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TITLE: Timing of Surgery and Rehabilitation to Optimize Outcome for Patients with Multiple Ligament Knee Injuries: A Multicenter Clinical Trial

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14. ABSTRACT: The overall purpose of this Clinical Trial Development Award (CTDA) was to plan a multicenter randomized clinical trial to investigate the effects of timing of surgery and rehabilitation to optimize clinical outcome and return to duty/activity for military personnel and civilians with a multiple ligament knee injury (MLKI). The objectives for the CTDA were to: 1) further develop the research network to ensure access to an adequate number individuals with a MLKI necessary for successful recruitment of the required number of subjects; 2) finalize the experimental design including issues related to subject eligibility, randomization and outcome measurement; 3) develop clinical protocols for surgery and post-operative rehabilitation; 4) finalize the required sample size and develop the statistical analysis and data management plans; 5) develop a clinical and safety monitoring plan; 6) establish a governance structure to oversee conduct of the study; 7) develop a site monitoring plan that includes guidelines for closing and adding sites; and 8) develop a transition plan to move to implementation of the clinical trial. All tasks for the CTDA were successfully completed resulting in an application that was funded to support the conduct of the trial.

15. SUBJECT TERMS: Multiple ligament knee injury, timing of surgery, timing of post-operative rehabilitation; optimizing return to activity/duty; patient reported outcome.

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Table of Contents

1. INTRODUCTION

The overall purpose of this Clinical Trial Development Award (CTDA) was to plan a multicenter randomized clinical trial to investigate the effects of timing of surgery and post-operative rehabilitation to optimize clinical outcome and return to duty/activity for military personnel and civilians with a multiple ligament knee injury (MLKI). We hypothesize that early surgery and early initiation of post-operative rehabilitation will lead to improved outcomes in terms of: 1) return to duty/work and sports, 2) patient-reported and performance-based measures of physical function and health-related quality of life; 3) restoration of normal laxity and range of motion with 4) no increased risk of complications. The overarching objectives for the CTDA are to: 1) further develop the research network to ensure access to a population of individuals with a MLKI injury that is necessary for successful recruitment of the required number of subjects; 2) finalize the experimental design including issues related to subject eligibility, randomization and outcome measurement; 3) develop clinical protocols for surgery and post-operative rehabilitation; 4) finalize the required sample size and develop the statistical analysis and data management plans; 5) develop a clinical and safety monitoring plan; 6) establish a governance structure to oversee conduct of the study; 7) develop a site monitoring plan that includes guidelines for closing and adding sites; and 8) develop a transition plan to move to implementation of the clinical trial.

2. KEYWORDS

Multiple ligament knee injury; timing of surgery; timing of post-operative rehabilitation; optimizing return to activity/duty; patient-reported outcome.

3. ACCOMPLISHMENTS

What were the major goals of the project?

Under the approved SOW, the project had the following major goals:

1) Develop Research Network for Multicenter Clinical Trial
2) Finalize Experimental Design
3) Develop Clinical Protocols
4) Finalize Sample Size and Develop Statistical Analysis & Data Management Plan
5) Establish Governance Structure to Oversee Study Management
6) Develop Clinical and Safety Monitoring Plan
7) Develop Site Monitoring Plan
8) Develop Transition Plan to Move to Clinical Trial
9) Prepare and Submit Application for Clinical Trial Award to Conduct Trial

What was accomplished under these goals?

1) Develop Research Network for Multicenter Clinical Trial (Task 1)

a) The research network for this planning grant included 16 clinical sites (3 US military treatment centers, 10 US civilian centers and 3 Canadian centers). As a result of the Clinical Trial Development Award, we were able to expand the clinical research network for the clinical trial to include 25 clinical sites of excellence for the treatment of complex knee injuries. In total 5 US military treatment centers, 3 Canadian and 17 US civilian centers have agreed to participate in the Surgical Timing and Rehabilitation (STaR) Trial for the Treatment of Multiple Ligament Knee Injuries (MLKIs). Investigators at all sites expressed interest and commitment to participating in the multicenter clinical trial and have participated in the regular investigators' conference calls and in-person investigators' meetings.

b) A medical record review to determine the mechanism of injury, timing of presentation and injury pattern of multiple ligament knee injuries (MLKIs) as well as associated injuries was completed. IRB approvals for chart review activities were obtained from 16 sites and chart review data was provided from 13 sites. In total 999 individuals with a MLKI were reviewed. The results were included as preliminary data in the grant application for an Integrated Clinical Trial Award to support the conduct of the study. Additionally, an abstract summarizing the results of this retrospective study was submitted to and accepted for presentation at the 2018 Annual Meeting of the American Academy of Orthopaedic Surgery.

c) Conference calls with investigators from the collaborating clinical sites were held on a regular basis. During these calls the investigators discussed issues related to the design of the clinical trial (subject eligibility criteria, study interventions, primary and secondary outcomes, etc.), budget and the governance structure for the multicenter clinical trial.

d) Two Investigators' Meeting were held during the project period. The first was March 1-2, 2016 at the AAOS Annual Meeting in Orlando, Fl; the second was July 7, 2016 at the AOSSM Annual Meeting in Colorado Spring, CO. The meetings covered the topics related to the timeline for submission and review of the grant application, summary and review of the results of the retrospective review study, issues related to study design including eligibility criteria, interventions and outcome measures, overview of IRB and HRPO regulatory procedures, coordinating site responsibilities, clinical site responsibilities and budget.

e) An in-person meeting of the Rehabilitation Committee was held on August 25, 2017 in Pittsburgh. At this meeting the rehabilitation protocol for the early and delayed post-operative rehabilitation programs were reviewed and finalized. Additionally, case report forms related to assessment of adherence to the assigned post-operative rehabilitation intervention and materials for communications to subjects and rehabilitation providers were reviewed and approved. Lastly, the development of training modules to educate the physical therapists providing the post-operative rehabilitation were planned and discussed.

2) Finalize Experimental Design and Develop Clinical Protocols (Task 2 and Task 3)

a) The study specific aims for the STAR Trial were revised and approved by the study investigators. They include:

Specific Aim 1: Determine the effects of timing of surgery and post-operative rehabilitation on time to return to pre-injury level of military duty, work and sports and patient-reported physical function. It is hypothesized that early surgery, early rehabilitation and the combination of early surgery with early rehabilitation will lead to an earlier and more complete return to pre-injury military duty, work and sports activity and better patient reported physical function.

Specific Aim 2: Determine the effects of timing of rehabilitation on time to return pre-injury level of military duty, work and sports and patient-reported physical function. It was hypothesized that early rehabilitation will lead to an earlier and more complete return to pre-injury military duty, work and sports activity and better patient-reported physical function.

Due to budget constraints for the Integrated Clinical Trial Award, plans to enroll individuals that had a MLKI that precluded randomization to surgery or rehabilitation into a parallel observational study were eliminated from the project.

b) Investigators finalized the eligibility criteria for each of the study objectives. The final eligibility criteria are:

Male and female military personnel and civilians between the ages of 16 and 55 with a MLKI (defined as a complete grade III injury of two or more ligaments) without a history of prior knee ligament reconstruction with or without a nerve injury or tendon rupture or avulsion are eligible to participate in the STaR trial. Individuals with a torn or avulsed patellar or quadriceps tendon, periarticular fracture that requires surgical reduction and fixation (i.e. KD V injury classification) or use of an external fixator to maintain reduction of the knee for greater than 10 days, that are unable to WB on the contralateral uninjured leg, or have a traumatic brain injury (TBI) that limits their ability to participate in their post-operative care are excluded from participation in these studies.

To be eligible to participate in the study for **Specific Aim 1** individuals with a MLKI have to present to orthopaedic surgery in time to undergo definitive surgery within 6 weeks if randomized to the early surgery group. Individuals with a vascular injury that dictates the timing of surgery, polytrauma that precludes surgery within 6 weeks, or a skin or soft tissue injury that precludes randomization to early surgery or early rehabilitation are excluded from the study for Specific Aim 1. Individuals are also excluded from participation in the study for Specific Aim 1 if they can not be randomized to early rehabilitation because the surgical procedure precludes early post-op WB and ROM (i.e. surgery for extensor mechanism rupture or avulsion, vascular graft surgery).

Subjects with a MLKI that present to orthopaedic surgery at a time the precludes

randomization to early surgery or have an injury that precludes randomizing the timing of surgery (such as a vascular injury) as well as those that refuse randomization to the timing of surgery are eligible to participate in the study for **Specific Aim 2**, in which subjects are randomized to only early vs. delayed rehabilitation. Individuals that can not be randomized to early rehabilitation including those that are unable to WB on the opposite limb or those that have a skin or soft tissue injury or undergo a surgical procedure that precludes early weightbearing and ROM (i.e. surgery for extensor mechanism rupture or avulsion, vascular graft surgery) are also excluded from participation in this study for Specific Aim 2.

c) The primary and secondary outcomes of the clinical trial were finalized by the investigators and are as follows:

The primary outcome is time to return to full pre-injury military duty, work and sports. Patient-reported physical function as measured with the Activities Limitation Scale of the Multiple Ligament Quality of Life (MLQoL) Questionnaire will be assessed as a secondary primary outcome 6, 12 and 24 months after randomization. To more precisely measure the time to return to pre-injury military duty, work and sports, a brief Return to Activity Monitoring Survey will be administered on a monthly basis starting 6 months after randomization and continuing through the 24-month follow-up. To determine successful return to activity we will compare patient-reported measures of military duty, work and sports to the individual's pre-injury level of military duty, work and sports. Individuals will be classified as having returned to activity if and when they have returned to their pre-injury level of military duty, work and sports.

Secondary outcome measures include additional knee-specific and general patient-reported measures of physical function and health related quality of life, recovery of range of motion (ROM), arthrofibrosis, residual laxity, complications/adverse events, re-injury and additional surgical procedures.

d) The Executive Committee in conjunction with the study investigators developed and agreed upon the definitions for early surgery (repair and/or reconstruction within 6 weeks of injury) and delayed surgery (repair and/or reconstruction 12 to 16 weeks after injury).

e) The Rehabilitation Committee in conjunction with the study investigators developed and agreed upon the early and delayed post-operative rehabilitation guidelines, as well as the universal rehabilitation procedures that will apply to all subjects regardless of group assignment.

3) Finalize Sample Size and Develop Statistical Analysis & Data Management Plan (Task 4)

a) The sample size and statistical analysis and data management plans for the multicenter clinical trial were finalized. As described below, the sample size analyses indicated that 392 subjects are necessary for the trial that randomizes the timing of surgery and rehabilitation and 298 are subjects are needed the trial that randomizes only the timing of post-operative rehabilitation.

Based on our preliminary retrospective study, we estimated that across 23 clinical sites there will be 1213 MLKIs over a 2-year recruitment period. After the exclusions for participation in the trial that randomizes timing of surgery and rehabilitation (*Aim 1*), we estimated that there will be approximately 650 eligible individuals with a MLKI that present to orthopaedics in time to make it possible to perform surgery within 6 weeks if randomized to early surgery. Assuming that approximately 60% of the eligible subjects agree to participate in the study, this would provide a total sample size of 392 (n= 98 per cell). Assuming 10% lost to follow-up over two years, we expect to have 352 subjects (n=88 per cell). This sample size would provide 80%-92% power to detect a 15% absolute difference (α=0.05) at 24 months follow-up in the rate of return to full pre-injury military duty, work and sports for the main effects (n=176 for each arm) for timing of surgery or timing of rehabilitation, assuming the delayed arm has a return rate of 30% to 70%. Additionally, we would have 80% power to detect a 17% to 21% absolute difference between the early surgery/early rehabilitation group (n=88) compared to any of the other 3 groups with rates from 30%-70%. With 176 subjects per main effect arm, we would have 82% power to detect a 15% difference in return to military duty, work and sports (hazard ratio=0.65, 35% improvement in the time to rate of return to duty, work and sports) using a log-rank test assuming two-year accrual, two-year follow-up for each participant, 10% dropout in each arm, and 5% crossover in each arm.

For the MLQoL Questionnaire Activity Limitations Scale, we determined that we would have 80% power to detect a 6.2 point difference at 24 months between early surgery and delayed surgery (or early rehabilitation and delayed rehabilitation) using a two-sided two-sample equal variance t-test (α=0.05, standard deviation=20.8) assuming a 10% attrition rate. This is equivalent to a small effect size of approximately 0.30. We will also have 80% power to detect a 10.2-point difference between the early surgery/early rehabilitation group and any of the other three groups using the same standard deviation and test (α=0.0167 adjustment for multiple comparisons).

For the trial in which subjects are only randomized to early vs. delayed rehabilitation (*Aim 2*), a total of 298 subjects randomized, will provide 79% to 84% power to detect an absolute difference of 15% between the groups assuming the delayed rehabilitation group has a return to military duty, work and sports rate of 65% to 70% and 10% attrition.

b) The data analysis plan for Aims 1 and 2 was also finalized. All analyses will follow the principle of intention-to-treat principle. The primary outcome of return to military duty, work and sports will be assessed at monthly intervals via text message, e-mail, or phone call from 6 to 24 months after randomization. This frequency of measurement will allow us to conduct more precise time to event analysis compared to having discrete time points several months apart. For those participants not returning to full activity and participation, the date of censoring for each participant will be the end of the two year follow up or last contact prior to 4 consecutive months of non-response/no data for this outcome.

For the trial in which subjects are randomized to timing of surgery and timing of post-operative rehabilitation (Aim 1), we will estimate and compare the time to event curves

using Kaplan-Meier estimation and log-rank tests. Although we are not powered for detecting an interaction, we will test the interaction between timing of surgery and timing of rehabilitation using a Cox proportional hazards model prior to looking at main effects. Assuming the interaction is not significant, we will compare the time to return to return to military duty, work and sports for both main effects, adjusting for site and the knee dislocation injury pattern. We will present results using hazard ratios and 95% confidence intervals.

Linear mixed models will be used to compare and test the mean patient-reported physical function across the groups accounting for repeated measurements within patient. The fixed effects of surgery (early vs. delayed), rehabilitation (early vs. delayed), time (baseline, 6, 12, 24 months), the two-way interactions, and the three-way interaction will be placed in the model controlling for site and KD injury pattern. Assuming the 3-way interaction is not significant, we will proceed to test the two-way interactions for surgery*time and rehabilitation*time. If the two-way interaction is significant, we will test the separate treatment effects at 24 months (primary time point of interest) using contrasts. All treatment effects will be presented using adjusted mean differences and 95% confidence intervals.

