Kinetic Chains: A Review of the Concept and Its Clinical Applications

Ninad Karandikar, MD, Oscar O. Ortiz Vargas, MD

During the past decade, our understanding of biomechanics and its importance in rehabilitation has advanced significantly. The kinetic chain, a concept borrowed from engineering, has helped us better understand the underlying physiology of human movement. This understanding, in turn, has facilitated the development of new and more rational rehabilitation strategies. The kinetic chain concept has application in a wide spectrum of clinical conditions, including musculoskeletal medicine, sports medicine, and neurorehabilitation, as well as prosthetics and orthotics. The purpose of this review is to provide insights into the biomechanics related to the concept of kinetic chains, with a specific focus on closed kinetic chains and its clinical applications in rehabilitation.

PM R 2011;3:739-745

INTRODUCTION

The concept of kinetic chain reaction originated from the German engineering scientist Franz Reuleaux (1829-1905), who is often called the "father of kinematics." Reuleaux first proposed the novel "link concept" in his book *The Kinematics of Machinery* in 1876 [1]. The link system concept, although initially related to engineering, has become a widely accepted and well-reviewed principle in rehabilitation [2-5].

As proposed by Reuleaux, in a rigid-link system, pin joints connect a series of overlapping rigid segments. If both ends of this system are fixed such that no movement can occur at either end, the application of an external force causes each segment to receive and transfer force to the adjacent segment, generating a chain reaction. As a result, movement at any joint will produce a predictable movement pattern at all other joints in the chain (Figure 1).

The extrapolation of this conceptual framework of kinetic links or the link system to the analysis of human movement was first introduced by Hans von Baeyer in 1933 at the International Orthopedic Congress while he gave a synopsis of muscle function. In his work, which focused on synergistic muscle actions in the limbs, he contrasted the effects occurring in the limb periphery with the effects at the proximal end of the limb lever arm [6].

The kinetic chain concept was then elaborated and popularized in the rehabilitation literature by Steindler in his book *Kinesiology of the Human Body*, which was published in 1955 [7]. Steindler proposed that the limbs be thought of as "rigid overlapping segments" in series. He defined the kinetic chain as "a combination of several successively arranged joints constituting a complex motor unit." Each bony segment in the lower extremity, such as the foot, lower leg, thigh, and pelvis, can be viewed as a rigid link, with the subtalar, ankle, knee, and hip joints acting as the connecting joints [8]. In later writings, Steindler [7] categorized the kinetic chain concept as open or closed depending on the loading of the terminal (most distal) segment.

DEFINITIONS

Biomechanics

Biomechanics is defined as the application of the mechanics of motion produced by biologic systems. The study of biomechanics requires consideration of resultant motions produced by forces. Kinetics refers to the study of forces that affect motion of a body, such as friction,

N.K. Department of PM&R, University of Kentucky, 2050 Versailles Blvd, Lexington, KY 40504. Address correspondence to: N.K.; e-mail: nkara2@email.uky.edu
Disclosure: nothing to disclose

O.O.O.V. Physical Medicine and Rehabilitation, Veterans Affair Medical Center Lexington, Lexington, KY; and Department of PM&R, University of Kentucky, Lexington, KY.
Disclosure: nothing to disclose

Disclosure Key can be found on the Table of Contents and at www.pmrjournal.org

Submitted for publication December 2, 2010; accepted February 19, 2011.

