ELSEVIER

Clinical Biomechanics 15 (2000) 160–166

CLINICAL BIOMECHANICS

www.elsevier.com/locate/clinbiomech

Review paper

Biomechanical considerations for rehabilitation of the knee

Gerald McGinty [a], James J. Irrgang [a,b,*], Dave Pezzullo [b]

[a] *Department of Physicial Therapy, University of Pittsburgh School of Health and Rehabilitation Sciences, Room 6010-A, Forbes Tower, Meyran Avenue, Pittsburgh, PA 15260, USA*

[b] *Centers for Rehabilitation Services, Pittsburgh, PA, USA*

Received 18 June 1999; accepted 28 July 1999

Abstract

Knowledge of the anatomy and biomechanics of the knee is critical for successful rehabilitation following knee injury and/or surgery. Biomechanics of both the tibiofemoral and patellofemoral joints must be considered. The purpose of this paper is to provide a framework for rehabilitation of the knee by reviewing the biomechanics of the tibiofemoral and patellofemoral joints. This will include discussion of the relevant arthrokinematics as well as the effects of open and closed chain exercises. The implications for rehabilitation of the knee will be highlighted.

1. Introduction

The knee joint is the largest and possibly the most complex synovial joint in the body. It is a combination of three articulations, one between the femur and patella and two between the femoral condyles and tibial plateaus. It is located between the two longest lever arms of the body and bears a majority of body weight. This relationship makes the knee vulnerable to trauma and overuse injuries. Since knee injuries can lead to significant functional limitations and disability, an understanding of this joint's biomechanics is a prerequisite for proper rehabilitation of the knee. The purpose of this paper is to review the biomechanics of the tibiofemoral and patellofemoral joints, which will provide the framework for the rehabilitation of any knee dysfunction.

2. The tibiofemoral joint

The tibiofemoral joint is usually described as a modified hinge joint with two degrees of freedom: flexion-extension and axial rotation. The amount of knee flexion will vary from 120° to 160° depending on the position of the hip. The range of knee extension is 0–15° of hyperextension and can be tested by lifting the heel off the table with the knee straight. The amount of axial rotation is dependent on the position of the knee. In full extension, the knee is in the close-packed position and minimal to no rotation is possible. At 90° of knee flexion the tibia can laterally rotate up to 40° and medially rotate up to 30°. More recently, the tibiofemoral joint has been described as having six degrees of freedom; flexion and extension with mediolateral translation around a mediolateral axis, varus-valgus angulation with anteroposterior translation around an anteroposterior axis, and internal and external rotation with superoinferior translation around a superoinferior axis [1].

During flexion and extension of the tibiofemoral joint there is a combined roll, glide, and spin of the articulating surfaces to help maintain the joint congruency [2]. These arthrokinematics are a result of the geometry of the joints and the tension produced in the ligamentous structures. During closed chain extension of the tibiofemoral joint the femoral condyles roll anteriorly and glide posteriorly on the tibial plateaus. There is also a conjunct medial rotation of the femur during the last 30° of extension. This is called the 'screw home' mechanism of the knee. In open chain extension, the tibial plateaus roll and glide anteriorly on the femoral condyles. In the last 30° this produces a conjunct lateral rotation of the tibia. During closed chain flexion of the knee the femoral condyles roll posteriorly and glide anteriorly on the tibia plateaus with a conjunct lateral rotation of the femur at the beginning of flexion, which is initiated by the politeus muscle. In open chain flexion the tibial plateaus roll and glide posteriorly on the femoral

* Corresponding author.
E-mail address: irrgang@newton.isd.upmc.edu (J.J. Irrgang).

0268-0033/00/$ - see front matter
PII: S 0 2 6 8 - 0 0 3 3 (9 9) 0 0 0 6 1 - 3

condyles with a conjunct internal rotation during the initial 30°.

The anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) help maintain normal arthokinematics of the knee through the four bar linkage system described by Muller [3]. The four bars in the linkage system include (1) ACL, (2) PCL, (3) a line connecting the femoral insertions of ACL and PCL, and (4) a line connecting the tibial insertions of the ACL and PCL. In a normal knee the cruciate ligaments are inelastic and maintain a constant length as the knee flexes and extends, helping to control rolling and gliding of the joint surfaces. During closed chain extension of the knee, the femoral condyles roll anteriorly increasing the distance between the insertions of the PCL. Since the PCL cannot lengthen, the femoral condyles are pulled posteriorly allowing full extension to occur. During closed chain flexion of the knee, the femoral condyles roll posteriorly increasing the distance between the insertions of the ACL. Since the ACL cannot lengthen, the femoral condyles are pulled anteriorly by the ACL. Injury to the cruciate ligaments disrupts the four bar linkage system and results in abnormal translation of the tibiofemoral joint during flexion and extension of the knee. This aberrant motion may damage the menisci and articular cartilage leading to early degenerative changes of the knee.

An understanding of the arthrokinematics of the tibiofemoral joint is helpful in the treatment of limited motion of the knee. For example, if a patient has limited knee extension secondary to limited anterior translation of the tibia, the therapist can apply an anterior glide of the tibia to help increase knee extension [4].

3. Effects of exercise on the tibiofemoral joint

Currently rehabilitation exercises for the knee joint are described as occurring in an open kinetic chain (OKC) or a closed kinetic chain (CKC) manner. Open kinetic chain exercises are defined as those in which the distal segment of the joint is free to move [5]. OKC exercises are typically non-weight bearing exercises such as knee extension performed when sitting on a leg extension machine. Closed kinetic chain exercises are defined as those in which the distal segment of the joint meets considerable resistance [5]. Examples of CKC exercises include a squat or step-up. OKC and CKC exercises produce different effects on the tibiofemoral and patellofemoral joints. An understanding of these differences can help the clinician design a comprehensive rehabilitation program.

4. OKC knee extension

OKC knee extension is produced by isolated contraction of the quadriceps, which results in anterior translation of the tibia. Palmitier et al. [6] developed a biomechanical model demonstrating the forces produced at the tibiofemoral joint during OKC extension. The resultant force on the knee can be resolved into a compressive component and a shear component. When the resistance is applied perpendicular to the distal aspect of the leg a posterior shear of the femur (anterior shear of the tibia) is produced. The ACL provides 85% of the restraining force to this anterior tibial shear [7].

Grood et al. [8] demonstated this stress on the ACL during OKC knee extension in cadaveric knees. They found that sectioning the ACL increased anterior tibial translation during the last 45° of knee extension. Thus, exercises performed in this range could have deleterious effects on the graft following ACL reconstruction or could stretch secondary restraints in an ACL-deficient knee.

Sawhney et al. [9] investigated the effects of isometric quadriceps contraction on tibial translation in subjects with an intact knee. Isometric OKC quadriceps contraction against 10 pounds of resistance applied to the distal aspect of the leg resulted in significant anterior tibial translation at 30° and 45° of flexion, with no significant tibial translation occurring at 60° and 75° of flexion. The authors determined that the quadriceps neutral angle (i.e. the angle at which quadriceps contraction produces no anterior or posterior tibial translation) occurs between 60° and 75° of flexion. OKC knee extension at angles less than the quadriceps neutral position results in anterior translation of the tibia. OKC knee extension at angles greater than the quadriceps neutral position result in posterior translation of the tibia.

Beynnon et al. [10] confirmed the above findings by implanting a Hall effect transducer in subjects to measure the strain characteristics of a normal ACL during commonly prescribed rehabilitation exercises. OKC knee extension produced strain on the ACL that was dependent on the angle of knee flexion and level of quadriceps activity. The average peak ACL strain during OKC knee extension without weight was 2.8%. Strain on the ACL during OKC knee extension with a 45-N weight strapped to the ankle was 3.8%. In both cases the peak strain occurred at 10° of knee flexion. Isometric OKC quadriceps contractions at 15° and 30° produced an average peak strain of 4.4% and 2.7%, respectively, while at 60° and 90° of knee flexion there was 0% ACL strain. Co-contraction of the quadriceps and hamstrings at 15° of flexion produced an average peak ACL strain of 2.8% but no strain was produced on the ACL at 30°, 60°, and 90° of flexion. The exercises that produced no to low ACL strain were either dominated by the hamstring muscles, involved quadriceps muscle activity with the knee flexed at 60° or greater, or involved unloaded knee motion between 35° and 90° of flexion.