To determine if early surgery and early rehabilitation is better that the other combinations, we will specifically compare the early surgery/early rehabilitation group to each of the 3 other intervention arms using contrasts in the full models for both the time to event outcome and patient-reported physical function.

We will use similar statistical procedures for analysis of the trial that randomizes only timing of rehabilitation (Aim 2). Time to full return to activity and participation will be estimated using Kaplan Meier curves and log-rank tests will be used to determine differences between the two groups. We will then test the curves adjusting for site and knee dislocation injury pattern using Cox proportional hazards model similar to the analysis in Aim 1. We will use linear mixed models to compare and test the mean patient-reported physical function between the two groups over time accounting for the repeated measurements within patient. The fixed effects of early vs. delayed rehabilitation and time (baseline, 6, 12, and 24 months) and their two-way interaction will be tested adjusting for site and knee dislocation injury pattern.

c) An electronic data management system has been developed by the Data Center at the University of Pittsburgh using the REDCap data capture system. Data collection forms have been built for screening, contact information, demographic and participant information, baseline clinical examination, inclusion/exclusion criteria, patient reported outcomes, surgical findings and procedures, clinic follow-up visit, rehabilitation adherence and assessment of return to activity. Additionally, event driven forms related to adverse events/serious adverse events, change in participant status and protocol deviations have been developed and converted to electronic format in REDCap. The baseline clinical examination and surgical forms underwent pilot testing and the results were used to revise and streamline the forms.

4) Establish Governance Structure to Oversee Study Management (Task 5)

a) The overall governance structure for the clinical trial has been established. This includes the establishment of the Executive Steering Committee as well as the Forms, Publications & Ancillary Studies, Quality Control, Recruitment and Adverse Event Committees.

The Executive Steering Committee consists of 10 members representing military and civilian sites, as well as geographic location. Members of the committee are James Irrgang (Chair), Volker Musahl (Co-Chair), Travis Burns, Christopher Harner, Bruce Levy, Andrew Lynch, Charity Patterson, Brett Owens, Robert Schenck and Daniel Whelan. The Executive Steering Committee provides oversight and direction for the trial. The Committee defined the vision and the scientific goals of the STaR Trial, reviewed and approved the final study protocol. Going forward, the Executive Steering Committee will review any proposed, monitor study progress including recruitment, retention, and site compliance with study procedures, resolve any conflicts that arise between investigators and review and issue final approval or recommend modification for all subcommittee decisions. The Executive Steering Committee met monthly or more frequently over the last year.

The Executive Steering Committee established and defined the purpose, structure and function of the Forms, Publications & Ancillary Studies, Rehabilitation, Quality Control, Recruitment, and Adverse Events Adjudication Committees.

- The Forms Committee drafted a set of forms for use in the proposed trial. Going forward, the Forms Committee will review and approve all form modifications, will regularly review and maintain a current set of approved forms and maintain a log of all form changes throughout the duration of the trial.

- The Publications and Ancillary Studies Committee established the policies and procedures for assigning working groups and approving STaR Trial-associated ancillary studies, secondary analyses of existing data and abstracts, presentations, and publications prior to their submission for dissemination. The Publications and Ancillary Studies Committee also established guidelines for authorship for investigators following the guidelines specified by the International Committee of Medical Journal Editors. The Publications and Ancillary Studies Committee reviewed and approved a manuscript summarizing the post-operative rehabilitation program that was published in Current Reviews in Musculoskeletal Medicine and an abstract summarizing the multicenter retrospective review study of MLKIs that was submitted and accepted for presentation at the 2018 Annual Meeting of the American Academy of Orthopaedic Surgery.

- The Rehabilitation Committee established the guidelines and protocols for early and delayed post-operative rehabilitation protocols that will be investigated in this study. Additionally, the Committee oversaw training and standardization of the rehabilitation procedures at all study sites through the development of training materials and learning modules. The Committee also created materials for home exercise programs as well as procedures to monitor and maximize compliance with

rehabilitation procedures at all sites. The Rehabilitation Committee has established a relationship with MedBridge to assist with training for the physical therapists that will provide the post-operative rehabilitation and to provide the study participants with access to an online home exercise program.

- The Quality Control Committee was established to review and affirm the quality of the conduct of the trial including implementation of the surgical and rehabilitation interventions as randomized. The Quality Control Committee is overseeing implementation of the study protocol, monitoring the study for completion of study procedures and missing data, reviewing loss to follow-up and protocol deviations in aggregate as well as by site and will be responsible for the oversight of site monitoring visits.

- The Recruitment Committee was established to create recruitment materials and to monitor recruitment and follow-up throughout the duration of the trial. Additionally, should a site be recruiting fewer subjects than expected, the committee will evaluate the site and make recommendations to improve recruitment or termination of the site.

- The Adverse Events Adjudication Committee was defined and includes three individuals external to the study investigators: Dr. Kurt Spindler, MD from the Cleveland Clinic and Dr. Kelley Fitzgerald, PT, PhD, FAPTA, and Susan Spillane, RN, CCRP, both at University of Pittsburgh. They will be responsible for reviewing and adjudicating any and all adverse events.

5) Develop Clinical and Safety Monitoring Plan (Task 6)

a) A Clinical Monitoring Plan has been established to create guidelines for and to conduct site monitoring visits and related tasks for monitoring the STaR Trial. As the Clinical Coordinating Center, the University of Pittsburgh will be responsible for Clinical Monitoring Plan under the leadership of Dr. Alexandra Gil, Co-Investigator and Quality Control Coordinator, and Maria Beatriz Catelani, Project Coordinator, in collaboration with Drs. Irrgang (Principal Investigator), Musahl (Co-Principal Investigator and Qualified Clinical Investigator for Surgery) and Lynch (Co-Investigator and Qualified Clinical Investigator for Rehabilitation) as well as Dr. Charity Patterson, (Co-Investigator and Director of the Data Coordinating Center). Dr. Gil and Ms. Catelani will serve as the Clinical Trial Monitors. The intent of the Clinical Monitoring Plan is to ensure compliance with the research protocol, the International Conference on Harmonization (ICH) Good Clinical Practice Guidelines, national and local regulations, and institutional policies across all sites. The focus of the Clinical Monitoring Plan includes: 1) site assessment review and staff training; 2) human subjects' protection; 3) protocol compliance; 4) regulatory compliance; 5) quality assurance; 6) adverse event reporting; and 7) integrity of research data. Implementation of the Clinical Monitoring Plan will include continuous year-round remote monitoring, such as review of electronic records and regular communication with Research Coordinators (e.g. biweekly phone calls) and annual on-site monitoring visits.

b) A Data and Safety Monitoring Plan (DSMP) has been developed to oversee the conduct of the study and to ensure integrity of the data and safety and protection of subjects. An independent Data and Safety Monitoring Board (DSMB) was convened to implement the DSMP. Logistical support for the DSMB will be provided by the University of Pittsburgh Clinical and Translational Science Institute. The DSMB consists of 7 individuals who have no financial, scientific, or other conflicts of interest with the trial and will include 3 orthopaedic surgeons and 3 physical therapists, one each representing military, Canadian and US civilian interests and a biostatistician. Prior to the start of recruitment, the DSMB reviewed the research protocol, informed consent documents and plans for data and safety monitoring and issued approval for the start of enrollment into the study. After enrollment begins, the DSMB will meet every 6 months to evaluate progress of the trial, consider factors external to the study, review clinical center performance, protect and report on safety of the subjects, monitor confidentiality of the trial and make recommendations concerning continuation, termination or other modifications of the trial. Templates for open and closed reports for the DSMB have been developed.

c) The STaR Trial has been designated greater than minimal risk. As such it was determined that a Research Monitor would be necessary. Dr. John Fowler, an orthopaedic surgeon with sub-specialization in hand and upper extremity surgery, has agreed to serve as the Research Monitor. Duties of the Research Monitor include oversight of study interactions or interventions, data collection, data storage and analysis, and review of monitoring plans and unanticipated problems involving risk to participants or others. The Research Monitor will consult on individual cases as necessary and will review and evaluate adverse event reports. The Research Monitor may discuss the research protocol with the investigators, interview subjects, consult with others outside of the study about the research and will promptly report any discrepancies or problems to the IRB. Site-specific Research Monitors may also be appointed to observe local subject recruitment, enrollment and/or the consent process. The Research Monitor will have the authority to stop the research study in progress, remove individuals from a study, and/or take any steps to protect the safety and well-being of subjects until the IRB can make an assessment.

6) Develop Site Monitoring Plan (Task 7)

a) The Clinical Monitoring Plan that was described above includes four types monitoring visits including a Site Initiation Visit, Interim Visits, For-Cause Visits and Study Close-Out Visit. The Site Initiation Visit will occur prior to site activation once IRB and Human Research Protections Office (HRPO) approvals and all subcontracts and agreements are in place. During the Site Initiation Visit preparedness of the site to execute the research protocol will be confirmed and any necessary training will be provided.

b) The first Interim Visit will be conducted remotely for each site after 2 to 3 subjects have been enrolled and followed for 3 to 6 months. Subsequent Interim Visits will be onsite and conducted annually. These visits will ensure that the subjects' rights are being protected, the study is being conducted according to the protocol and applicable regulations and that the interventions, subject safety data and study endpoints are being

accurately reported.

c) For-Cause Visits will be conducted to address any unanticipated issues that arise which require training, remediation or other situations for which the site requires assistance. For-Cause Visits will be conducted remotely or on-site if mandated by the Quality Control Coordinator, PI, or Director of the Data Coordinating Center.

d) The Close-Out Visit will be conducted to ensure that all study data and other study documentation is complete and accurate and that all study records have been reconciled. Close-Out Visits will be conducted at the completion of the study or earlier in the case of termination of the site's participation in the study or termination of the study overall.

7) Develop Transition Plan to Move to Clinical Trial (Task 8)

a) Data collection forms were developed for recording clinical findings, surgical findings and procedures, patient reported outcome measures, adverse events, complications, and subject tracking. All forms have been converted to electronic format for a web-based electronic data capture system using REDCap. Testing and debugging the electronic data capture system were completed in April 2018 under the approved no cost extension period.

b) A Clinical Protocol, Manual of Operations and related training materials were developed and reviewed. The Clinical Protocol was approved by the DSMB and distributed to the clinical sites in May 2018 under the no cost extension that has been approved.

c) The University of Pittsburgh Institutional Review Board (IRB) is serving as the single IRB of record for all US military and civilian sites. The SMARTIRB process was used to facilitate the execution of the reliance agreements with the US civilian sites. Separate reliance agreements with the US military sites were established. The University of Pittsburgh IRB can not serve as the IRB of record for the Canadian sites and as such, each Canadian site will need to obtain local IRB approval for the study. Initial IRB approval at the University of Pittsburgh was obtained in December 2017. At that time, the protocol and consent forms were submitted to the Department of Defense for review and approval by the Human Research Protections Office (HRPO). Following HRPO approval, any necessary modifications in the protocol or consent forms were submitted to the University of Pittsburgh IRB. The IRB protocol and template of the consent forms submitted to all of the sites for their review, consideration and adoption.

d) Additional activities that were completed during the no cost extension included completion and testing of the electronic data capture system for the study, translation of patient-facing study materials (recruitment flyers, screening and verbal consent forms, informed consent forms and all patient-reported measures) into Spanish and completion of the clinical protocol and manual of operations.

8) Prepare and Submit Application for CTA to Conduct Trial (Task 9)

a) The full application for the Integrated Clinical Trial Award (Funding Opportunity: W81XWH-16-PRORP-ICTA) was submitted on December 6, 2016. The investigators received notice that the DoD intended to fund the project on May 30, 2017, pending appropriate responses to the scientific and administrative review. The final notice of the award, indicating approval of the project was received September 30, 2017.

What opportunities for training and professional development has the project provided?

Nothing to report.

How were the results disseminated to communities of interest?

Nothing to report.

What do you plan to do during the next reporting period to accomplish the goals?

Nothing to report.

4. IMPACT

What was the impact on the development of the principal discipline(s) of the project?

The results of this Clinical Trial Development Award led to the successful submission and approval of STaR Trial which is a 25-site multicenter randomized trial to evaluate the effects of timing of surgery and post-operative rehabilitation on time to return to pre-injury military duty, work and sports activity.

Successful completion of the STaR Trial will provide high-level evidence to set standards for improved treatment of MLKIs in military personnel and civilians. In doing so, the STaR Trial has the potential to challenge the belief that surgery must be delayed to reduce the risk of limited range of motion (ROM) and joint contracture and that rehabilitation must be delayed to prevent disruption of the repaired and reconstructed tissues. The principles of early anatomical repair and reconstruction of injured structures and early initiation of post-op rehabilitation are directly translatable to the military medical system and have the potential to improve the military standard of care for these devastating injuries, positively influencing unit readiness and return to duty capabilities. Ultimately, the results of these trials may enable us to determine those MLKIs that are best treated with early surgery and rehabilitation while other injury patterns may be better served with delayed treatment. Additionally, the primary outcome of return to military duty, work and sports is of primary interest and highly relevant to unit readiness and return to duty capabilities. Long-term follow-up (5 and 10 years) of individuals enrolled in this study will enable us to determine the effects of timing of surgery and timing of rehabilitation on the development of early PTOA, which is a burden for a large number of military personnel and the most common reason for disability-related medical separation from military service.

What was the impact on other disciplines?

Nothing to report.

What was the impact on technology transfer?

Nothing to report.

What was the impact on society beyond science and technology?

Nothing to report.

5. CHANGES/PROBLEMS

Changes in approach and reasons for change.

Nothing to report.

Actual or anticipated problems or delays and actions or plans to resolve them.

A one-year No Cost Extension was requested and granted to complete the planning activities that were necessary to initiate the STaR Trial. The activities that were performed under the No Cost Extension included completion and testing of the electronic data capture system for the study, translation of patient-facing study materials (recruitment flyers, screening and verbal consent forms, informed consent forms and all patient-reported measures) into Spanish and completion of the clinical protocol and manual of operations. Completion of these activities contributed to the timely implementation of the STaR Trial.