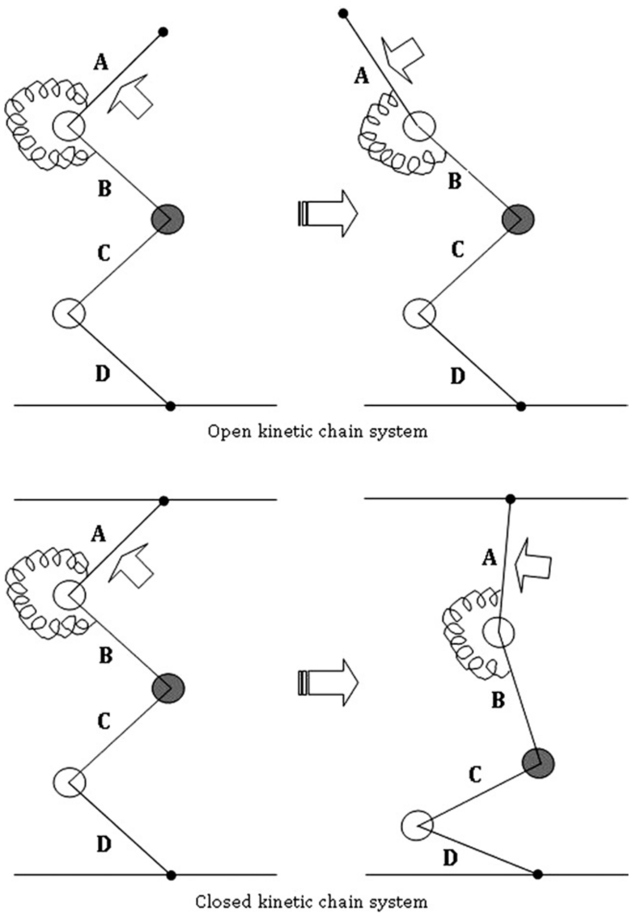

Figure 1. In an OKC system, a force (arrow) applied to a terminal segment (A) will cause movement to only that segment (A). In contrast, in a CKC system, the same force applied to the segment A (now fixed) will cause movement in all segments (B, C, and D).

gravity, or pressure. In contrast, kinematics is the study of the spatial and temporal characteristics of motion without regard to the causative forces.

Open and Closed Kinetic Chain Systems

Steindler defined an open kinetic chain (OKC) system as “a combination of successively arranged joints in which the terminal segment can move freely” [7]. In an OKC system, the distal segment is therefore free to move in space.

Steindler initially defined a closed kinetic chain (CKC) system as “a condition or environment in which the distal segment meets considerable external resistance that prohibits or restrains its free motion” [7]. In a CKC system, a force applied to one of the segments produces motion at all other segments (kinetic chain) in a predictable fashion.

It is now known that muscle recruitment and joint movement patterns vary based on the type of kinetic chain involved [9]. The nature and physiology of underlying muscle contractions involved in performing the joint motion (eg, isotonic, isometric, or isokinetic) are closely related but independent concepts that are not discussed in this review.

This concept of open and closed kinetic chain joint motions can be applied directly to exercises and daily activities. Most therapeutic exercises are complex and involve a combination of open and closed kinetic chain characteristics. For the purpose of this review, we define CKC exercises as those that resembles CKC system characteristics and OKC exercises as those that resemble OKC system characteristics in a specific joint targeted by that exercise.

A clinical example of an OKC exercise is the seated knee extension leg curl (Figure 2). During this exercise, the distal segment (the leg) is free to move in space, whereas the proximal segments (the thigh and trunk) are fixed. With OKC exercises, a single joint is usually the focus of the OKC motion—the knee, in the case of the leg curl. A clinical example of a CKC exercise is the standing squat exercise (Figure 3). During this exercise, the feet remain fixed to the ground and motion occurs uniformly across multiple lower extremity joints.

In many activities of daily living and sports, the activation sequence in the link involves a CKC whereby the activity is initiated from a firm base of support and the resultant force is then transferred through the links to the more mobile distal segments. Although most activities can be classified as OKC or CKC, in some instances this distinction is difficult to make. For example, in swimming and cycling, which traditionally are viewed as OKC activities, there is a load on the distal segment, yet the distal segment is not *fixed* or restricted from movement.

Dillman [10] proposed that the classification be determined by whether the terminal segment in the chain is movable or fixed and whether it bears a load. An activity with

Figure 2. Open kinetic chain exercise.

Figure 3. Closed kinetic chain exercise.

a fixed terminal segment and no load does not exist. Considering the variables of load and mobility of the terminal segment, all activities can be classified as one of the following:

1. Moveable, no load (resembles an open chain system)
2. Fixed, external load (resembles a closed chain system)
3. Moveable, external load (a combination of closed and open chain systems)

More recently, Kibler [11] defined a closed-chain activity as a sequential combination of joint motions in which the distal segment of the kinetic chain meets considerable resistance but does not have to be fixed.