Presently it is unknown how much strain is detrimental or beneficial to a graft following ACL reconstruction. It has been reported that a strain of 10–15% is necessary to cause visible failure of the ACL [11]. It appears that OKC extension exercises will not adversely effect a normal ACL or mature ACL graft. However, the healing graft may be vulnerable to overloading and may fail if rehabilitation is too aggressive. To minimize PCL stress, OKC knee extension should be performed at angles between 60° and 0° of flexion.

5. OKC knee flexion

OKC knee flexion results from isolated contraction of the hamstrings, which results in posterior translation of the tibia and places stress on the PCL. Grood et al. [12] demonstrated increased posterior translation following removal of the PCL in cadaveric knees. The additional posterior translation was least in full extension and increased progressively with an increase in knee flexion angle, reaching 11.4 mm at 90° of knee flexion. Lutz et al. [13] found that isometric OKC knee flexion at 30°, 60°, and 90° of flexion produced large posterior shear forces at the tibiofemoral joint. The posterior shear forces increased as flexion progressed from 30° to 90°. Kaufman et al. [14] analyzed forces on the tibiofemoral joint during OKC isokinetic exercise. A posterior shear force existed throughout the entire range of flexion, reaching a peak at 75° of knee flexion. The maximum posterior shear force was 1.7× body weight at 60°/s and 1.4× body weight at 180°/s. Beynnon et al. [10] measured ACL strain in vivo and verified that OKC isometric hamstring contractions produce no to low strain on the ACL.

The above studies present evidence that all OKC knee flexion exercises place substantial stress on the PCL and should be used judiciously during rehabilitation following PCL injury and/or reconstruction. It also reinforces the concept that OKC flexion does not produce deleterious loads on the ACL and should be employed during ACL rehabilitation.

6. Closed chain exercises

CKC exercises occur when the distal segment of the joint is relatively fixed so that movement at one joint results in simultaneous movement of all the other joints in a predictable manner. An example of a CKC exercise is a squat, which results in simultaneous ankle dorsiflexion, knee flexion, and hip flexion. CKC exercises are widely used in the rehabilitation of the lower extremity especially following ACL reconstruction. It is believed that CKC exercises minimize stress on the ACL by decreasing the tibiofemoral shear forces through increased joint compression and muscular co-contraction.

Biomechanical models demonstrate reduced tibiofemoral shear forces when the line of force is applied more axially in relation to the tibia [6]. Markolf et al. [15] confirmed that axial compression decreased joint displacement and concluded that joint compression may be an important protective mechanism that reduces ligament strain. Yack et al. [16] examined the effects of progressive loading of the knee extensors during weight-bearing and non-weight-bearing isometric exercise in ACL-deficient knees. The results demonstrated less anterior tibial translation under weight-bearing conditions than non-weight-bearing conditions. Progressive loading of the lower limb when weight-bearing did not increase anterior tibial translation. Stuart et al. [17] reported that a power squat, front squat, and lunge all produced a posterior tibiofemoral shear force indicating that the potential loading on the injured or reconstructed ACL is not significant. Torzilla et al. [18] studied the combined effects of joint compression and quadriceps force on joint stability. They found a significant decrease in total anteroposterior translation with the application of a joint compressive load and/or quadriceps force. The joint compressive load and quadriceps force significantly decreased total anteroposterior translation by as much as 50–66% in ACL-intact knees and by as much as 42–71% in ACL-deficient knees.

CKC exercises result in co-contraction of the hamstrings and quadriceps muscles. Ohkoshi et al. [19] investigated this by measuring the electromyographic activity in the thigh muscles when squatting. Their results revealed simultaneous contraction of the hamstrings and quadriceps muscles when squatting on both legs and an increase in activity of the hamstrings with anterior flexion of the trunk. Muscular co-contraction occurs as the quadriceps contract to counteract the flexion moment arm at the knee and the hamstrings contract to counteract the flexion moment arm at the hip [6].