Changes that had a significant impact on expenditures.

Nothing to report.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents.

Nothing to report.

Significant changes in use or care of human subjects.

Nothing to report.

Significant changes in use or care of vertebrate animals.

Nothing to report.

Significant changes in use of biohazards and/or select agents.

Nothing to report.

6. PRODUCTS

Publications, conference papers, and presentations.

Journal publications.

Lynch AD, Chmielewski T, Bailey L, Stuart M, Cooper J, Coady C, Sgroi T, Owens J, Schenck R, Whelan D, Musalk V, Irrgang JJ and the STaR Trial Investigators. Current Concepts and Controversies in Rehabilitation after Surgery for Multiple Ligament Knee Injury. Current Reviews in Musculoskeletal Medicine; 2017 Sep; 10(3): 328–345. (Funding from DoD Congressionally Directed Medical Research Program Acknowledged)

Books or other non-periodical, one-time publications.

Nothing to report.

Other publications, conference papers, and presentations.

Irrgang JJ, Lynch AD, Burns TC, Harner CD , Levy BA, Owens BD, Schenck RC, Musahl V, Oostdyk AM, Popchak, AJ, Burnham JM, Patterson CM, Getgood A, Hodax J, Cooper JM, Ranawat AS, Marx RG, Coady CM, Wong IH, Macalena JA, Nelson BJ, Arciero RA, Edgar C, Cote M, Johnson DL, Jacobs C, Richter D, Treme G, Veitch AJ, Wascher DC, Black BS, Bailey L, Miller MD, Hart J. Mechanism, Presentation, Injury Pattern and Associated Injuries for Multiple Ligament Knee Injuries: A Multicenter Study from the Surgical Timing and Rehabilitation (STaR) Trial for MLKIs Network. American Academy of Orthopedic Surgeons Annual Meeting; New Orleans, LA; March 2018.

Website(s) or other Internet site(s).

Nothing to report.

Technologies or techniques.

Nothing to report.

Inventions, patent applications, and/or licenses.

Nothing to report.

Other Products.

Nothing to report.

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?

Name:	James Irrgang
Project Role:	Principal Investigator
Nearest person month worked:	1
Contribution to Project:	Dr. Irrgang was responsible for overseeing and ensuring completion of all planning activities that were conducted during this CTDA.

Name:	Volker Musahl
Project Role:	Co-Investigator
Nearest person month worked:	1
Contribution to Project:	Dr. Musahl was instrumental in developing and refining the subject eligibility criteria, developing the surgical protocol and developing and testing the surgical forms that will be utilized during the STaR Trial. He has participated in the monthly conference calls.

Name:	Andrew Lynch
Project Role:	Co-Investigator
Nearest person month worked:	1
Contribution to Project:	Dr. Lynch was instrumental in developing the rehabilitation procedures for the STaR Trial. Additionally, he contributed to the planning of the study, including the study design, eligibility criteria, methods for assessing outcomes and fidelity of the rehabilitation interventions. He also contributed to the writing of the grant application and the Manual of Operations and Procedures.

Name:	Charity Moore Patterson
Project Role:	Co-Investigator
Nearest person month worked:	1
Contribution to Project:	Dr. Patterson has been instrumental in assisting with the study design, data analysis plan and sample size calculations for the full clinical trial application. In addition, she oversaw the development of the electronic data capture system at the Physical Therapy Data Center at the University of Pittsburgh, where she serves as the director.

Name:	Alicia Oostdyk
Project Role:	Project Coordinator
Nearest person month worked:	3
Contribution to Project:	Ms. Oostdyk participated in the calls during the planning of the STaR Trial from the receipt of the CTDA until July 2017, at which time she left to pursue a PhD degree. She made substantial contributions to grant application and has worked with Dr. Moore-Patterson to generate the initial drafts of the case report forms.

Name:	Maria Beatriz Catelani
Project Role:	Project Coordinator
Nearest person month worked:	3
Contribution to Project:	Ms. Catelani participated in the monthly conference calls during the no cost extension period in 2018. She made substantial contributions to Clinical Protocol and Manual of Operations and Procedures. Additionally she worked with Dr. Patterson to test the case report forms and the REDCap electronic data system.

Name:	Megan Dalzell
Project Role:	Project Coordinator
Nearest person month worked:	3
Contribution to Project:	Ms. Dalzell participated in the monthly conference calls during the no cost extension period in 2018. She made substantial contributions to IRB application and served as the primary contact person site investigators and research coordinators.

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to report

What other organizations were involved as partners?

Organizations Originally Included in Clinical Trial Development Award:

Organization Name: Brown University
Location of Organization: Providence, RI, USA
Partner's contribution to the project: Collaboration and Other: data

Organization Name: HealthPartners
Location of Organization: Minneapolis, MN, USA
Partner's contribution to the project: Collaboration and Other: data

Organization Name: Hospital for Special Surgery
Location of Organization: New York City, NY, USA
Partner's contribution to the project: Collaboration and Other: data

Organization Name: Keller Community Army Hospital
Location of Organization: West Point, NY, USA
Partner's contribution to the project: Collaboration and Other: data

Organization Name: Mayo Clinic
Location of Organization: Rochester, MN, USA
Partner's contribution to the project: Collaboration

Organization Name: Nova Scotia Health Authority
Location of Organization: Halifax, ON, Canada
Partner's contribution to the project: Collaboration and Other: data

Organization Name: St. Michael's Hospital
Location of Organization: Toronto, ON, Canada
Partner's contribution to the project: Collaboration and Other: data

Organization Name: San Antonio Military Medical Center
Location of Organization: San Antonio, TX, USA
Partner's contribution to the project: Collaboration and Other: data

Organization Name: TRIA/University of Minnesota
Location of Organization: Minneapolis, MN, USA
Partner's contribution to the project: Collaboration, and Other: data

Organization Name: Tripler Army Medical Center
Location of Organization: Honolulu HI, USA
Partner's contribution to the project: Collaboration

Organization Name: University of Connecticut
Location of Organization: Storrs, CT, USA
Partner's contribution to the project: Collaboration, and Other: data

Organization Name: University of Kentucky
Location of Organization: Lexington, KY, USA
Partner's contribution to the project: Collaboration, and Other: data

Organization Name: University of New Mexico
Location of Organization: Albuquerque, NM, USA
Partner's contribution to the project: Collaboration, and Other: data

Organization Name: University of Virginia
Location of Organization: Charlottesville, VA, USA
Partner's contribution to the project: Collaboration, and Other: data

Organization Name: Walter Reed National Military Medical Center
Location of Organization: Bethesda, MD, USA
Partner's contribution to the project: Collaboration

Organization Name: Washington University in St. Louis
Location of Organization: St. Louis, MO, USA
Partner's contribution to the project: Collaboration

Organization Name: Western University / Fowler Kennedy Sports Medicine Clinic
Location of Organization: London, ON, Canada
Partner's contribution to the project: Collaboration, and Other: data

Organization Name: William Beaumont Army Medical Center
Location of Organization: El Paso, TX, USA
Partner's contribution to the project: Collaboration

Organizations added to STaR Trial Network during the period of the Clinical Trial Development Award:

Organization Name: University of Cincinnati
Location of Organization: Cincinnati, OH, USA
Partner's contribution to the project: Collaboration

Organization Name: University of Michigan
Location of Organization: Ann Arbor, MI, USA
Partner's contribution to the project: Collaboration

Organization Name: University of Washington
Location of Organization: Seattle, WA, USA
Partner's contribution to the project: Collaboration

Organization Name: Wake Forest University
Location of Organization: Salem, NC, USA
Partner's contribution to the project: Collaboration

Other Organizations:

Organization Name: MedBridge
Location of Organization: Seattle, WA, USA
Partner's contribution to the project: Other: in kind services for internet-based platform for training of physical therapists in study rehabilitation procedures and access to a home exercise program for study participants

8. SPECIAL REPORTING REQUIREMENTS

***Collaborative Awards*:**

Nothing to report.

***QUAD Charts*:**

Nothing to report.

9. APPENDICES:

See attached Appendix

Mechanism, Presentation, Injury Pattern and Associated Injuries for Multiple Ligament Knee Injuries: A Multicenter Study from the Surgical Timing and Rehabilitation (STaR) Trial for MLKIs Network

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[1]University of Pittsburgh, [2]University of Texas at Houston, [3]Mayo Clinic, [4]University Orthopedics, [5]UPMC Rooney Sports Medicine Complex, [6]Carolinas HealthSystem, [7]Fowler Kennedy Sport Medicine Clinic, [8]Brown University School of Medicine, [9]Orthopaedics & Sports Medicine, [10]Hosp for Special Surgery, [11]Veteran's Memorial Bldg, [12]University of Minnesota, [13]Univ of CT Health Center, [14]University of Connecticut, [15]UCONN Hlth Ctr, [16]Kentucky Clinic, [17]University of Kentucky, [18]University of New Mexico, [19]Department of Orthopaedics & Rehabilitation, [20]Ironman Sports Medicine Institute, [21]University of Virginia

INTRODUCTION:

Multiple ligament knee injuries (MLKIs) represent a spectrum of injury from disruption of two ligaments to complete dislocation of the knee with disruption of both cruciates and collateral ligaments. MLKIs are often associated with concomitant tendon avulsions/ruptures, compromised nerve or vascular function and fractures. Treatment of MLKIs is complex and post-operative complications are frequent. However, there has not been a large, multicenter study of the presentation and treatment of these injuries. The purpose of this multicenter retrospective study was to determine the mechanism of injury, timing of presentation, injury pattern and associated injuries for MLKIs.

METHODS: This was a retrospective review of MLKIs that occurred between 2012 and 2014. Cases with a MLKI, defined as a grade III (complete tear) of two or more ligaments that underwent surgical repair or reconstruction were included. An electronic case report form was developed and pilot tested to capture demographic information (age, sex, BMI); date and mechanism of injury; date of presentation to an orthopaedic surgeon and surgery; ligament injury pattern; associated injuries to bone, menisci, cartilage, tendons, nerves, vessels and skin/soft tissue; surgical procedures and complications. Injury pattern was defined in terms of the Knee Dislocation (KD) Grade. Data were summarized with frequencies (percentages), means (standard deviations [SD]) and medians (inter-quartile ranges [IQR]), where appropriate.

RESULTS:

999 individuals from 13 centers that underwent surgery for the treatment of a MLKI were reviewed. Average age of the subjects was 29.7 yrs. (SD 12.7 range 14 to 72) years, 70.7% were males. The most common mechanism of injury was sports (47.2%) followed by motor vehicle accident (22.3%) and 24.8% of the patients had associated polytrauma. The median time from injury to presentation to the orthopaedic surgeon was 9 days (IQR 2 – 35), median time from injury to surgery was 47 days (IQR 20 to 136). The most common injury pattern was a single cruciate tear combined with injury of the posteromedial corner (PMC) or posterolateral corner (PLC) (KD-I) (65.4%). A bicruciate injury with injury to the PMC (KD-III M), PLC (KD-III L) or PMC and PLC (KD-IV) accounted for 11.2%, 12.7% and 3.9% of MLKIs, respectively. Only 2.6% of the MLKIs involved a periarticular fracture (KD-V). Associated injuries involved tendons (11.9%), nerves (11.2%), skin/soft tissue (10.6%) and vasculature (3.4%). External fixators were most commonly used with KD-IV (36.8%), KD-III L (19.4%) and KD-V (20.0%) injuries. Staged procedures were performed most commonly for KD-III L (24.2%), KD-IV (37.1%) and KD-V (21.7%) injuries. Repair or reconstruction of the injured ligamentous structures at the time of initial surgery and subsequent surgeries are summarized in Table 1. Intra-operative complications were rare (<1%). Loss of motion (6.3%) and infection (2.8%) were the most common post-operative complications. Additional surgeries, beyond the definitive stabilization procedure were performed for 7.8% of the cases.

DISCUSSION AND CONCLUSION: The most common MLKI pattern was injury to a single cruciate with PMC or PLC injury, however 32% of the injuries were bicruciate injuries with or without injury to the PMC and/or PLC. The most common associated injuries involved tendons, nerves or skin/soft tissue. External fixators were most commonly used with KD-III L, KD-IV and KD-V injuries. This retrospective study illustrates the variability and complexity of MLKIs. The results of this study may be used to plan randomized trials to determine the optimal timing of surgery and post-operative rehabilitation for MLKIs.