CKC AND OKC EXERCISES: BIOMECHANICAL DIFFERENCES

Open-chain exercises result in isolated movement at a given joint and are effective when isolated strengthening for se-

Table 1. *Characteristic properties of closed kinetic chain and open kinetic chain exercises*

Characteristics of closed kinetic chain exercises
Increased joint compressive forces
Increased joint congruency (and therefore increased stability)
Decreased shear forces
Characteristics of open kinetic chain exercises
Increased joint distraction and rotational forces
Increased joint deformation (and therefore reduced stability)
Increased shear forces

lected muscle groups is desired. In contrast, CKC exercises cause co-contraction of the agonist and antagonist muscle groups. This biomechanical difference makes CKC exercises useful once isolated weakness is eliminated [12]. Other benefits achieved with CKC rehabilitation include (1) the establishment of early proximal stability (shoulders, hips, trunk), providing a more stable base for distal function [13] and ambulation [14]; and (2) improvement of proprioception, neuromuscular control, and subsequently functional stability of the joint (Table 1) [15,16]. For example, during OKC knee extension, the quadriceps perform most of the work related to the motion, whereas the hamstrings are activated to control the motion without contributing significantly to the work performed. In contrast, in a CKC system, eg, in a straight squat, with the center of gravity placed directly over the knee, both the quadriceps and hamstrings work simultaneously to control knee flexion. The result is stabilization of the knee through simultaneous activity of 2 opposing muscle groups [17]. As the leg moves into terminal extension in OKC, the work required to lift the leg increases because the moment arm of the resistance force (gravity) increases. This phenomenon requires an increasing force production by the quadriceps in the terminal 30° of knee extension. This action causes an anterior translation of the tibia, resulting in a high shear force across the knee. In contrast, in a CKC knee extension, through simultaneous co-contraction of the hamstrings and quadriceps, significantly less shear stress and increased stability occurs across the knee joint [5,17].

Lefever [8], in an excellent review, emphasizes the importance of 2 variables in CKC exercise: (1) placement of center of gravity and (2) placement of the terminal limb, especially in the lower extremity. Performing a knee flexion-extension movement in a CKC position can activate different muscle groups, depending on where the center of gravity is placed in relation to the knee [8] (Figure 4). If the center of gravity is placed directly over the knee (Figure 4, center), the knee extensors work to control the movement, whereas if the center of gravity is placed behind the knee (Figure 4, left), more stress is placed on the hip extensors to control the movement. However, if the center of gravity is placed in front of the knee (Figure 4, right), the gastrocnemius must control the movement. Thus the position of

Figure 4. Effects of moving the center of gravity over the joint axis on muscle recruitment pattern in closed kinetic chain activity.

the center of gravity over the joint axis can directly influence muscle recruitment.

Position of the terminal segment in the transverse or coronal plane is also important when one performs CKC exercises [8]. For instance, when the foot is placed in pronation, excessive internal rotation of the entire lower limb might occur, causing increased stress to the knee [18]. This stress may cause or worsen patellofemoral pain [19,20] or potentially affect the healing of capsuloligamentous structures around the knee [21].

CLINICAL APPLICATIONS

Despite some controversy, CKC exercises have gained popularity over more traditionally used OKC exercises in the past decade. Many clinicians believe that CKC exercises are more functional and safer than OKC exercises because they produce stresses that are less of a threat to healing and repaired structures [22,23]. The principle and evidence basis of CKC exercise, as clinically applied in several areas of rehabilitation, is reviewed in the following sections.

Anterior Cruciate Ligament Reconstruction

During the past few decades, CKC techniques have been used as the rehabilitation method of choice to improve functional outcomes after anterior cruciate ligament (ACL) reconstruction. The first randomized controlled trial that compared OKC exercises and CKC exercises in ACL injury was performed in 1995. It showed that CKC exercises were safe, effective, and could offer the advantage of less stress on the healing graft and less patellofemoral pain [24].

More recent studies have shown that CKC exercises produce less pain and laxity and better subjective outcomes than do OKC exercises after ACL reconstruction [25]. It is proposed that this benefit of CKC exercises results from co-contraction of the quadriceps, hamstrings, and gastrocnemius muscles, decrease shear forces between tibia and fibula, and increase joint compression, thus enhancing joint stability and protecting the graft [26,27].

