or worse, but Van Ruijven and co-workers evaluated a method to improve accuracy in modelling articular surfaces up to a RMS of 0.07 to 0.18 mm [36]. Shabani and colleagues used 3D, real-time assessment tool (KneeKg™ System) to study the in vivo evaluation of the behaviour of the anterior cruciate ligament-deficient (ACLD) knees during walking in comparison with normal knees [37]. Kinematic data were recorded during treadmill walking at self-selected speed. Flexion/extension, abduction/ adduction, anterior/posterior tibial translation and external/internal tibial rotation were compared between groups. Significant alterations of joint kinematics in the ACLD knee were revealed in this study by manifesting a higher flexion gait strategy and excessive internal tibial rotation during walking that could result in a more rapid cartilage thinning throughout the knee. The findings in this study indicate that ACLD knee may adapt functionally to prevent excessive anterior–posterior translation but they fail to avoid rotational instability [37]. Sato *et al*. compared anterior tibial translation (ATT) during isokinetic concentric contraction exercise 18–20 months after two different methods of ACL reconstruction (bone-tendon-bone (BTB) grafts or hamstring tendon (ST) grafts) using a computerized electrogoniometer [38]. The electrogoniometer system (CA-4000) fitted to a lower limb of a patient sitting on a Biodex seat.

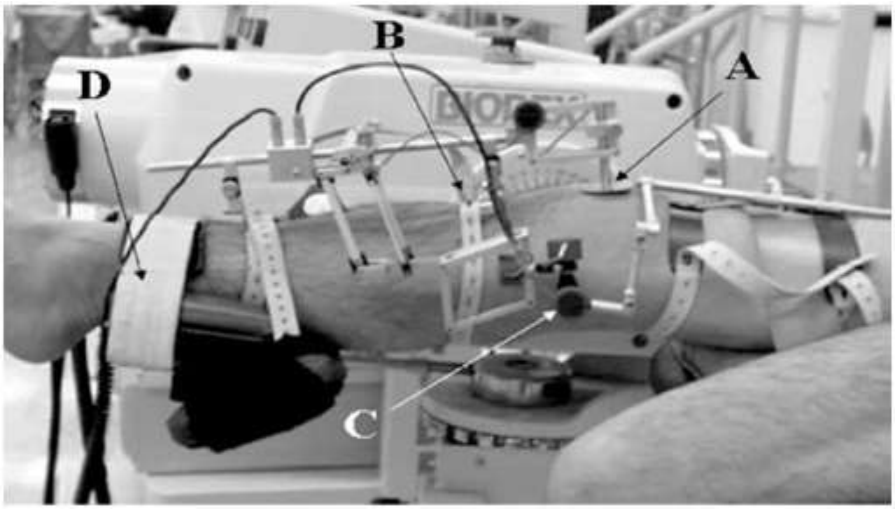

Fig. 2: A Computerized Goniometer

To measure ATT, a computerized goniometer linkage (CA-4000, OSI, Hayward, CA, USA) was fixed to the knee with broad elastic bands (Fig. 2). Only the sagittal plane translation (mm) and the change in flexion angles (degrees) were studied by two different measurements (isokinetic and passive motion) assisted by the Biodex machine. For comparison, the same procedure was repeated on the unaffected side.

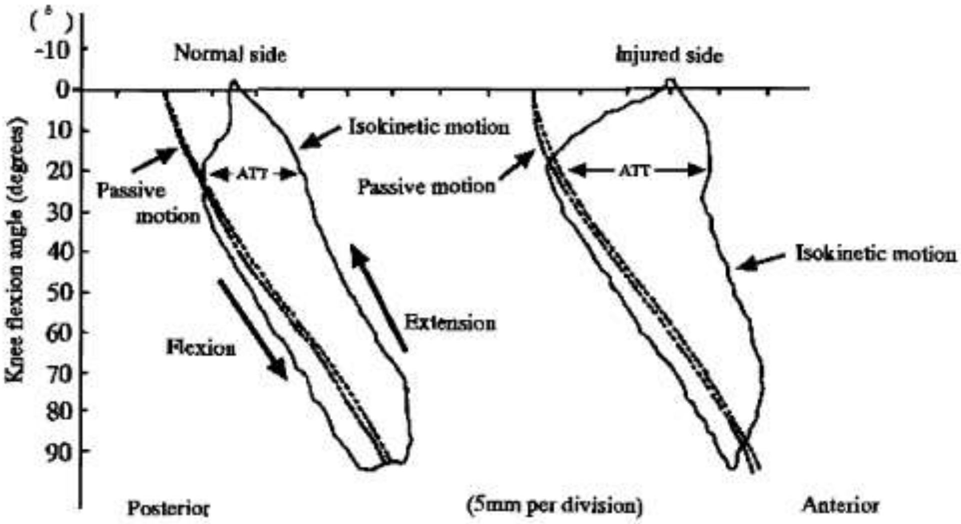

Fig. 3: Typical graphical display (CA-4000 system) of sagittal plane knee translation during passive and isokinetic test cycles.