Table 1 – Repair or Reconstruction of Injured Ligamentous Structure at Time of Initial Injury & Subsequent Surgeries

		Initial surgery				
	No Injury	Repair	Recon.	Non-Op Treatment	Repair or Reconstruction at Subsequent Surgery	Undefined Injury & Treatment in Record (Missing)
ACL	99	8	655	45	80	1
PCL	417	16	289	66	56	31
MCL	336	112	157	101	24	72
LCL	541	38	89	28	41	90
PLC	453	47	252	46	64	202
PMC	643	37	39	71	8	344

Current Concepts and Controversies in Rehabilitation After Surgery for Multiple Ligament Knee Injury

The STaR Trial Investigators

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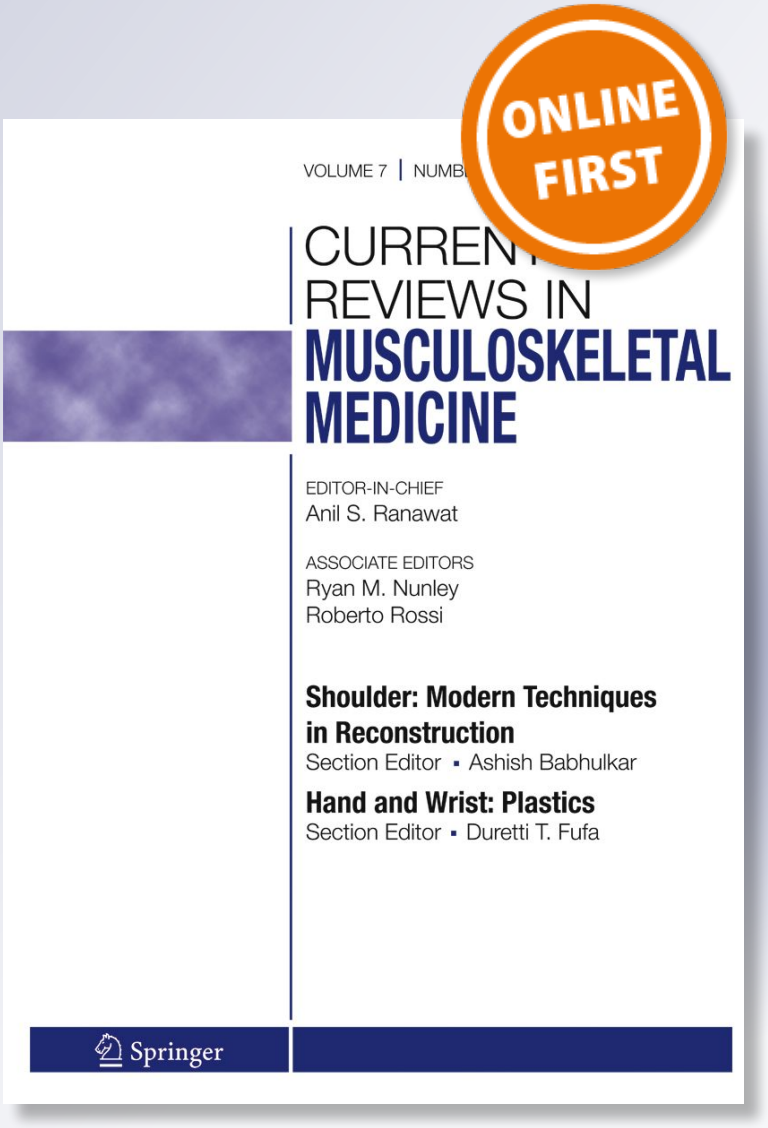

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Current Concepts and Controversies in Rehabilitation After Surgery for Multiple Ligament Knee Injury

Andrew D. Lynch[1] · Terese Chmielewski[2] · Lane Bailey[3] · Michael Stuart[4] · Jonathan Cooper[5] · Cathy Coady[6] · Terrance Sgroi[7] · Johnny Owens[8] · Robert Schenck[9] · Daniel Whelan[10] · Volker Musahl[11] · James Irrgang[1] · The STaR Trial Investigators

Abstract

Purpose of Review The purpose of this manuscript is twofold: (1) to review the literature related to rehabilitation after surgery for multiple ligament knee injury (MLKI) and after isolated surgery for the posterior cruciate ligament (PCL), posterolateral corner (PLC), and medial side of the knee and (2) to present a hierarchy of anatomic structures needing the most protection to guide rehabilitation.

Recent Findings MLKIs continue to be a rare but devastating injury. Recent evidence indicates that clinicians may be providing too much protection from early weight bearing and range of motion, but an accelerated approach has not been rigorously tested.

Summary Consideration of the nature and quality of surgical procedures (repair and reconstruction) can help clinicians determine the structures needing the most protection during the rehabilitation period. The biomechanical literature and prior clinical experience can aid clinicians to better structure rehabilitation after surgery for MLKI and improve clinical outcome for patients.

Keywords Multiple ligament knee injury · Post-surgical rehabilitation · Knee dislocation · Early weight bearing · Early range of motion

This article is part of the Topical Collection on *ACL Rehab*

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Introduction

Multiple ligament knee injuries (MLKIs), including knee dislocations, represent a spectrum of injury ranging from disruption of two ligaments (one cruciate ligament and one collateral ligament) to all four ligaments (both cruciates and both collateral ligaments). These injuries are potentially devastating and are often associated with significant injury to multiple structures of the knee including the ligaments, capsule, tendons, menisci, chondral surfaces, bone, nerves, and blood vessels [1–5]. While multiple studies have reported treatment algorithms and outcomes for MLKIs, many of these studies are retrospective in nature with small sample sizes. Only a few prospective studies have been published, and to date, there are no randomized controlled studies that have investigated optimal treatment methods for these complex knee injuries.

The lack of high-level evidence related to treatment of MLKIs is due to both the heterogeneity of the injury and the relatively low incidence of MLKIs compared to isolated ligament injury. The incidence of ACL injuries ranges from 0.31 to 0.69 per 1000 person-years [6, 7]. The incidence of MLKIs in the general population has

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not been precisely reported; however, in civilians with an orthopedic injury, the incidence of a MLKI has recently been estimated to be 0.072 per 100 patient-years [8].

Operative management is superior to non-operative management for MLKIs [9••, 10–12]. Patients treated surgically are significantly more likely to return to work [13, 14] and sports [9••, 14, 15]. Furthermore, patients who underwent operative treatment for MLKI have been shown to develop end-stage arthritis less frequently and have reported superior patient-reported outcome scores than their peers who underwent non-operative management [9••]. However, there is controversy over the optimal time to perform surgery (early versus late) [11, 16, 17••] and, specifically, which surgical procedures should be performed (repair versus reconstruction) [18••, 19–22].

The variability in surgical procedures has resulted in a relative paucity of studies investigating the timing and composition of rehabilitation protocols. As a result, this issue has been poorly understood and remains the subject of intense debate. Early motion and weight bearing after surgery presents a perceived risk to the individual as it is thought to negatively affect healing and long-term joint stability of surgically repaired or reconstructed tissues [23–26]. However, some experts recommend early motion to prevent scar tissue from limiting joint motion and to lessen the impact of muscle atrophy [19, 27, 28], while others propose a hybrid approach. Results from a systematic review of clinical trials indicate that delayed rehabilitation runs the risk of poorer patient-reported and knee-related outcomes [17••].

Surgically repaired tissues need significant protection to prevent disruption. Repair of the medial or posterolateral corner (PLC) structures relies on suture fixation of soft tissues to bone, which must be protected from excessive forces to prevent failure [18••, 19, 29]. Repair or reconstruction of the posterior cruciate ligament (PCL) or PLC may be overly stressed by posterior translation, varus, and/or external rotation of the tibia, which can be caused by gravity or hamstring contraction [30–33]. In contrast, the anterior cruciate ligament (ACL) is typically reconstructed by placement of a graft through bone tunnels with the use of hardware that provides good graft security that should not be disrupted by early weight bearing (WB), early motion, or early exercise [34].

While protection after MLKI surgery is important to allow the surgically repaired or reconstructed tissues to heal, massive injuries and complicated surgeries are more likely to develop knee joint stiffness, loss of motion, and arthrofibrosis [17••]. The balance between protection from disruption and prevention of motion loss often favors over-protection, resulting in potentially more motion loss.

The combination of variable procedures and recommendations with the relative scarcity of these injuries results in many rehabilitation professionals being directed to treat every patient in a different manner. Therefore, the purpose of this manuscript is twofold:

1. To review the literature related to rehabilitation after surgery for MLKI and after isolated surgery for the PCL, PLC, and medial-sided knee injuries.
2. To present a hierarchy of structures needing the most protection to guide rehabilitation.

Rehabilitation Controversies After Surgery for MLKI

There have been no comparative clinical trials to determine the optimal timing of rehabilitation after surgery for MLKI. However, Mook and colleagues [17••] systematically reviewed the available literature through 2008 concerning both the timing of operative intervention and post-operative rehabilitation. Early surgery and immediate motion resulted in fewer instances of posterior instability, varus laxity, valgus laxity, flexion loss greater than 10°, extension loss greater than 5°, and poorer outcome scores compared to early surgery and delayed rehabilitation [17••]. These results are specific to the mobility component of rehabilitation as "early mobility" was defined as allowing for greater than 30° of knee motion prior to 3 weeks after surgery. Therefore, it is not reasonable to compare early motion and WB with a strict immobilization protocol after surgery for MLKI. However, many reports still advocate up to 3 weeks of immobilization in extension, limited in motion [35–40], or motion controlled by a continuous passive motion device [41, 42].

Many reports call for an extended period of non-weight bearing (NWB) after surgery for MLKI ranging from 4 to 6 weeks after surgery [35–38, 41, 43, 44, 45••]. Very few protocols recommend WB as tolerated (WBAT) [39], while others recommend early partial WB (PWB) [5, 9••, 19, 33, 40, 42, 46] or toe-touch WB (TTWB) [47–49].

Recommendations for rehabilitation after surgery for MLKI are variably described and likely differ based on the tissues involved (Table 1). Low-impact activities such as stationary cycling are initiated at various times after surgery ranging from 6 to 12 weeks [39, 40, 44, 59, 61, 62]. Initiation of resisted hamstring exercise has been reported to start at various times, most often from 8 to 16 weeks depending on the involvement of PCL injuries and/or other posterior structures (i.e., PLC, hamstrings, joint capsule) [5, 23, 27, 33, 40, 42, 43, 45••, 57, 59, 60]. Initiation of impact activities, such as running, is also variable, ranging from initiation at 3 to as late as 10 months [5, 27, 33, 40, 44, 46, 47, 59, 62]. Full activity has been typically promoted between 8 and 12 months from surgery [5, 23, 27, 33, 37, 40–43, 54, 45••], but may be

Table 1 Rehabilitation Recommendations from the Literature Concerning Initiation of Rehabilitation and Gait Activities

Author	Population	Initiation of ROM	Initiation of WB	Initiation of HS Ex	Initiation of WB LE TE	Initiation of NWB LE TE	Notes
Edson, 2006 [26]	MCL (combined with ACL)	Weeks 0-3: locked in extension Week 3+: ROM as tolerated Week 6 goal: 90 to 120	Weeks 0-6: NWB Weeks 6-10: Add 25% BW per week Week 10: transition to functional brace	NR	Week 10+	Week 0: quadriceps isometrics and SLR, NMES	
LaPrade, 2012 [50]	Medial Side	Weeks 0-2: PROM extension to max flexion within safe zone Week 2 Goal: 90 Week 2+: as tolerated Week 6 Goal: 130	Weeks 0-6: NWB; braced unless exercising Week 6+: WBAT with crutches, brace unlocked per quadriceps control	Weeks 2 to 6	Week 6: WB TE including 70° knee flexion on leg press	Week 0: quadriceps sets, SLR (flex, abd, ext) Prohibited through week 12; unclear as to when to initiate	"Safe zone" for ROM determined intra-operatively as the allowable tissue tension immediately after surgery; Goal is 0 to 90
Chhabra, 2005 [51]	MLKI	Week 0-4: Locked in extension Week 0: PROM extension Week 2: PROM to 90 with tibial support Week 6+: A/PROM and stretching initiated	Week 0-4: PWB and progress to FWB	Week 6: active flexion Week 12: resisted flexion		Week 0: quadriceps isometrics Week 4: NWB quads from 75 to 60	
Cole, 1999 [52]	MLKI	Week 0: PROM with tibial support 6 months Goal: Full ROM	Weeks 0-4: NWB with knee locked in extension Week 4+: WBAT (unless PLC involved then PWB until 12 weeks)	12 weeks		Week 0: quadriceps isometrics	
Edson, 2011 [38]	MLKI	Weeks 0-5: brace locked in extension 24h/day Week 10 Goal: 100 Week 24 Goal: 120	Weeks 0-5: NWB with brace locked Weeks 6-10: Initiate WB, add 20% BW per week to FWB at 10 weeks			Weeks 0-5: quadriceps isometrics, NMES Weeks 6-10: Isometrics at 60° with NMES Week 16+: full quadriceps strengthening	
Engebretsen, 2009 [42]	MLKI	Weeks 0-4: locked in extension, 2h/day of CPM from 0 to 60 (or PROM in prone) Week 4 goal: 90° Week 8: d/c brace & increase ROM exercise	Weeks 0-4: PWB with crutches Week 8+: FWB	Week 8	Week 8	Week 0: quadriceps isometrics and SLR in brace; otherwise – NR	
Eranki, 2010 [53]	MLKI	Weeks 0 to 4 Goal: achieve maximum possible ROM	NR	NR	NR	NR	Week 4+: strength exercises Month 3: light activity
Fanelli, 2011 [54]	MLKI	Weeks 0-5: Braced in extension Weeks 5-10: Progressive ROM Week 10: d/c post-op brace, transition to PCL brace	Weeks 0-5: NWB locked in extension	NR	Week 11	NR	
Harner, 2004 [40]	MLKI	Week 0: full extension Weeks 2-6: passive flexion with tibial support to 90; If PLC involvement: limit to 0 Week 12 goal: symmetrical flexion; Flexion <90 between 8-12 weeks - MUA	Week 0: PWB with brace locked in ext; Week 4-6: WBAT, brace unlocked Brace d/c when 90° flexion achieved; Crutches d/c @ 6-8 weeks pending swelling, ROM	6 weeks: active knee flexion 12 weeks: resisted knee flexion	Between weeks 4 and 6	Week 0: isometric extension to restore SLR without lag; NMES in extension; Week 4+: LAQ 75°-60°; 6 weeks: AROM/PROM, stretching	Refers to Irrgang, 2000 #689
Hubert, 2011 [28]	MLKI			NR	Weeks 4-6	Months 5-6	

Table 1 (continued)