Fitzgerald [22], emphasizing a different perspective, states that the critical difference between OKC exercises and CKC exercises is not the kinematic arrangement but the resultant loads transmitted to the knee. With controlled but not aggressive training loads, OKC exercises appear to be as safe as CKC exercises. This finding has led Perry and colleagues [28] to hypothesize that the difference in outcome between CKC and OKC exercise could be related to a difference in training dose, with more intense therapy when performing CKC rehabilitation. Further complicating this issue, Mikkelsen and colleagues [29] used a combined OKC and CKC exercise program to show greater improvement in outcomes of patients with ACL repair, which questions the validity of a CKC-only rehabilitation approach.

Patellofemoral Pain Syndrome

The realization that open and closed kinetic chain exercises have different effects in rehabilitation of patients with patellofemoral pain syndrome (PFPS) started in the 1980s. Biomechanical analyses have demonstrated less patella-femoral contact stress during knee flexion in CKC when compared with OKC exercises [30-32]. These findings were later confirmed with more direct approaches [33,34].

Early controlled trials also revealed better restoration of function [35], making the use of CKC exercises the cornerstone of the treatment for PFPS in the mid 1990s [36]. In more recent studies, however, investigators have revealed that patella-femoral stress can be equally high in both CKC and OKC exercises. Compressive forces have been found to be equally high in near-full flexion with CKC exercises and in full extension with OKC exercises [37,38]. Despite all the theoretical benefits, several high-quality randomized controlled trials have failed to prove significant differences in outcome between CKC and OKC exercises in the treatment of PFPS [39-41].

Currently, most protocols recommend including a combination of both CKC and OKC exercises for management of PFPS [42,43]. Resistance training usually is started in the acute phase with isometric OKC exercises, at 30°-45° knee flexion [44]. In the subacute phase, training can progress gradually to short-arc OKC exercises, followed by long-arc OKC exercises, as tolerated [45]. In the chronic phase, emphasis should be placed on CKC exercises. There is some evidence that OKC exercises in the chronic phase might preferentially activate vastus lateralis instead of vastus medialis obliquus, which in turn may have a counterproductive effect because of potential induction of excessive lateral tracking of the patella [46].

Shoulder Pain

The biomechanical model for the throwing shoulder in elite athletes has been extensively reviewed in a series of articles [47-49]. In a landmark article [50], Kibler explains that shoulder function in throwing requires contributions from all body segments to generate the forces necessary to propel the ball and pass the forces and loads to the mobile distal segments. This coordinated sequencing of the segments is a prime example of the CKC concept. In the normal kinetic chain of throwing, the ground, legs, and trunk act as the force generators; the shoulder acts as a funnel and force regulator; and the arm acts as the force delivery mechanism [49]. Understanding this kinetic chain then helps to correlate how a pathology such as weak core muscles, abnormal hip, or knee rotation eventually may lead to shoulder impingement, scapular dyskinesias, or labral tears with repetitive motion [51]. Evaluation of athletes with suspected shoulder lesions should include tests to check kinetic chain functioning, including a leg and back examination [51]. We hypothesize that the same concept can be applied to non-athletes involved with work-related repetitive overuse shoulder injuries, such as manual laborers.

The kinetic chain principle further helps the practicing clinician to plan the appropriate rehabilitation regimen for the injured shoulder [5]. The rehabilitation program for shoulder training should involve a graduated progression, starting with non–weight-bearing isometric exercises, progressing to low-weight CKC through a pain-free motion, usually in the mid range, and then progressing to weight-bearing OKC exercises. Along with training for muscular endurance, proprioception, neuromuscular control, and kinetic chain training should be advanced throughout the rehabilitation program [52].

Spinal Cord Injury

Application of the principle of CKC in persons with a spinal cord injury can help with pressure relief, transfers, and wheelchair propulsion in patients with injuries as high as C5 [53]. The major barrier to gaining independence in performing daily activities in high-level quadriplegics is the lack of active antigravity strength of elbow extension. The principles and mechanics of CKC, when used appropriately in this patient population, can help improve independence with some activities. It involves the use of the anterior deltoid, biceps, and brachialis muscles, all innervated by the C5 spinal nerve root, in a CKC to convert the regular elbow/shoulder flexion moment to an elbow extension moment when the hand is fixed on the wheelchair hand rim by friction [53].

Gait, Prosthetics, and Orthotics

Kinetic chain principles also are applicable in the field of gait analysis and prosthetics and orthotics. The primary goal of gait is energy-efficient locomotion, which is achieved by using a stable kinetic chain of multiple limb segments that work congruently to transport the passenger unit (head, arms, and trunk) on the locomotor unit (lower limbs and pelvis).