Wilk et al. [20] reported that not all CKC exercises produce co-contraction of the quadriceps and hamstring muscles. It appears that squats promote co-contraction whereas a leg press produces a quadriceps muscle dominant contraction. During the horizontal leg press the body is positioned behind the knee joint and the quadriceps must contract to control the increasing knee flexion angle. Conversely, during the vertical squat, the body is positioned only slightly posterior to the knee joint resulting in more of a co-contraction between the quadriceps and hamstring muscles.

Beynnon et al. [21] implanted a transducer on the anteriomedial bundle of the ACL to measure strain in the ligament during squatting with and without elastic resistance and during active open chain flexion and extension of the knee. The results revealed that the average maximum ACL strain values produced by OKC extension (3.8%) and CKC squatting (3.6%) were similar. This finding indicates that squatting, which produces a compressive joint force does not necessarily protect the ACL more than active extension of the leg. Fleming et al. [22] used the same instrument as Beynnon and colleagues to measured ACL strain in vivo during stationary bicycling. The mean peak ACL strain values generated during bicycling were relatively low (1.7%). This indicates bicycling is a CKC exercise that can be used to challenge the thigh musculature without increasing ACL strain values.

CKC exercises are assumed to be more functional than OKC exercises because they produce a muscle recruitment pattern that simulates functional activities. During CKC exercise, simultaneous hip and knee extension occur when arising from the flexed position causing the rectus femoris to lengthen across the hip while shortening across the knee. Conversely, the hamstrings lengthen across the knee and shorten across the hip. The resultant concentric and eccentric contraction at opposite ends of the muscle produce a 'pseudoisometric contraction' described by Palmitier et al. [6] as the 'concurrent shift'. This type of contraction is utilized during functional activities such as walking, stair climbing, running, and jumping and cannot be reproduced by isolated OKC exercises.

Snyder-Mackler et al. [23] suggested that CKC exercise alone may not provide an adequate stimulus to the quadriceps femoris to permit normal function of the knee. Subjects who performed OKC knee extension with high-intensity electrical stimulation demonstrated greater increases in quadriceps femoris muscle torque compared to subjects performing CKC exercise alone. The increase in muscle torque was correlated with improved kinematics during the stance phase of gait. Ninos et al. [24] studied muscle activity with the addition of the extremity during the performance of a squat against 25% of body weight. The results indicated that maximum quadriceps activity was between 20% and 30% of maximum voluntary isometric contraction and the maximum hamstring activity was between 10% and 15% of maximum voluntary isometric contraction. Therefore, CKC exercises may not provide an adequate stimulus for optimal quadriceps strengthening. Open kinetic chain knee extension and flexion exercises, within an appropriate range of motion as determined by the underlying pathology, should be used to perform isolated strengthening of the quadriceps and hamstrings.

7. The patellofemoral joint

The patellofemoral joint is a sellar joint between the patella and the femur [25]. Stability of the patellofemoral joint is dependent on the passive and dynamic restraints around the knee. The medial patellofemoral ligament is the primary passive restraint to lateral patellar translation at 20° of flexion, contributing 60% of the total restraining force [26]. The medial patellomeniscal ligament and the lateral retinaculum contribute 13% and 10% of the restraint to lateral translation of the patella, respectively. The passive restraints to medial patellar translation are provided by the structures that form the superficial and deep lateral retinaculum. The superficial retinaculum consists of fibers from vastus lateralis and iliotibial band [27]. The deep retinaculum consists of the lateral patellofemoral ligament, the deep fibers of the iliotibial band, and the lateral patellotibial ligament [27]. Tightness of the lateral retinacular structures may result in abnormal tracking or excessive lateral compression of the patellofemoral joint. The inability to lift the lateral border of the patella above the horizontal plane indicates tightness of the lateral retinaculum [28] and is an indication for patellar mobilization.

The primary dynamic restraint are the quadriceps muscles. The quadriceps consist of the rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis. The vastus medialis can be divided into the vastus medialis longus and the vastus medialis obliquus (VMO). All of the quadriceps muscles extend the knee except the VMO, which acts only to stabilize the patella medially [29]. Historically, treatment of patellofemoral pain has focused on strengthening the VMO to improve dynamic patella stability [30,31]. However, there is no conclusive evidence that specific exercises can be performed to selectively recruit the VMO [32]. It may be that successful treatment of patellofemoral pain can be achieved by general quadriceps strengthening exercises.