Author	Population	Initiation of ROM	Initiation of WB	Initiation of HS Ex	Initiation of WB LE TE	Initiation of NWB LE TE	Notes
		Week 0-2: unlocked brace except for ambulation Week 6 Goal: 0 to 90	POD 1: WBAT with crutches in brace Week 6 Goal: Relatively normal gait; d/c brace when achieved				
Irrgang, 2000 [33]	MLKI	Week 1 Goal: full extension, 0° if PCL or PLC involved Week 4 Goal: 90° flexion Week 8 to 12 Goal: Full ROM	Week 0: PWB with crutches and brace locked in extension Week 6: WBAT (generally) D/c crutches when 90° flexion, full extension, no lag, normal gait	Avoid if HS contraction will stress surgery site; 12 weeks otherwise	Weeks 4 to 6	Week 0: quadriceps isometrics, SLR, NMES	
Jenkins, 2011 [45••]	MLKI	Weeks 0 – 6: hinged knee brace from full extension to 90°	Weeks 0-4: NWB Weeks 4-6: PWB Week 6+: progress to FWB	Weeks 0-6: If PCL involved, no active flexion 8 weeks: WB and isometric 12 weeks: isotonic	Week 6+: leg press, calf raise, mini squat	Week 0-2: quadriceps isometrics, prone SLR; Week 2-6: AAROM flexion, hip, calf, quadriceps isometrics Week 6+: NWB PREs for quad	
Lachman, 2015 [55]	MLKI	Week 0-6: 0 to 90	NR	NR	NR	NR	
Noyes, 1997 [27]	MLKI	Week 0-4: 10-90; split cylinder cast when not exercising Week 5-8: 0 – 110; hinged brace used Week 9-12: 135 No hyperextension for 6 months	Weeks 0-4: TTWB Weeks 4-6: 25# WB, slow advancement to FWB by week 12 with weaning of crutches	Week 12	Week 4: mini-squats	Weeks 0-4: quadriceps isometrics, SLR, NMES Week 8: PREs initiated	
Owens, 2007 [41]	MLKI	POD1: CPM 0 to 30, progress to 90 by POD10 8 Week Goal: 120 Week 12: MUA if not 0-120	Weeks 0-8: NWB Weeks 8-12: PWB with crutches Week 12+ Goal: WBAT without crutches	Avoid weeks 0-4; Week 4: begin HS co-contraction	Week 12	Week 16-24	
Rinh 2004 [25]	MLKI	Week 0-4: Locked in extension Week 2-6: PROM with PT, limited to 90 12 weeks: Goal is full PLC involvement: 0° stop in place Weeks 8-12: MUA if flexion is less than 90°	Week 0-4: PWB with brace locked in extension & progress to WBAT; Week 4-6: WBAT, brace unlocked If lateral repair or reconstruction: PWB and locked in extension for 8 weeks Brace d/c when 90° flexion achieved; Crutches d/c @ 6-8 weeks (pending strength, ROM, ambulatory ability)	6 weeks: Avoid active flexion (hamstring contraction) & WB HS TE 12 Weeks: No OKC flexion for 12 weeks		Week 0: isometric extension to restore SLR without lag; NMES in extension; Week 4+: LAQ 75°-60°; 6 weeks: AROM/PROM, stretching	Refers to Irrgang, 2000 #689
Skendzel, 2012 [23]	MLKI	Week 0: patellar mobilization Week 6 goal: 90° flexion Week 12 goal: 120° flexion	Weeks 0-6: NWB Weeks 0-3: brace locked in extension Initiation of PWB depends on muscle control, increase by 25% BW	12 weeks	Used until (70% quad symmetry)	Week 0: isometrics & NMES to enhance quad recruitment	Activities gradually increased from 4 to 6 months

Table 1 (continued)

Author	Population	Initiation of ROM	Initiation of WB	Initiation of HS Ex	Initiation of WB LE TE	Initiation of NWB LE TE	Notes
			per week to WBAT				
Talbot, 2004 [49]	MLKI	Week 0	Week 0: TTWB Week 6: Progress to WBAT (pending muscle strength)	NR	Week 6	NR	
Tzurbakis, 2006 [5]	MLKI	Week 1-2: Full extension Week 4: Goal of 90 Week 8: Full flexion PLC/PCL involvement: protect posterior sag Extensor mechanism repair - 30 flexion for 3 to 4 weeks	Week 0 -4/6: PWB with brace in extension Week 12 (approx): FWB pending quadriceps strength recovery)	If PLC involved: 16 weeks	6 weeks	Immediate quadriceps isometrics	
Yasuda, 2009 [56] KSSTA	MLKI	Week 1: locked in extension Week 3-4: PROM 0 to 90 Week 5-8: AROM 0 to 120 Week 9-12: AROM 0 to 140 Month 4-6: Full range	Week 1: NWB Week 2: PWB, locked in extension Week 3-4: WBAT, locked in extension Week 5: unlock brace	Week 3-4: quadriceps and hamstrings co-contraction Month 7: PREs	Week 9-12: 45° static squat Month 4-6: Squats to 30, progress to 60, stairs exercise Month 7: full squat	Week 1: SLR (flex, abd, ext) Week 2: quadriceps isometrics Week 5-8: add 45° isometrics Month 7: PREs	
Richter, 2002 [9••]	MLKI – Functional Rehab	POD0-2: immobilization in bed POD2-Week 6: 0 to 60 (with PT and in CPM) Week 6+: unrestricted	POD2-Week 6: PWB in brace from 0 to 60 Week 6+: WBAT with full motion	NR	NR	NR	
Richter, 2002 [9••]	MLKI – Immobilization Protocol	POD0-2: immobilization in bed POD2-Week 6: immobilization in cast or external fixator Week 6+: unrestricted	POD2-Week 6: PWB in locked brace Week 6+: WBAT with full motion	NR	NR	NR	
Hua, 2016 [57]	MLKI (repair)	Week 1: Full ROM as tolerated in brace Week 4+ Goal: 0-120	Month 4: PWB with crutches Month 7: WBAT without crutches	12 weeks: co-contraction and WB exercise 16 weeks	NR	POD1: quadriceps isometrics and SLR Month 4+: exercise initiated Month 6: Begin PREs	Brace locked at 30
Shelbourne, 2007 [58]	MLKI with lateral repair	POD 0: bed rest and CPM 0 to 30, progress to 90 by POD 7 with maximum flexion 4x/day for 10 minutes Week 0 to 2: prevent hyperextension	POD 0-7: bed rest with ambulation to the bathroom only Week 1+: WBAT with or without crutches	NR	Week 2: gentle quadriceps exercises	NS	
Edson, 2006 [26]	MLKI with MCL	Weeks 0-3: locked in extension Week 3+: ROM as tolerated Week 6 goal: 90 to 120	Weeks 0-6: NWB Weeks 6-10: Add 25% BW per week Week 10: transition to functional brace	Week 16: active TE Week 20: Resistive TE		Week 0: quadriceps isometrics and SLR, NMES	Brace recommended for 18 months
Werner, 2014 [48]	MLKI with medial injury	Week 1: unspecified therapy in a knee brace	Week 0: TTWB	NR	NR	NR	
Quelard, 2010 [59]	PCL	POD1-45 Goal: 0 – 60; flexion ROM with tibial support; locked in extension except for exercise POD45:Goal 90 POD 45-90 Goal: 120 POD 90+: unlimited	POD10-45: FWB POD21: remove brace POD45-90: Removal of brace, then crutches	24 weeks	POD 45: ROM 0-60	POD15: eccentric knee flexion initiated	
Lee 2011 [60]	PCL (Chronic) and PLC	POD 3-5: PROM with tibial support Week 0-6: 0 to 90	Week 0-6: PWB	16 weeks	NR	NR	

Table 1 (continued)

Author	Population	Initiation of ROM	Initiation of WB	Initiation of HS Ex	Initiation of WB LE TE	Initiation of NWB LE TE	Notes
		Week 12 to 24 goal: full ROM	Week 0-3: brace locked in extension Week 3-6: PCL brace Week 6+: WBAT (pending pain)				
Fanelli, 2015 #3750	PCL and Medial Sided Injury	Weeks 0-3: Braced in extension Weeks 3-10: Progressive ROM Week 10: d/c post-op brace	Week 0-3: NWB locked in extension Weeks 3-5: Progressive WB	NR	Week 12	NR	
Fanelli, 2007 [35]	PCL and PLC	Weeks 0-3: Braced in extension Weeks 3-6: Progressive ROM	Week 0-3: NWB locked in extension Weeks 4-6: NWB with unlocked brace Weeks 7-10: Add 25% BW per week	NR	NR	NR	
Kim, 2013 [61]	PCL and PLC	Week 0 to 6: immobilization in extension Week 2: prone passive flexion initiated Week 6+: brace unlocked	Week 0 to 6: TTWB Week 6: WBAT	NR	Week 6: initiated loaded flexion, progress to 90 Week 8: WB TE initiated Week 12+: full squatting allowed	Week 0: quadriceps isometrics	Week 12: stair stepper, single leg stance
Chahla, 2016 [62]	PLC	Week 0-2: 0-90 Week 2+: Full ROM as tolerated	Weeks 0-6: NWB with immobilizer Week 6+: d/c crutches	16 weeks	After d/c of crutches	NR	
Murphy, 2006 [47]	PLC & LCL	Week 0-2: 0-90 Week 5-6 goal: 0-110	Week 0-2: TTWB, locked in ext Week 3-4: PWB, locked in ext with crutches Week 5-6: WBAT, unlocked; Crutches d/c when gait is normalized Brace d/c at weeks 9-12	NR	NR	Week 0-2: SLR	
Geeslin, 2011 [44]	PLC (Isolated & Combined)	Weeks 0-2: locked in extension except when exercising in "safe zone" 4x/day Week 2+: "safe zone" flexion increased Weeks 12-16 Goal: Full ROM	Weeks 0-6: NWB Week 6: PWB, progresses as tolerated Weeks 12-16 Goal: Normal gait	NR	Week 6: Leg press to max 70° flexion with 25% BW	NR	"Safe zone" for ROM determined intra-operatively as the allowable tissue tension; goal was 0-90, but further motion that would not cause damage was allowable
Gormeli, 2015 [32]	PLC (isolated and combined)	Weeks 0-4: immobilization in a brace Week 4+: flexion as tolerated	Week 0: WBAT	NR	Week 6-8 Week 10-12: stair stepping, single leg stance Week 12: full squatting allowed	Week 0: isometric quadriceps exercises	
LaPrade, 2010 [39]	PLC (isolated and combined)	Weeks 0-2: ROM TE 4x/day, increase as tolerated Weeks 0-2: Goal 90° Week 6: Goal Full ROM Weeks 13-16 Goal: Full ROM	Weeks 0-6: NWB Week 6+: progressive WB; crutches d/c when limp resolved Weeks 13-16 Goal: Normal gait	16 weeks	16 weeks: 25% to 50% body weight to 70° knee flexion on leg press or mini squat	Week 0-6: quadriceps sets and SLR (using an immobilizer pending lag); Week 0-6: NWB lower extremity and core exercise avoiding varus, tibial ER, or hyperextension	No loaded weight bearing beyond 70 degrees (unspecified time frame); Months 4-6: Focus on endurance without impact

Table 1 (continued)

Author	Population	Initiation of ROM	Initiation of WB	Initiation of HS Ex	Initiation of WB LE TE	Initiation of NWB LE TE	Notes
Camarda, 2010 [43]	PLC (Isolated)	Week 0-3: Locked in extension Week 3: PROM begins Week 4: 0-110	Week 4+: "Partial" WBAT with crutches Week 7: WBAT Week 12: d/c brace	NR	NR	NR	
Stannard, 2005 [46]	PLC (Isolated)	POD 0-10: knee immobilizer POD 10-14: "aggressive" ROM with CPM (0 to 3), progressing to 0 to 90	Week 0-1: PWB with crutches; Week 1+: Progress to FWB (pending other injuries)	NR	NR	NR	
Stannard, 2005 [19]	PLC combined with cruciate recon	POD1: Early "aggressive" ROM with CPM (0 to 3), progressing to 0 to 90	Week 0-1: PWB with crutches; Week 1+: Progress to FWB (pending other injuries)	NR	"Dictated by cruciate ligament injuries" with early closed chain exercise	NR	

allowed as early as 4 to 6 months post-operatively [39, 47, 58, 65].

Rehabilitation Outcomes After Repair and Reconstruction for MLKIs

Multiple ligament knee injuries result in significant time away from military duty, work, and sports [63–66]. In fact, the return to duty rate after combat-related MLKIs has been reported as low as 41% [64] to 50% [63] and is substantially lower than the average reported civilian return to work rate of 81% [9••, 12, 67]. Return-to-sport rates after MLKI are generally lower than return-to-work rates, ranging from 17 to 81%, with a mean of 50% [12]. Strength outcomes are poor in individuals after surgery for MLKI, with considerable deficits reported at 2 years after surgery in both the quadriceps and hamstrings [45••].

Criterion-Based Rehabilitation Progression

To improve motion, strength, and return to activity, it is prudent to follow a criterion-based rehabilitation progression that allows symptom-free activity and can be modified on an individual basis. The goals of our criterion-based rehabilitation progression are to return individuals to (1) normal activities of daily living and (2) work, military duty, and sports activities at the same level of participation as before injury. We have outlined three phases of rehabilitation after surgery: (1) tissue protection, (2) restoration of motor control, and (3) optimization of function. As a general rule, patients should be encouraged to exercise and ambulate without causing pain or discomfort greater than 3/10.

Knee joint inflammation should be measured via the amount of swelling, pain, range of motion (ROM) restriction, and joint warmth (see Table 2). As the signs of inflammation subside, activity should progress. Soft tissue swelling and/or an effusion should not occur in response to increasing loads. Pain should steadily decrease, and pain exceeding 5/10 should result in activity reduction or modification. Any increased joint pain or pain in the surgical tissues from exercise should subside within a few hours. Pain increases lasting greater than 12 to 24 h indicate that exercise was too aggressive and should be modified appropriately. Range of motion (ROM) limitations are often accompanied with pain at the end ROM without over-pressure, and when this occurs, exercises or over-pressure near end range should be avoided. Pain at rest should result in activity modification or reduction. Lastly, any palpable joint warmth should result in avoidance of further joint loads and tissue stress. The knee should be continually monitored for signs of inflammation that may indicate that the repaired/reconstructed structures were exposed to excessive

Table 2 Knee Joint Inflammation Scale

Level	Effusion	Pain Status	ROM Status	Other
High	at least 2+ on sweep test*	moderate to severe pain (> 6/10)	limited with pain before end range	increased skin temperature
Moderate	stable 1+ or lower on sweep test	mild and stable pain levels (3 to 5/10)	pain around the end of ROM	
Low	trace or zero with sweep test	no pain at rest or with ADLs	may have some pain with overpressure at end of ROM	

load. Though rare, increasing joint warmth or erythema should prompt the clinician to rule out the presence of a post-operative infection. Rehabilitation activities progress based on a combination of time from surgery, performance of basic tasks, and tissue response to increased loading. The progression is best described as an "as-tolerated" approach to restoring motion, WB, and activity.

Rehabilitation and Activity Progression in the Tissue Protection Phase

The goals of the tissue protection phase focus on restoration of knee motion without over-stressing the repaired/reconstructed tissues, prevention of muscle atrophy, and reestablishment of appropriate gait patterns with assistive devices that improve function.