Gait involves 2 main phases: stance and swing. The entire stance phase of gait involves closed chain kinetics, while the swing phase is all open chain. The first functional task in the stance phase is weight acceptance. The demand for immediate transfer of body weight onto the limb as soon as it contacts the ground requires initial limb stability and shock absorption while simultaneously preserving the momentum of progression. When the functional task of weight acceptance has been achieved, the individual is said to demonstrate a stable kinetic chain [54].

In the field of orthotics, one of the most common prescriptions in physiatric practice is the ankle foot orthosis. The rationale behind using an ankle foot orthosis for quadriceps weakness can be explained easily with the principle of CKC systems. With a normal gait, the quadriceps muscle undergoes eccentric contraction in the early stance to prevent knee flexion instability or "knee buckling," and again in the late stance to help control rate and amount of knee flexion. With the foot on the ground in CKC in the early stance phase, an ankle foot orthosis in plantar-flexion in a patient with quadriceps weakness will create an extension moment at the knee and thereby prevent flexion instability. This orthotic intervention simulates the body's normal compensation of recruiting the ankle plantar flexors and/or hip extensors for lack of knee control caused by loss of quadriceps strength [55].

The concept of CKC also can help us to understand the underlying principles frequently used in amputee rehabilitation. For below-knee amputees, to support body weight with the knee in a flexed attitude, the quadriceps must act with sufficient force to restrain the flexion moment. When this occurs, pressure between the anterodistal surface of the tibia and the socket is increased, causing anterodistal stump discomfort at heel strike. In CKC, at heel strike, activation of the hip extensors can create a knee extension moment. By using this principle, below-knee amputee patients with quadriceps weakness use their hip extensor musculature strength to facilitate knee extension when the prosthetic limb is in the early stance phase. This counteraction reduces the chance of anterodistal stump discomfort [56].

CONCLUSIONS

The principle of kinetic chains has been extensively used in biomechanical engineering for decades. The application of this concept to musculoskeletal medicine, sports injuries, and amputee rehabilitation enables the prescription of individualized exercise programs.

A comprehensive rehabilitation program should integrate a blend of OKC and CKC exercises determined by the clinical scenario. CKC exercises provide more stability and less stress to weight-bearing joints. However, OKC exercises could be considered more appropriate when there is dysfunction associated with injury, and the predictable pattern of movement that occurs with CKC activity may not be possible because of pain, swelling, weakness, or loss of motion. In addition, OKC exercises might be the only option in any situation where the patient is unable to bear weight on the extremity. More research is needed to understand how biomechanical concepts such as open and closed kinetic chain can be applied to the rehabilitation of musculoskeletal conditions to improve safety and functional outcomes.

ACKNOWLEDGMENTS

We thank Dr. Helen O'Donnell for her valuable comments regarding the manuscript and Raquel Nazario for her help with the photos.