The patella glides superiorly and inferiorly on the femur during extension and flexion of the knee, respectively. The total excursion of the patella from full knee extension to full knee flexion is 5–7 cm [33]. Limited superior glide of the patella may result in limited active knee extension. Limited superior glide of the patella can be treated with patellar mobilization to improve superior glide [4]. Limited inferior glide of the patella may result in limited knee flexion. Limited inferior glide of the patella can be managed with patellar mobilization to improve inferior glide [4].

Only part of the patella articulates with the femoral trochlea at any given time. The patella is not in contact with the distal femur in full extension but sits above the trochlear notch without significant compressive load [34]. Initial contact between the inferior aspect of the patella and the trochlea occurs at approximately 20° of flexion [35]. The contact area moves proximal as the knee flexes so that by 90° of flexion the superior portion of the patella contacts the trochlea. Beyond 90° of flexion the patella rides down into the intercondylar notch and the quadriceps tendon articulates with the trochlear groove of the femur. It is not until 135° of flexion that the odd facet of the patella makes contact with the medial femoral condyle [34]. The location of a chondral lesion can influence exercise prescription. For example, if the patient has a painful proximal lesion on the patella, exercises between 60° and 90° of flexion should be avoided.

8. Effects of exercise on the patellofemoral joint

Ficat and Hungerford [36] calculated the area of patellofemoral contact at varying angles of knee flexion. Patellofemoral contact area increases with increasing flexion of the knee. The average values were 2.0 cm^2 at 30° of flexion, 3.1 cm^2 at 60° of flexion, and 4.7 cm^2 at 90° of flexion. The increased contact area helps to distribute compressive forces over a larger area, which reduces contact stress.

The patellofemoral joint reaction force (PFJRF) is a measure of compression of the patella against the femur. The magnitude of this force depends on the quadriceps and patellar tendon tension and the angle of knee flexion [35]. During CKC exercises the flexion moment arm of the knee increases as the angle of knee flexion increases. Greater quadriceps and patellar tendon tension is required to counteract the increasing flexion moment arm. This results in greater PFJRF as the knee flexes. During level walking, the PFJRF is half the body weight, when ascending and descending stairs the force is 3–4 times the body weight, and during squatting it is 7–8 times the body weight [37]. This information helps explain why patients with patellofemoral pain experience an increase in their symptoms during activities involving flexion of the knee when weight bearing.

During OKC extension, the flexion moment arm of the knee increases and the extensor moment arm of the patella decreases [8]. This results in the need for increasing quadriceps force to extend the knee especially at terminal extension. The large forces needed to achieve full extension explain why an extensor lag occurs with quadriceps weakness. Reilly and Martens [37] calculated the peak PFJRF for OKC knee extension to be 1.4 times the body weight at 36° of flexion that decreased to half of body weight at full extension. This explains why straight leg raises and short arc quadriceps exercises from 20° to 0° provide maximum stress to the quadriceps with minimal patellofemoral complaints.

Hungerford and Barry [35] compared patellofemoral contact stresses between OKC knee extension against a 9-kg load and squatting under body weight. The contact stress was less for OKC knee extension against a 9-kg load than when squatting under body weight between 90° and 53° of knee flexion. The contact stress were less when squatting under body weight than when performing OKC knee extension against a 9-kg load between 0° and 53° of flexion.

Steinkamp et al. [38] compared PFJRF and patellofemoral contact stress during a leg press with OKC leg extension exercises at 0°, 30°, 60°, and 90° of flexion. Their results indicated that PFJRF and patellofemoral contact stress were significantly greater during OKC leg extension exercise compared to the leg press between 0° and 45° of knee flexion. Between 50° and 90° of knee flexion, PFJRF and contact stress were significantly greater for the leg press compared to the OKC leg extension exercise. The PFJRF for leg press and OKC leg extension intersected at 48° of knee flexion.

Both of the above studies indicate that patellofemoral joint stress can be increased or decreased depending on the mode (OKC or CKC) and flexion angle at which the exercise is performed. During OKC exercises the forces across the patella are lowest at 90° of flexion [39]. As the knee extends from 90° of flexion the PFJRF increases and patellofemoral contact area decreases. This results in an increase in contact stress with extension until approximately 20° when the patella no longer contacts the trochlea. During CKC exercise the forces across the patella are lowest at 0° of extension [39]. As the knee flexes, PFJRF increases along with the patellofemoral contact area. This results in a decrease in contact stress initially then an increase in contact stress with more flexion secondary to the increasing joint reaction force.