Range of Motion

During the first tissue protection phase, pain during ROM interventions should not exceed 3/10. For flexion, end-range over-pressure, muscle stretching, and aggressive mobilization should be avoided during the first 4 weeks post-operatively. For extension, MLKI can be limited to neutral extension (avoiding hyperextension) for 6 weeks. Patient-specific factors, such as generalized joint hyperlaxity, should also be considered during the progression of knee ROM. Specifically, rehabilitation professionals should exercise caution and avoid early aggressive hyperextension as additional ROM will be gained throughout the later phases of rehabilitation. Patellofemoral mobilizations in the non-restricted range can begin immediately after surgery.

Range of motion may need to be limited due to specific surgical procedures (see "Tissue-Specific Restrictions" section). Aggressive patellofemoral mobilization and stretching at end-range should begin around 4 weeks post-operatively if the patient has not achieved neutral knee joint extension (anatomic 0°) or 60° of knee flexion. In the case of posterolateral or posteromedial reconstruction or repair, the physical therapist should avoid hyperextension and exercise care in stretching the hamstrings, gastrocnemius, and posterior capsule so as not to disrupt the surgical repairs.

If a knee joint contracture of 10° or greater (compared to anatomic 0°) exists at 6 weeks, the patient should be referred to their treating surgeon for further assessment. If the patient has not achieved 90° of flexion by 12 weeks post-surgery, the surgeon should also be notified. Additionally, if the patient loses ROM consistently at any point after surgery, referral back to the surgeon is warranted.

Restoring knee flexion can present issues for individuals with PLC or PCL surgery. Active contraction of the hamstrings to flex the knee can cause a posterior drawer effect, which could stress the repaired/reconstruction tissues. Therefore, initial flexion exercises should be performed passively, either prone to eliminate gravity causing a posterior sag or supine with support provided to the posterior tibia, for at least 6 weeks.

Stationary Cycling for ROM Cycling can begin when the individual has achieved neutral extension and 90° of flexion but no earlier than post-operative week 3. Other protocols have recommended waiting 6 to 7 weeks [44, 59, 62] to 10 [39]or 12 weeks [65]. However, stationary cycling has been shown to produce minimal strain on the ACL [68] and should be completed without resistance.

The goal of this exercise is promote ROM until 10 weeks post-surgery. Resistance should be kept to a minimum, and the individual should move in a smooth and controlled motion. Individuals who cannot complete a full revolution due to limited knee flexion should not force motion and only move in a comfortable arc. Seat height may be adjusted to limit the flexion necessary to complete a full revolution and may be lowered as ROM improves. After 10 weeks, cycling for cardiovascular endurance may begin pending the recovery of motion. Prior to 10 weeks, cycling for endurance may promote unwanted, excessive hamstring contractions. Additionally, the use of toe clips has been shown to increase hamstring co-contraction.

Weight Bearing and Gait Progression in the Tissue Protection Phase

Weight bearing recommendations are highly variable after surgery for MLKI. However, laboratory studies indicate that individuals do not use a consistent amount of WB when given recommendations for PWB and TTWB [69] [70] [71].

Clinical training paradigms to standardize the forces through the limb have been suggested but not validated [72, 73]. Considering the lack of outcome measurement after MLKI surgery, there is little evidence to support the need for NWB status. Conversely, controlled WB benefits cartilage and meniscal nutrition [74], can provide beneficial proprioceptive input to the knee, and promotes muscle activity. Therefore, we have operationally defined a method to dose WB to tolerance based on the presence or absence of the cardinal signs of inflammation in the surgical knee.

Patients are instructed to bear weight on their surgical limb to tolerance based on the response of the knee as measured by the presence of pain and effusion. Initially, WB should be performed in a locked, double upright knee brace to prevent excessive sagittal or frontal plane motion. The brace and axillary crutches are used for at least 6 weeks for safety, but the patient may bear as little weight through the crutches as tolerable. Gait activities are progressed based on knee inflammation and ROM, quadriceps strength, neuromuscular control, and general improvements in gait patterns. Criteria to progress gait activities are in Table 3.

Patients must be able to perform a straight leg raise with less than a 5° lag in order to begin weight bearing with an unlocked brace. A lag is present when the range of maximum knee extension during the straight leg raise is more flexed than the maximum knee joint extension measured in a resting position.

Unlocking the Post-Operative Brace When the criteria are met, the brace may be unlocked to 45° or 60° for ambulation, depending on the settings available on the brace. The individual should also be performing basic bilateral WB exercises (see below), which should include gait training. The physical therapist should focus on the patient using the available ROM in swing and weight acceptance and proper sequencing with the crutches to prevent over-loading.

Discontinuation of Crutches The primary concern with discontinuing use of crutches is adequate quadriceps strength and neuromuscular control required for safely negotiating stairs. Therefore, the individual should be able to complete five repetitions of step-up and step-down exercises to a 7-in step with general safety and control. Patients should be instructed to use a non-reciprocal stair negotiation pattern until safety is assured.

Discontinuation of Post-Operative Brace and Crutches Criteria are presented in Table 3. To screen for compensations and poor control in stair negotiation, a step-down test and step-up task to a 7-in step may be used, considering the criteria provided by Piva et al. [75]. Generally, the gait cycle must also be symmetrical and without the presence of a limp.

Once the orthosis and crutches have been discontinued, treadmill or over-ground walking may be initiated to improve cardiovascular conditioning, but careful attention should be paid to joint inflammation. Time and distance walked should not progress faster than 10 to 20% increments per week.

Initiation and Progression of Rehabilitation Exercises for Strengthening in the Tissue Protection Phase

Immediate Exercise Prescription

Patients should begin motor control exercises immediately after surgery while still in the tissue protection phase. Patients may perform exercises to restore quadriceps activation including isometric quadriceps setting with the knee in neutral and within safe ranges of flexion. All patients should receive high-intensity neuromuscular electrical stimulation [76, 77]. Other therapeutic exercises should include gluteal sets, ankle pumps, and four-way straight leg raises (i.e., hip flexion, abduction, extension, adduction modified per the "Tissue-Specific Restrictions" section).

Home exercise programs to promote knee extension to neutral; improve quadriceps muscle activation; prevent atrophy of the hamstring, calf, and gluteal muscles; and prevent fibrosis of the patellofemoral joint are essential additions to formal physical therapy.

Progressive Resistive Exercises and Body Weight Exercises

Patients may begin NWB knee extension exercises, bilateral WB exercises, unilateral WB exercises, and stationary cycling prior to 4 weeks post-surgery, provided the individual meets the knee inflammation guidelines outlined (see Table 3) assuming that there are no peri-articular or extra-articular fractures. The gradual introduction of activities prior to 4 weeks provides the patient and physical therapist an opportunity to slowly increase the load on the surgical tissues while monitoring tissue response.

Progressive resistive exercises (PREs) to recover muscle strength and endurance may begin as early as 1 week after surgery. A combination of both WB and NWB exercises should be used depending on tissue tolerance. To avoid excessive posterior tibial translation, resisted hamstring strengthening should be avoided for 12 weeks in all patients who underwent repair or reconstruction of the PCL, PLC, or menisci.

After ACL reconstruction, WB and NWB exercises are initiated early on to restore quadriceps muscle function [34], reduce disuse atrophy, and restore ROM and gait to pre-injury conditions without adverse effects [78, 79]. Non-weight bearing knee extension exercises should be completed in a safe

Table 3 Criterion Based Rehabilitation Progression – Tissue Protection and Restoration of Motor Control Phases

Activity	Time to Begin in		Knee Joint Inflammation	Range of Motion	Strength	Neuromuscular Control & Task Mastery
	Early Group	Delayed Group				
Gait – WBAT using bilateral crutches with locked brace	Week 0	Week 4	High	Able to wear brace locked in extension comfortably	--	Able to sequence gait with bilateral crutches safely
Exercise – NWB Quadriceps	Week 1			90^o flexion		Active quadriceps contraction
Exercise – Basic Bilateral WB for LE			Moderate	Neutral extension (anatomic 0^o) to 45^o		
Gait – WBAT using bilateral crutches with unlocked brace				Neutral extension to 60^o	Lag < 5^o with SLR	Able to demonstrate single leg balance for 5-10 seconds and semi-normal gait pattern
Exercise – Basic Unilateral WB for LE	Week 3					Able to demonstrate single leg balance for 5-10 seconds
Gait – WBAT with unlocked brace and no crutches				Neutral extension to 90^o	Lag < 3^o with SLR	Semi-normal gait pattern 5 reps each limb of 7" step up without obvious compensation
Exercise – Stationary Cycling for ROM						Able to weight shift to 75% WB on surgical limb
Exercise – Advanced WB LE Strengthening	Week 6		Low			5 reps each limb of 7" step up without obvious compensation
Gait – without brace or crutches				Neutral extension to 120^o		Generally normal gait pattern Reciprocal stair negotiation 10 repetitions each of step ups AND step downs to a 7" step without pain or aberrant movements
Exercise – Active HS Strengthening without Resistance	Week 8		Moderate	Neutral extension to 90^o	Pain free contraction of the HS	Absence of posterior drawer with hamstring activation
Exercise – Active Resistive HS Strengthening	Week 12		Low			

Abbreviations: WBAT – weight bearing as tolerated; NWB – non-weight bearing; LE – lower extremity; reps – repetitions; ROM – range of motion; HS - hamstrings

range from 90° to 60° of flexion including isotonic and isometric exercise [80]. Range of motion for WB exercise is limited to 45° of flexion early in rehabilitation. Even though hamstring co-contraction occurs with WB [80], the moment arm of the hamstrings to produce a posterior translation near extension is extremely small [31] and can be minimized by keeping a more neutral trunk as in the low-range squat and wall sit exercises [81]. This is well controlled with the leg press exercise [82]. A 45° range also balances stress applied to a reconstructed PCL (and likely PLC) with the added benefit of quadriceps strengthening [83]. Cruciate ligament stress in unilateral stance and unilateral squatting exercises at less than 45° is similar when compared to bilateral squatting exercises [84].

Resisted exercises should follow a timeline to gradually introduce forces to the knee and to not provide excessive stress. The first exercises to be implemented should be unilateral NWB and bilateral WB exercises as early as 1 week after surgery. Unilateral WB strength exercises may begin 3 weeks after surgery. Advanced WB lower extremity strengthening should not begin until at least 6 weeks after surgery.

Non-weight Bearing Quadriceps Strengthening Exercises In the first 6 weeks after surgery, fewer than 10 lb of external resistance should be used [80]. Early external resistance should be performed with cuff weights to prevent overloading the patellofemoral joint. Isometric exercises at 90°, 75°, and 60° of flexion may be used with proximal resistance and an intensity that does not cause pain. From 6 to 8 weeks, resistance may be increased beyond 10 lb and may transition to resistance equipment for training, as tolerated. Range of motion may be increased to 45° at 8 weeks, and ROM restrictions may be lifted at 12 weeks. Progression should initially focus on quadriceps endurance (12 to 20 repetitions) and progress to quadriceps strengthening (8 to 12 repetitions).

Weight Bearing Strengthening Exercises Initiation of WB may cause some knee discomfort. Exercises should be performed in a safe environment where the individual has external support for balance if needed (e.g., therapist support, parallel bars, etc.) and should be performed in the post-operative brace (Table 4). These exercises target the general strengthening of the lower extremity musculature while preparing the individual to resume a normal gait pattern.

When basic unilateral WB strengthening begins, gait training is the first unilateral strengthening exercise in an unlocked brace using one or two crutches, as necessary. The focus of gait training should be on reciprocal motions for each leg and normal knee excursion through swing and stance. Step-up exercises and step-and-hold exercises may begin at this time, as well (see Table 5).

Advanced weight bearing strengthening exercises are operationally defined as requiring significant eccentric control of the lower extremity or ROM greater than 45° of knee flexion. Initially, exercises should be performed in the post-operative brace and can begin when the individual is 6 weeks out from surgery and has met all criteria for discontinuation of crutches. Weight bearing flexion beyond 45° loads the PCL, while not excessively loading the ACL [83] [84]. Lunging exercises should be implemented cautiously in PCL-injured and PLC-injured subjects, with careful attention paid to the ROM due to the loads placed on the posterior stabilizers beyond 45° [85]. These exercises do not appreciably load the ACL.

When advanced WB strengthening begins, gait training without the post-operative brace may begin during rehabilitation (Table 6).

Tissue-Specific Restrictions

Progression of rehabilitation should be altered to respect the structure addressed during surgery that has the slowest time course for healing or that has the greatest probability of failure (typically soft tissue repairs). Biomechanical studies have indicated that some muscle activities need to be restricted to protect surgically repaired tissues [30–33]. The authors have agreed on a set of specific guidelines to protect vulnerable healing structures (Table 7). Reconstruction or fixation with hardware and bone tunnels is regarded as strong and able to withstand early stress, whereas soft tissue repairs performed with sutures are more likely to fail with early stress. As a reference, the ACL reconstruction rehabilitation is the standard and includes early unlimited ROM and unrestricted WB. Each additional procedure provides additional considerations.

Posterolateral Corner Repair and Reconstruction/ Posterior Cruciate Ligament Repair and Reconstruction Repair or reconstruction of the PLC requires protection of

Table 4 Bilateral Weight Bearing Exercises

Exercise	Limitations and Considerations
Squats to no more than 45° knee flexion	Place a chair, table, or box behind the individual to block excessive motion
Leg Press from 45° to 0°	Loads no greater than body weight
Isometric wall sits to 45°	Begin with short duration (~10 seconds)
Terminal Knee Extension	Avoid hyperextension in PCL/PLC surgery
Weight Shifting	Can perform laterally, anteriorly, and in a 45° stagger

Table 5 Unilateral Weight Bearing Exercises

Exercise	Limitations and Considerations
Gait Training (Braced)	• Avoid compensations at the hip/trunk • Ensure reciprocal gait with decreasing dependence on crutches • Emphasize knee flexion through loading response • Emphasize knee extension at initial contact and in midstance
Step Up Exercises	• Up to 5 weeks - no higher than 4 inches • Up to 6 weeks - no higher than 7 inches (ADA maximum height)
Step and Hold Exercise	• Patient steps from the uninjured onto the injured limb, at least the distance of the normal stride • The individual is cued to imagine they are stepping over a puddle of water and to land with a heel-toe gait pattern to simulate walking • Avoid excessive stiffening, knee flexion, or medial collapse

ROM from excessive hyperextension and varus forces, posterior tibial sag, and forceful contractions of the biceps femoris and gastrocnemius. Soft tissue repairs of the PLC, including the posterior capsule, mid-substance tears of the biceps femoris, and iliotibial band, require protection. For reconstruction of the popliteofibular ligament or lateral collateral ligament, similar restrictions are in place with heightened awareness for varus loading of the knee.