REFERENCES

1. Reuleaux F. Kinematics of Machinery: Outlines of a Theory of Machines. Charleston, SC: Nabu Press; 2010.
2. Butler PB, Major RE. The missing link? Therapy issues of open and closed chains. Physiotherapy 2003;89:465-470.
3. Moon FC. Franz Reuleaux: Contributions to 19th century kinematics and theory of machines. Appl Mech Rev 2003;56:261-285.
4. Ellenbecker TS, Davies GJ. Closed Kinetic Chain Exercise: A Comprehensive Guide to Multiple Joint Exercise. Champaign, IL: Human Kinetics; 2001.
5. Kibler WB, Livingston B. Closed-chain rehabilitation for upper and lower extremities. J Am Acad Orthop Surg 2001;9:412-421.
6. Steindler A. A historical review of the studies and investigations made in relation to human gait. J Bone Joint Surg Am 1953;35:540-542.
7. Steindler A. Kinesiology of the Human Body. Springfield, IL: Charles C Thomas; 1955.
8. Lefever S. Closed kinetic chain training. In: Hall CM, Brody LT, eds. Therapeutic Exercise: Moving Towards Function. Philadelphia, PA: Lippincott Williams & Wilkins; 2005, 283.
9. Voight M. Clinical application of closed chain exercise. J Sports Rehab 1995;5:25-44.
10. Dillman C. Biomechanical differences of open and closed chain exercises with respect to the shoulder. J Sports Rehab 1994;3:228-238.
11. Kibler WB. Closed kinetic chain rehabilitation for sports injuries. Phys Med Rehabil Clin N Am 2000;11:369-384.
12. Lephart SM, Henry TJ. Functional rehabilitation for the upper and lower extremity. Orthop Clin North Am 1995;26:579-592.
13. Dillman C, Murray T, Hintermeister R. Biomechanical differences of open and closed chain exercises with respect of proprioception, neuromuscular control and subsequently functional stability of the joint. J Sport Rehab 1994;3:228-238.
14. Palmitier RA, An KN, Scott SG, Chao EY. Kinetic chain exercise in knee rehabilitation. Sports Med 1991;11:402-413.
15. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med 1997;25:130-137.
16. Rogol IM, Ernst G, Perrin DH. Open and closed kinetic chain exercises improve shoulder joint reposition sense equally in healthy subjects. J Athl Train 1998;33:315-318.
17. Houglum PA. Muscle strength and endurance. In: Houglum PA, ed. Therapeutic Exercise for Musculoskeletal Injuries. Champaign, IL: Human Kinetics; 2010, 222.
18. Souza RB, Draper CE, Fredericson M, Powers CM. Femur rotation and patellofemoral joint kinematics: A weight-bearing magnetic resonance imaging analysis. J Orthop Sports Phys Ther 2010;40:277-285.
19. Barton CJ, Bonanno D, Levinger P, Menz HB. Foot and ankle characteristics in patellofemoral pain syndrome: A case control and reliability study. J Orthop Sports Phys Ther 2010;40:286-296.
20. Barton CJ, Munteanu SE, Menz HB, Crossley KM. The efficacy of foot orthoses in the treatment of individuals with patellofemoral pain syndrome: A systematic review. Sports Med 2010;40:377-395.
21. Shultz SJ, Nguyen AD, Levine BJ. The relationship between lower extremity alignment characteristics and anterior knee joint laxity. Sports Health 2009;1:54-60.
22. Fitzgerald GK. Open versus closed kinetic chain exercise: Issues in rehabilitation after anterior cruciate ligament reconstructive surgery. Phys Ther 1997;77:1747-1754.