Both OKC and CKC exercises can be utilized in the treatment of patients with patellofemoral pain if performed within a pain free range. CKC exercises may be better tolerated by the patellofemoral joint in the range of 0–45° of knee flexion. In this range, suggested exercises include step-ups, mini-squats, and leg presses. OKC exercises may be better tolerated by the patellofemoral joint in the ranges from 90–50° and 20–0° of knee flexion. In these ranges, suggested exercises include short arc isotonics, multiple angle isometrics, straight leg raises, and quadriceps sets. Performing CKC and OKC exercises in these specific ranges loads the quadriceps while minimizing stress on the patella. The evidence suggests that both OKC and CKC exercises should be incorporated into rehabilitation programs.

9. Summary and conclusion

The anatomy and biomechanics of the knee as well as their implications for rehabilitation have been reviewed.

Successful rehabilitation requires the clinician to understand and apply these biomechanical concepts. When applied to the rehabilitation process, understanding of these concepts can maximize patient function while minimizing the risk for further symptoms or injury.

References

[1] Goodfellow J, O'Connor J. The mechanics of the knee and prosthesis design. Journal of Bone and Joint Surgery 1978;60B:358.

[2] Kapandi IA. The Physiology of the joints, vol. 2, Lower limb. 5th ed. Edinburgh: Churchhill Livingstone, 1985.

[3] Muller W. The knee: form, function, and ligament reconstruction. New York: Springer, 1983.

[4] Maitland GD. Peripheral manipulation. 2nd ed. London: Butterworths, 1977.

[5] Steindler A. Kinesiology of the human body under normal and pathological conditions. Springfield IL: Charles C. Thomas, 1973:63.

[6] Palmitier RA, An K, Scott SG, Chao EYS. Kinetic chain exercise in knee rehabilitation. Sports Medicine 1991;11:402–13.

[7] Butler DL, Noyes FR, Grood ES. Ligamentous restraints of anterior–posterior drawer in the human knee: a biomechanical study. Journal of Bone and Joint Surgery 1980;62A:259–70.

[8] Grood ES, Suntay WJ, Noyes FR, Butler DL. Biomechanics of the knee-extension exercise. Journal of Bone and Joint Surgery 1984;66A:725–33.

[9] Sawhney R, Dearwater S, Irrgang JJ, Fu FH. Quadriceps exercise following anterior cruciate ligament reconstruction without anterior tibial displacement. Presented at the American Conference of the American Physical Therapy Association. Anaheim, CA, 1990.

[10] Beynnon BD, Fleming BC, Johnson RJ, Nichols CE, Renström PA, Pope MH. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. The American Journal of Sports Medicine 1995;23(1):24–34.

[11] Noyes FR, Bulter DL, Grood ES. Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. Journal of Bone and Joint Surgery 1984;66A(3):344–52.

[12] Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee: effect of sectioning the posterior cruciate ligament and posterolateral structures. Journal of Bone and Joint Surgery 1988;70A:88–97.

[13] Lutz GE, Palmitier RA, An KN, Chao EYS. Comparison of tibiofemoral joint forces during open-kinetic-chain and closed-kinetic-chain exercises. Journal of Bone and Joint Surgery 1993;75A:732–9.

[14] Kaufman KR, An K, Litchy WJ, Morrey BF, Chao EYS. Dynamic joint forces during knee isokinetic exercise. The American Journal of Sports Medicine 1991;19(3):305–19.

[15] Markolf KL, Bargar WL, Shoemaker SC, Amstutz HC. The role of joint load in knee stability. Journal of Bone and Joint Surgery 1981;63A:570–85.

[16] Yack HJ, Riley LM, Whieldon TR. Anterior tibial translation during progressive loading of the acl-deficient knee during weight-bearing and nonweight-bearing isometric exercise. Journal of Orthopaedic and Sports Physical Therapy 1994;20(5):247–52.