Anterior tibial translation (ATT), in terms of the difference with isokinetic extension exercise compared with the value for passive extension motion with the Biodex system, was measured at every 10° position with the help of a computer (Fig. 3). In conclusion, the maximal ATT during isokinetic concentric contraction exercise was restored to a level within the normal range by the BTB and ST methods. With the BTB method, no articular instability was observed during isokinetic concentric contraction exercise in the knee between 0 and 90°, while with the ST method, joint instability was observed during isokinetic concentric contraction exercise between 30 and 50° [38, 39].

Stergiou *et al*. reported that ACL reconstruction surgeries were unable to correct the excessive tibial rotation in activities demand anterior and rotational loading more than walking [40]. These findings are regardless of the graft selection for the ACL reconstruction (bone-patellar tendon-bone or semitendinosus and gracilis grafts). They proposed a theoretical perspective for the development of osteoarthritis in both the ACL-deficient and the ACL-reconstructed knees. The excessive tibial rotation will lead to abnormal loading on the cartilage areas, where are not normally loaded in healthy knees. Over time, this abnormal loading will lead to osteoarthritis. They hypothesised that the development of new surgical procedures and grafts, such as a more horizontally oriented femoral tunnel or a double-bundle ACL reconstruction, could possibly restore tibial rotation to normal levels and prevent future knee pathology.

However, *in vivo* gait analysis studies are needed to examine the effects of these surgical procedures on tibial rotation.

In brief, there is still an inconsistency in the literature regarding the amounts of the translatory measurements of the tibia with respect to the femur in the knee joint. The most accurate data showing tibial-related movement comes from the studies carried out using an invasive *in vivo* method via intra-cortical pins. In brief, many studies have been conducted to find out if tibial translation has been increased in ACL-minus knee. However, most of these studies are *in vitro* or static *in vivo*. By now, most studies have demonstrated more A-P tibial displacement in the ACL-deficient knee when the knee is around 30-40° of flexion. The instrumentation used are also inappropriate to overcome the problems exist in this area. When an instrument such as gonioemter/electrogoniometer is used, the main problem is that skin and soft tissue movement, which affects the accuracy of the measurement during locomotion. When an optic/optoelectronic device is used, the inability of the current systems to measure the amounts of tibial translatory movement is the main problem. The most accurate data can be resulted from studies that directly measure tibial movements. Intra-cortical pins and Roentgen Stereo-photogrammetry are the systems have been used in this regards. However, because of the invasive procedures and the danger of infections, radiations and anaesthesia, the methods have not been popularly accepted and duplication of the methods is also not easy in most laboratories.

CONCLUSION

Because of the small amounts of tibial translatory motion relative to the femur and the existence of a semi-circular locus of the instant centre in the knee joint, finding an accurate and non-invasive method to analyse tibial movement relative to the femur *in vivo* situations is very difficult and all of the above-mentioned methods have their own inherent limitations. It is now clear that the most comprehensive and acceptable data can be obtained from non-invasive dynamic *in vivo* situation studies. It is recommended that new non-invasive method using an optic/optoelectronic device should be used to provide data from a dynamic *in vivo* study to better evaluate the excessive tibial translation in normal and ACL-deficient knee joints. Improved appreciation of knee kinematics throughout functional ranges of sagittal knee motion will continue to evolve from non-invasive in vivo studies of the living knee with greater accuracy from newer technologies. This may lead to revised definitions and classifications of post traumatic knee derangements especially in ACL injuries. The need to reproduce pre-injury knee kinematics and rotational stability necessarily demands changes in post injury rehabilitation protocols and a more anatomic reproduction of the ACL during surgical reconstruction. Attempts to achieve the latter include a more horizontally oriented femoral tunnel or double bundle ACL reconstruction.

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