Repair or reconstruction of the PCL is also at risk for failure with excessive posterior translation of the tibia. When the hamstrings contract without an opposing contraction from the quadriceps in ranges beyond 20° to 30° of flexion, there is a significant posterior drawer force [31, 32] [86]. Therefore, after PCL repair or reconstruction, the therapist should prevent posterior tibial translation as knee flexion is performed for 6 weeks after surgery. In the presence of pain or discomfort with flexion, the physical therapist may apply manual tibial external rotation or anterior tibial glide to remove tension from the surgical sites.

Isolated hamstring strengthening has been recommended to begin from 8 to 24 weeks after surgery [5, 23, 27, 40, 42, 43, 45••, 57, 59, 60, 87]. For both PLC and PCL procedures, patients may initiate active hamstring contraction without resistance and gentle stretching after 8 weeks. The patient should be monitored for posterior knee pain and an active posterior drawer, in which the tibia visually glides posteriorly when performed isometrically at 90° of flexion at 50% effort. Exercises may include active heel slides on a smooth surface as well as prone and standing hamstring curls.

Resisted hamstring strengthening can begin 12 weeks after surgery if hamstring contraction does not cause posterior pain or an active posterior drawer effect when performed isometrically at 90° of flexion at 75% effort. Exercises may include resisted hamstring curls, both prone and standing, and multiple-angle isometrics. As performance improves, eccentric training may occur to include Romanian dead lifts, Nordic hamstring curls, and other exercises. The emphasis for individuals returning to activity should focus on eccentric control of the hamstrings that occurs with sprinting, landing from a jump, and pivoting.

Meniscus Repair Meniscus repairs require protection from excessive shear forces and translation for 4 weeks, but can tolerate early weight bearing in a brace [88–91]. Non-weight bearing flexion should be limited to 90°. Additionally, WB flexion should be limited to no more than 30° and with no more than one-half body weight (i.e., bilateral WB). Unilateral WB should be permitted with the knee braced in extension to allow ambulation. After 4 weeks, activity progression can resume as tolerated. Meniscal root repairs (especially medial) require protection from hamstring contraction; therefore,

Table 6 Advanced Strengthening Exercises

Exercise	Limitations and Considerations
Gait Training (Unbraced)	• Avoid compensations at the hip/trunk • Ensure reciprocal gait with decreasing dependence on crutches • Emphasize knee flexion through loading response • Emphasize knee extension at initial contact and in midstance
Step Down Exercises	• Can be performed posterior, lateral, and anterior
Squats to no more than 90°	• Careful progression should be used to increase range from 45°
Wall sits to no more than 90°	• Careful progression should be used to increase range from 45°
Forced-use/Preferential squats	• A staggered stance is assumed with the surgical limb positioned under the body and the non-surgical limb positioned in front of the body. This forces the individual to use the surgical limb and prevents off-loading to the non-surgical limb.

Table 7 Tissue Specific Considerations

Tissue Involved	Rehabilitation Modifications
ACL	No modifications to rehabilitation
PCL	Protect posterior translation of the femur for 6 weeks
	- Anterior tibial glide with knee flexion
	- Avoid gravity causing posterior glide
	Protected Hamstrings Contractions:
	- Weeks 0 to 8 – No active hamstring contractions
	Passive flexion ROM with support to the posterior tibia x 6 wks
	- Weeks 8 to 12 – Active hamstrings contractions without external resistance
	Based on absence of active posterior drawer with hamstring activation
	Active hamstring exercises (heel slides, prone knee flexion, WB flexion)
	Gentle hamstring stretching
	- Weeks 12+ - Resisted hamstring contractions allowed
	Based on absence of active posterior drawer with hamstring activation
PLC	Extension ROM limited to 0^{o} (no hyperextension)
	Protect posterior translation of the femur for 6 weeks
	- Anterior tibial glide with knee flexion
	- Avoid gravity causing posterior glide
	Avoid excessive varus forces on knee joint
	Hamstring restrictions same as PCL
MCL	ROM exercises with foot internally rotated
	Avoid excessive valgus forces on knee joint
Meniscus Body Repair	Brace locked in extension for 4 weeks for ambulation, WBAT
	Avoid unilateral WB flexion (any range) & bilateral WB flexion beyond 30^{o} for 4 wks
	NWB flexion ROM to 90^{o} for 4 weeks
Meniscus Root Repair	NWB x 4 weeks
	Protected Hamstrings Contractions:
	- Weeks 0 to 6 – No active hamstring contractions
	Passive flexion ROM with support to the posterior tibia x 6 wks
	- Weeks 6 to 12 – Active hamstrings contractions without external resistance
	Based on absence of posterior pain at the repair site with hamstring activation
	Active hamstring exercises (heel slides, prone knee flexion, WB flexion)
	- Weeks 12+ - Resisted hamstring contractions allowed
	Based on absence of posterior pain at the repair site with hamstring activation

hamstring protection similar to a PCL or PLC should be implemented [92, 93].

Medial Collateral Ligament Repairs and Reconstructions Medial sided repairs (MCL, medial capsule) should be protected from excessive valgus force or lateral rotation [94]. In the presence of pain or discomfort with flexion, the physical therapist may apply manual tibial internal rotation or slight varus to reduce tension from the repair sites.

Rehabilitation and Activity Progression in the Restoration of Motor Control Phase

In the restoration of motor control phase, surgical tissues can be loaded in a graduated fashion. Full ROM compared to the opposite limb, nearly symmetrical muscle strength, normal gait, and return to activities of daily living are the goals of this phase. The general progression of rehabilitation activities is continued in Table 3, along with the criteria necessary to begin those activities.

Return to Loaded Weight Bearing Strengthening Exercise Initial rehabilitation activities use body weight as the primary resistance to increase strength. As strength returns, body weight exercises reach a point of diminishing returns, and external resistance is needed, which increases the challenge but also may overload the surgical knee. Therefore, external resistance should not be added to exercises until the individual can perform a bilateral squat to 90° without pain and a step down from a 7-in

Table 8 Criterion Based Rehabilitation Progression – Optimization of Function

Activity	Time to Begin	Knee Joint Irritability	Range of Motion	Strength	Neuromuscular Control & Task Mastery
Cycling for Conditioning	10 weeks	Moderate	Neutral extension to 120°		Able to control rotation of cycling revolutions
Elliptical Trainer for Conditioning	12 weeks			70% QI	Normal walking gait without antalgia or deviations
Bilateral LE Weight Training with free weights		Low			Able to complete body weight squat to 90° without aberrant movements Active terminal knee extension in standing
Walk-Jog-Run Progression	16 weeks		Full (within 5° of contralateral)	80% QI 50% H:Q Ratio	30 Step & Holds without deviations 10 single leg squats to 45° without deviations
Basic Agility Drills, Jumping Drills	18 weeks				Able to run 1 mile without deviations 10 single leg squats to 60° without deviations
Hopping, Cutting/Pivoting, & Sport-Specific Drills	20 weeks			85% QI 60% H:Q Ratio	Perform full effort sagittal and frontal plane direction changes without compensations Perform full effort sagittal and frontal plane jumping without compensations
Return to Unrestricted Training	24 weeks			90% QI 70% H:Q Ratio	Complete Return to Training Testing

Abbreviations: QI – Quadriceps Index; H:Q Ratio – Hamstrings to Quadriceps Ratio

step without pain or compensation (score <2 per Piva criteria) [95]. Inflammation should be kept to a minimum. This should occur no earlier than 12 weeks after surgery and only when inflammation is low and quadriceps strength symmetry has achieved 70%.

Conditioning Exercises Because of the relatively long period of relative immobilization that allows the tissues to recover, conditioning exercises are important to initiate when safe. Cycling for aerobic conditioning can be initiated 10 weeks after surgery when the individual has the necessary ROM and control of the lower extremity to initiate and safely stop cycling (i.e., they can control the momentum of the pedals adequately). This is a direct progression from cycling for ROM.

When the individual can walk independently without a post-operative brace or crutches, and there is sufficient quadriceps strength, the individual may begin training on an elliptical machine. For treadmill walking, stationary cycling, and the elliptical machine, training should start with constant load and constant speed exercises to provide an initial conditioning stimulus. Individuals may progress to an interval training program with variable speed and resistance as tolerated. Training loads should be progressed slowly (approximately 10 to 20% per week).

Rehabilitation and Activity Progression in the Optimization of Function Phase

The ultimate goal of surgery for MLKI is to restore the function of the individual to their pre-morbid level. Rehabilitation plays an important role in this process. At the point of functional optimization, most tissue-specific considerations are not relevant, and the rehabilitation specialist is able to advance function without the restrictions of tissue protection. The reader is referred to available clinical commentaries that address return to sport and injury prevention for the knee joint (e.g., [96, 97]). Sample criteria and timelines are provided in Table 8.

Conclusion

Rehabilitation after surgery for MLKI depends on the condition of the host, including comorbidities, the anatomic structures that were injured, the quality of the repaired/reconstructed tissues, the strength of the fixation method, and any associated injuries. In addition, guiding rehabilitation with an as-tolerated approach that considers inflammation, ROM, and muscle strength will lead to gradual and safe increases in activity. Careful progression should reduce the risk for post-operative complications and maximize clinical outcomes for patients.

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Compliance with Ethical Standards

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Anil Ranawat is on the Speaker Bureau for Stryker Mako and Arthrex. He is a paid consultant for Stryker Mako, Arthrex, and Moximed. Dr. Ranawat also reports research support for Arthrex and Depuy Mitek. He reports stock with Confromis. Dr. Ranawat reports royalties from Saunders and Springer. He is the editor-in-chief of *Current Reviews in Musculoskeletal Medicine*.

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References

Papers of particular interest, published recently, have been highlighted as:
•• Of major importance

1. Medina O, Arom GA, Yeranosian MG, Petrigliano FA, McAllister DR. Vascular and nerve injury after knee dislocation: a systematic review. Clin Orthop Relat Res. 2014;472(9):2621–9. doi:10.1007/s11999-014-3511-3.