[17] Stuart MJ, Meglan DA, Lutz GE, Growney ES, An K. Comparison of intersegmental tibiofemoral joint forces and muscle activity during various closed kinetic chain exercises. The American Journal of Sports Medicine 1996;24(6):792–9.

[18] Torzilla PA, Deng X, Warren RF. The effects of joint-compressive load and quadriceps muscle force on knee motion in the intact and anterior cruciate ligament-sectioned knee. The American Journal of Sports Medicine 1994;22(1):105–12.

[19] Ohkoshi Y, Yasuda K, Kaneda K, Wada T, Yamanaka M. Biomechanical analysis of rehabilitation in the standing position. The American Journal of Sports Medicine 1991;19(6):605–11.

[20] Wilk KE, Escamilla RF, Fleisig GS, Barrentine ST, Andrews JR, Boyd ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. The American Journal of Sports Medicine 1996;24(4):518–27.

[21] Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renström PA, Nichols CE. The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension. The American Journal of Sports Medicine ;25(6):823–29.

[22] Fleming BC, Beynnon BD, Renström PA, Peura GD, Nichols CE, Johnson RJ. The strain behavior of the anterior cruciate ligament during bicycling. The American Journal of Sports Medicine 26(1):109–18.

[23] Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. Journal of Bone and Joint Surgery 1995;77A(8):1166–73.

[24] Ninos JC, Irrgang JJ, Burdett R, Weiss JR. Electromyographic analysis of the squat performed in self-selected lower extremity neutral rotation and 30° of lower extremity turn-out from the self-selected neutral position. Journal of Orthopaedic and Sports Physical Therapy 1997;25(5):307–15.

[25] Williams PL, Warwick R. Gray's anatomy. 36th ed. Philadelphia: Saunders, 1980.

[26] Desio SM, Burks RT, Bachus KN. Soft tissue restraints to lateral patellar translation in the human knee. The American Journal of Sports Medicine 1998;26(1):59–65.

[27] Terry GC, Hughston JC, Norwood LA. The anatomy of the iliopatellar band and iliotibial tract. The American Journal of Sports Medicine 1986;14(1):39–44.

[28] Kolowich PA, Paulos LE, Rosenberg TD, Farnsworth S. Lateral release of the patella: indications and contraindications. The American Journal of Sports Medicine 1990;18(4):359–65.

[29] Lieb FJ, Perry J. Quadriceps function: an anatomical and mechanical study using amputated limbs. Journal of Bone and Joint Surgery 1968;50A:1535–48.

[30] Hanten WP, Schulthies SS. Exercise effect on electromyographic activity of the vastus medialis oblique and the vastus lateralis muscles. Physical Therapy 1990;70:561–5.

[31] Leveau BF, Rodgers C. Selective training of the vastus medialis muscle using EMG biofeedback. Physical Therapy 1980;60:1410–5.

[32] Powers CM. Rehabilitation of patellofemoral joint disorders: a critical review. Journal of Orthopaedic and Sports Physical Therapy 1998;28(5):345–54.

[33] Carson W, James S, Larson R. Patello-femoral disorders – parts I and II. Clinical Orthopaedics and Related Research 1984;185:165–74.

[34] Goodfellow JW, Hungerford DS, Zindel M. Patellofemoral mechanics and pathology: I Functional anatomy of the patellofemoral joint. Journal of Bone and Joint Surgery 1976;58B:287.

[35] Hungerford DS, Barry BS. Biomechanics of the patellofemoral joint. Clinical Orthopaedics 1979;144:9–15.

[36] Ficat P, Hungerford D. Disorders of the patellofemoral joint. London: Williams and Wilkins, 1979.

[37] Reilly DT, Martens M. Experimental analysis of the quadriceps muscle force and patello-femoral joint reaction force for various activities. Acta Orthopaedica Scandinavica 1972;43:126–37.

[38] Steinkamp LA, Dillingham MF, Markel MD, Hill JA, Kaufman KR. Biomechanical considerations in patellofemoral joint rehabilitation. The American Journal of Sports Medicine 1993;21(3):438–44.

[39] Grelsamer RP, Colman WW, Mow VC. Anatomy and mechanics of the patellofemoral joint. Sports Medicine Arthroscopy Review 1994;2:178–88.