23. Shelbourne KD, Nitz P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. Am J Sports Med 1990;18:292-299.
24. Bynum EB, Barrack RL, Alexander AH. Open versus closed chain kinetic exercises after anterior cruciate ligament reconstruction. A prospective randomized study. Am J Sports Med 1995;23:401-406.
25. Andersson D, Samuelsson K, Karlsson J. Treatment of anterior cruciate ligament injuries with special reference to surgical technique and rehabilitation: An assessment of randomized controlled trials. Arthroscopy 2009;25:653-685.
26. Schulthies SS, Ricard MD, Alexander KJ, Myrer JW. An electromyographic investigation of 4 elastic-tubing closed kinetic chain exercises after anterior cruciate ligament reconstruction. J Athl Train 1998;33:328-335.
27. Kvist J, Gillquist J. Sagittal plane knee translation and electromyographic activity during closed and open kinetic chain exercises in anterior cruciate ligament-deficient patients and control subjects. Am J Sports Med 2001;29:72-82.
28. Perry MC, Morrissey MC, King JB, Morrissey D, Earnshaw P. Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-week post-operative period after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2005;13:357-369.
29. Mikkelsen C, Werner S, Eriksson E. Closed kinetic chain alone compared to combined open and closed kinetic chain exercises for quadriceps strengthening after anterior cruciate ligament reconstruction with respect to return to sports: A prospective matched follow-up study. Knee Surg Sports Traumatol Arthrosc 2000;8:337-342.
30. Hungerford DS, Lennox DW. Rehabilitation of the knee in disorders of the patellofemoral joint: Relevant biomechanics. Orthop Clin North Am 1983;14:397-402.
31. Henning C, Lynch M, Glick K. An in vivo strain gauge study of elongation of the anterior cruciate ligament. Am J Sports Med 1985;13:22-26.
32. Howell D. Commentary: Modification of quadriceps femoris muscle exercises during knee rehabilitation. Phys Ther 1986;66:1250-1251.
33. Steinkamp LA, Dillingham MF, Markel MD, Hill JA, Kaufman KR. Biomechanical considerations in patellofemoral joint rehabilitation. Am J Sports Med 1993;21:438-444.
34. Kaufman KR, An KN, Litchy WJ, Morrey BF, Chao EY. Dynamic joint forces during knee isokinetic exercise. Am J Sports Med 1991;19:305-316.
35. Stiene HA, Brosky T, Reinking MF, Nyland J, Mason MB. A comparison of closed kinetic chain and isokinetic joint isolation exercise in patients with patellofemoral dysfunction. J Orthop Sports Phys Ther 1996;24:136-141.
36. Woodall WR, Welsh J. A biomechanical basis for rehabilitation programs involving the patellofemoral joint. J Orthop Sports Phys Ther 1990;11:535-542.
37. Wilk KE, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR, Boyd ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. Am J Sports Med 1996;24:518-527.
38. Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Wilk KE, Andrews JR. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc 1998;30:556-569.
39. Witvrouw E, Lysens R, Bellemans J, Peers K, Vanderstraeten G. Open versus closed kinetic chain exercises for patellofemoral pain. A prospective, randomized study. Am J Sports Med 2000;28:687-694.
40. Witvrouw E, Danneels L, Tiggelen DV, Willems TM, Cambier D. Open versus closed kinetic chain exercises in patellofemoral pain: A 5-year prospective randomized study. Am J Sports Med 2004;32:1122-1130.
41. Herrington L, Al-Sherhi A. A controlled trial of weight-bearing versus non-weight-bearing exercises for patellofemoral pain. J Orthop Sports Phys Ther 2007;37:155-160.
42. Earl JE, Vetter CS. Patellofemoral pain. Phys Med Rehabil Clin N Am 2007;18:439-458, viii.
43. Collado H, Fredericson M. Patellofemoral pain syndrome. Clin Sports Med 2010;29:379-398.
44. Felicio LR, Saad MC, Liporaci RF, Prado Ad, Dos AC, Bevilaqua-Grossi D. Evaluating patellar kinematics through magnetic resonance imaging during open- and closed-kinetic-chain exercises. J Sport Rehabil 2010;19:1-11.
45. Bhave A, Baker E. Prescribing quality patellofemoral rehabilitation before advocating operative care. Orthop Clin North Am 2008;39:275-285, v.
46. Irish SE, Millward AJ, Wride J, Haas BM, K GL. The effect of closed-kinetic chain exercises and open-kinetic chain exercise on the muscle activity of vastus medialis oblique and vastus lateralis. J Strength Cond Res 2010;24:1256-1262.
47. Kibler WB, McMullen J, Uhl T. Shoulder rehabilitation strategies, guidelines, and practice. Orthop Clin North Am 2001;32:527-538.
48. Fleisig GS, Barrentine SW, Escamilla RF, Andrews JR. Biomechanics of overhand throwing with implications for injuries. Sports Med 1996;21:421-437.
49. Burkhart SS, Morgan CD, Kibler WB. The disabled throwing shoulder: Spectrum of pathology Part I: Pathoanatomy and biomechanics. Arthroscopy 2003;19:404-420.
50. Kibler WB. Biomechanical analysis of the shoulder during tennis activities. Clin Sports Med 1195:79-86.
51. Burkhart SS, Morgan CD, Kibler WB. The disabled throwing shoulder: Spectrum of pathology Part III: The SICK scapula, scapular dyskinesis, the kinetic chain, and rehabilitation. Arthroscopy 2003;19:641-661.
52. Kennedy DJ, Visco CJ, Press J. Current concepts for shoulder training in the overhead athlete. Curr Sports Med Rep 2009;8:154-160.
53. Little JW, Goldstein B, Hammond MC. Spinal cord injury rehabilitation. In: Belandres PV, Dillingham TR, eds. Rehabilitation of the Injured Combatant. Washington, DC: Department of the Army; 2000, 177.
54. Ayyappa E. Normal Human Locomotion, Part 1: Basic Concepts and Terminology. J Prosthet Orthot 1997;9:10-17.
55. Lehman JF. Ankle foot orthoses for paresis and paralysis. Phys Med Rehab Clin North Am 1992;3:139-159.
56. Berger NM. Gait analysis. In: Berger NM, Fishman SPD, eds. Lower Limb Prosthetics. New York, NY: Prosthetic-Orthotic Publications; 1998, 145.