2. Niall DM, Nutton RW, Keating JF. Palsy of the common peroneal nerve after traumatic dislocation of the knee. J Bone Joint Surg Br. 2005;87(5):664–7. doi:10.1302/0301-620X.87B5.15607.
3. Burrus MT, Werner BC, Griffin JW, Gwathmey FW, Miller MD. Diagnostic and management strategies for multiligament knee injuries: a critical analysis review. JBJS Rev. 2016;4(2). doi:10.2106/JBJS.RVW.O.00020.
4. Whelan DB, Dold AP, Trajkovski T, Chahal J. Risk factors for the development of heterotopic ossification after knee dislocation. Clin Orthop Relat Res. 2014;472(9):2698–704. doi:10.1007/s11999-014-3730-7.
5. Tzurbakis M, Diamantopoulos A, Xenakis T, Georgoulis A. Surgical treatment of multiple knee ligament injuries in 44 patients: 2-8 years follow-up results. Knee Surg Sports Traumatol Arthrosc. 2006;14(8):739–49. doi:10.1007/s00167-006-0039-4.
6. Sanders TL, Pareek A, Kremers HM, Bryan AJ, Levy BA, Stuart MJ, et al. Long-term follow-up of isolated ACL tears treated without ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2016; doi:10.1007/s00167-016-4172-4.
7. Nielsen AB, Yde J. Epidemiology of acute knee injuries: a prospective hospital investigation. J Trauma. 1991;31(12):1644–8.
8. Arom GA, Yeranosian MG, Petrigliano FA, Terrell RD, McAllister DR. The changing demographics of knee dislocation: a retrospective database review. Clin Orthop Relat Res. 2014;472(9):2609–14. doi:10.1007/s11999-013-3373-0.
9.•• Richter M, Bosch U, Wippermann B, Hofmann A, Krettek C. Comparison of surgical repair or reconstruction of the cruciate ligaments versus nonsurgical treatment in patients with traumatic knee dislocations. Am J Sports Med. 2002;(5):30, 718–727. Key article discussing operative and non-operative rehabilitation outcomes
10. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE. Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. Journal of orthopaedic research : official publication of the Orthopaedic Research Society. 2004;22(1):85–9. doi:10.1016/S0736-0266(03)00133-5.
11. Levy BA, Dajani KA, Whelan DB, Stannard JP, Fanelli GC, Stuart MJ, et al. Decision making in the multiligament-injured knee: an evidence-based systematic review. Arthroscopy. 2009;25(4):430–8. doi:10.1016/j.arthro.2009.01.008.
12. Peskun CJ, Whelan DB. Outcomes of operative and nonoperative treatment of multiligament knee injuries: an evidence-based review. Sports Med Arthrosc. 2011;19(2):167–73. doi:10.1097/JSA.0b013e3182107d5f.
13. Rios A, Villa A, Fahandezh H, de Jose C, Vaquero J. Results after treatment of traumatic knee dislocations: a report of 26 cases. J Trauma. 2003;55(3):489–94. doi:10.1097/01.TA.0000043921.09208.76.
14. Wong CH, Tan JL, Chang HC, Khin LW, Low CO. Knee dislocations—a retrospective study comparing operative versus closed immobilization treatment outcomes. Knee Surg Sports Traumatol Arthrosc. 2004;12(6):540–4. doi:10.1007/s00167-003-0490-4.
15. Dedmond BT, Almekinders LC. Operative versus nonoperative treatment of knee dislocations: a meta-analysis. Am J KneeSurg. 2001;14(1):33–8.
16. Jiang W, Yao J, He Y, Sun W, Huang Y, Kong D. The timing of surgical treatment of knee dislocations: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2015;23(10):3108–13. doi:10.1007/s00167-014-3435-1.
17.•• Mook WR, Miller MD, Diduch DR, Hertel J, Boachie-Adjei Y, Hart JM. Multiple-ligament knee injuries: a systematic review of the timing of operative intervention and postoperative rehabilitation. J Bone Joint Surg Am. 2009;91(12):2946–57. doi:10.2106/JBJS.H.01328. Recent systematic review that Investigates the timing of both surgery and rehabilitation after surgery for MLKI
18.•• Levy BA, Dajani KA, Morgan JA, Shah JP, Dahm DL, Stuart MJ. Repair versus reconstruction of the fibular collateral ligament and posterolateral corner in the multiligament-injured knee. Am J Sports Med. 2010;38(4):804–9. doi:10.1177/0363546509352459. Recent systematic review that investigates repair versus reconstruction for MLKI
19. Stannard JP, Brown SL, Farris RC, McGwin G Jr, Volgas DA. The posterolateral corner of the knee: repair versus reconstruction. Am J Sports Med. 2005;33(6):881–8. doi:10.1177/0363546504271208.
20. Geeslin AG, Moulton SG, LaPrade RF. A systematic review of the outcomes of posterolateral corner knee injuries, part 1: surgical treatment of acute injuries. Am J Sports Med. 2016;44(5):1336–42. doi:10.1177/0363546515592828.
21. King AH, Krych AJ, Prince MR, Pareek A, Stuart MJ, Levy BA. Surgical outcomes of medial versus lateral multiligament-injured. Dislocated Knees Arthroscopy. 2016;32(9):1814–9. doi:10.1016/j.arthro.2016.01.038.
22. Kovachevich R, Shah JP, Arens AM, Stuart MJ, Dahm DL, Levy BA. Operative management of the medial collateral ligament in the multi-ligament injured knee: an evidence-based systematic review. KneeSurg Sports TraumatolArthrosc. 2009;17(7):823–9. doi:10.1007/s00167-009-0810-4.
23. Skendzel JG, Sekiya JK, Wojtys EM. Diagnosis and management of the multiligament-injured knee. J Orthop Sports PhysTher. 2012;42(3):234–42. doi:10.2519/jospt.2012.3678.
24. Fanelli GC. Posterior cruciate ligament rehabilitation: how slow should we go? Arthroscopy. 2008;24(2):234–5.
25. Rihn JA, Groff YJ, Harner CD, Cha PS. The acutely dislocated knee: evaluation and management. J Am Acad Orthop Surgeons. 2004;12(5):334–46.
26. Edson CJ. Conservative and postoperative rehabilitation of isolated and combined injuries of the medial collateral ligament. Sports Med Arthrosc Rev. 2006;14(2):105–10. doi:10.1097/01.jsa.0000212308.32076.f2.
27. Noyes FR, Barber-Westin SD. Reconstruction of the anterior and posterior cruciate ligaments after knee dislocation. Use of early protected postoperative motion to decrease arthrofibrosis. Am J Sports Med. 1997;25(6):769–78.
28. Hubert MG, Stannard JP. Surgical treatment of acute and chronic anterior and posterior cruciate ligament and medial-side injuries of the knee. Sports Med Arthrosc Rev. 2011;19(2):104–9. doi:10.1097/JSA.0b013e3182191874.
29. Stannard JP, Black BS, Azbell C, Volgas DA. Posteromedial corner injury in knee dislocations. J Knee Surg. 2012;25(5):429–34. doi:10.1055/s-0032-1322605.
30. Lasmar RC, Marques de Almeida A, Serbino JW Jr, Mota Albuquerque RF, Hernandez AJ. Importance of the different posterolateral knee static stabilizers: biomechanical study. Clinics. 2010;65(4):433–40. doi:10.1590/S1807-59322010000400013.
31. Grood ES, Stowers SF, Noyes F. Limits of movement in the human knee: effect of sectioning the posterior cruciate ligament and posterolateral structures. J Bone Joint Surg. 1988;70A:88–97.
32. Lutz GE, Palmitier RA, An KN, Chao EYS. Comparison of tibiofemoral joint forces during open-kinetic-chain and closed-kinetic-chain exercises. J Bone Joint Surg. 1993;75(A):732–9.
33. Irrgang JJ, Fitzgerald GK. Rehabilitation of the multiple-ligament-injured knee. Clin Sport Med. 2000;19(3):–545. doi:10.1016/S0278-5919(05)70223-4.
34. 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(6):337–42. doi:10.1007/s001670000143.
35. Fanelli GC, Edson CJ, Reinheimer KN, Garofalo R. Posterior cruciate ligament and posterolateral corner reconstruction. Sports Med

Arthrosc. 2007;15(4):168–75. doi:10.1097/JSA.0b013e31815afa25.
36. Fanelli GC, Beck JD, Edson CJ. Combined PCL-ACL lateral and medial side injuries: treatment and results. Sports Med Arthrosc. 2011;19(2):120–30. doi:10.1097/JSA.0b013e318219149c.
37. Fanelli GC, Fanelli DG. Management of chronic combined PCL medial posteromedial instability of the knee. Sports Med Arthrosc Rev. 2015;23(2):96–103. doi:10.1097/JSA.0000000000000061.
38. Edson CJ, Fanelli GC, Beck JD. Rehabilitation after multiple-ligament reconstruction of the knee. Sports Med Arthrosc Rev. 2011;19(2):162–6. doi:10.1097/JSA.0b013e31821918b2.
39. Gormeli G, Gormeli CA, Elmali N, Karakaplan M, Ertem K, Ersoy Y. Outcome of the treatment of chronic isolated and combined posterolateral corner knee injuries with 2- to 6-year follow-up. Arch Orthop Trauma Surg. 2015;135(10):1363–8. doi:10.1007/s00402-015-2291-x.
40. Harner CD, Waltrip RL, Bennett CH, Francis KA, Cole B, Irrgang JJ. Surgical management of knee dislocations. J Bone Joint Surg Am. 2004;86-A(2):262–73.
41. Owens BD, Neault M, Benson E, Busconi BD. Primary repair of knee dislocations: results in 25 patients (28 knees) at a mean follow-up of four years. J Orthop Trauma. 2007;21(2):92–6. doi:10.1097/BOT.0b013e3180321318.
42. Engebretsen L, Risberg MA, Robertson B, Ludvigsen TC, Johansen S. Outcome after knee dislocations: a 2-9 years follow-up of 85 consecutive patients. Knee Surg Sports Traumatol Arthrosc. 2009;17(9):1013–26. doi:10.1007/s00167-009-0869-y.
43. LaPrade RF, Johansen S, Agel J, Risberg MA, Moksnes H, Engebretsen L. Outcomes of an anatomic posterolateral knee reconstruction. J Bone Joint Surg Am. 2010;92(1):16–22. doi:10.2106/JBJS.I.00474.
44. Geeslin AG, LaPrade RF. Outcomes of treatment of acute grade-III isolated and combined posterolateral knee injuries: a prospective case series and surgical technique. J Bone Joint Surg Am. 2011;93(18):1672–83. doi:10.2106/JBJS.J.01639.
45.•• Jenkins PJ, Clifton R, Gillespie GN, Will EM, Keating JF. Strength and function recovery after multiple-ligament reconstruction of the knee. Injury. 2011;42(12):1426–9. doi:10.1016/j.injury.2011.03.026. ***One of few publications with good sterngth outcome data***
46. Camarda L, Condello V, Madonna V, Cortese F, D'Arienzo M, Zorzi C. Results of isolated posterolateral corner reconstruction. J Orthop Traumatol Off J Italian Soc Orthop Traumatol. 2010;11(2):73–9. doi:10.1007/s10195-010-0088-9.
47. Murphy KP, Helgeson MD, Lehman RA Jr. Surgical treatment of acute lateral collateral ligament and posterolateral corner injuries. Sports Med Arthrosc Rev. 2006;14(1):23–7. doi:10.1097/01.jsa.0000189950.44704.0d.
48. Werner BC, Hadeed MM, Gwathmey FW Jr, Gaskin CM, Hart JM, Miller MD. Medial injury in knee dislocations: what are the common injury patterns and surgical outcomes? Clin Orthop Relat Res. 2014;472(9):2658–66. doi:10.1007/s11999-014-3483-3.
49. Talbot M, Berry G, Fernandes J, Ranger P. Knee dislocations: experience at the Hopital du Sacre-Coeur de Montreal. CanJ Surg. 2004;47(1):20–4.
50. Laprade RF, Wijdicks CA. The management of injuries to the medial side of the knee. J Orthop Sports Phys Ther. 2012;42(3):221–33. doi:10.2519/jospt.2012.3624.
51. Chhabra A, Cha PS, Rihn JA, Cole B, Bennett CH, Waltrip RL, et al. Surgical management of knee dislocations. Surgical technique. J Bone Joint Surg Am. 2005;87 Suppl 1(Pt 1):1–21. doi:10.2106/JBJS.D.02711.
52. Cole BJ, Harner CD. The multiple ligament injured knee. Clin Sports Med. 1999;18(1):241–62.
53. Eranki V, Begg C, Wallace B. Outcomes of operatively treated acute knee dislocations. Open Orthop J. 2010;4:22–30. doi:10.2174/1874325001004010022.
54. Fanelli GC. Multiple ligament-injured (dislocated) knee. Sports Med Arthrosc Rev. 2011;19(2):81. doi:10.1097/JSA.0b013e31821912cd.
55. Lachman JR, Rehman S, Pipitone PS. Traumatic knee dislocations: evaluation, management, and surgical treatment. Orthop Clin North Am. 2015;46(4):479–93. doi:10.1016/j.ocl.2015.06.004.
56. Yasuda K, Kitamura N, Kondo E, Hayashi R, Inoue M. One-stage anatomic double-bundle anterior and posterior cruciate ligament reconstruction using the autogenous hamstring tendons. Knee Surg Sports Traumatol Arthrosc. 2009;17(7):800–5. doi:10.1007/s00167-009-0800-6.
57. Hua X, Tao H, Fang W, Tang J. Single-stage in situ suture repair of multiple-ligament knee injury: a retrospective study of 17 patients (18 knees). BMC Musculoskelet Disord. 2016;17:41. doi:10.1186/s12891-016-0894-1.
58. Shelbourne KD, Dickens JE. Joint space narrowing after partial medial meniscectomy in the anterior cruciate ligament-intact knee. J Am Acad Orthop Surgeons. 2007;15(9):519–24.
59. Quelard B, Sonnery-Cottet B, Zayni R, Badet R, Fournier Y, Hager JP, et al. Isolated posterior cruciate ligament reconstruction: is non-aggressive rehabilitation the right protocol? Orthop Traumatol Surg Res. 2010;96(3):256–62. doi:10.1016/j.otsr.2009.12.011.
60. Lee KH, Jung YB, Jung HJ, Jang EC, Song KS, Kim JY, et al. Combined posterolateral corner reconstruction with remnant tensioning and augmentation in chronic posterior cruciate ligament injuries: minimum 2-year follow-up. Arthroscopy. 2011;27(4):507–15. doi:10.1016/j.arthro.2010.11.007.
61. Kim SJ, Kim SG, Lee IS, Han HD, Chung IH, Kim SH, et al. Effect of physiological posterolateral rotatory laxity on early results of posterior cruciate ligament reconstruction with posterolateral corner reconstruction. J Bone Joint Surg Am. 2013;95(13):1222–7. doi:10.2106/JBJS.L.00861.
62. Chahla J, Moatshe G, Dean CS, LaPrade RF. Posterolateral corner of the knee: current concepts. Arch Bone Joint Surg. 2016;4(2):97–103.
63. Ross AE, Taylor KF, Kirk KL, Murphy KP. Functional outcome of multiligamentous knee injuries treated arthroscopically in active duty soldiers. Mil Med. 2009;174(10):1113–7.
64. Barrow A, Sheean A, Burns T. Return to duty rates after combat-related multiligamentous knee injury. Arthroscopy. 2016;31(6):e1–2. doi:10.1016/j.arthro.2015.04.007.
65. Denti M, Tornese D, Melegati G, Schonhuber H, Quaglia A, Volpi P. Combined chronic anterior cruciate ligament and posterior cruciate ligament reconstruction: functional and clinical results. Knee Surg Sports Traumatol Arthrosc. 2015;23(10):2853–8. doi:10.1007/s00167-015-3764-8.
66. Panigrahi R, Kumari Mahapatra A, Priyadarshi A, Singha Das D, Palo N, Ranjan BM. Outcome of simultaneous arthroscopic anterior cruciate ligament and posterior cruciate ligament reconstruction with hamstring tendon autograft: a multicenter prospective study. Asian J Sports Med. 2016;7(1):e29287. doi:10.5812/asjsm.29287.
67. Stannard JP, Riley RS, Sheils TM, McGwin G Jr, Volgas DA. Anatomic reconstruction of the posterior cruciate ligament after multiligament knee injuries. A combination of the tibial-inlay and two-femoral-tunnel techniques. Am J Sports Med. 2003;31(2):196–202.
68. Fleming BC, Brady MF, Bradley MP, Banerjee R, Hulstyn MJ, Fadale PD. Tibiofemoral compression force differences using laxity- and force-based initial graft tensioning techniques in the anterior cruciate ligament-reconstructed cadaveric knee. Arthroscopy. 2008;24(9):1052–60. doi:10.1016/j.arthro.2008.05.013.
69. Dabke HV, Gupta SK, Holt CA, O'Callaghan P, Dent CM. How accurate is partial weightbearing? Clin Orthop Relat Res. 2004;421:282–6.
70. Hurkmans HL, Bussmann JB, Selles RW, Benda E, Stam HJ, Verhaar JA. The difference between actual and prescribed weight bearing of total hip patients with a trochanteric osteotomy: long-term vertical force measurements inside and outside the hospital.

Arch Phys Med Rehabil. 2007;88(2):200–6. doi:10.1016/j.apmr.2006.11.005.
71. Yu S, McDonald T, Jesudason C, Stiller K, Sullivan T. Orthopedic inpatients' ability to accurately reproduce partial weight bearing orders. Orthopedics. 2014;37(1):e10–8.
72. Hustedt JW, Blizzard DJ, Baumgaertner MR, Leslie MP, Grauer JN. Is it possible to train patients to limit weight bearing on a lower extremity? Orthopedics. 2012;35(1):e31–7. doi:10.3928/01477447-20111122-14.
73. Hurkmans HL, Bussmann JB, Benda E, Verhaar JA, Stam HJ. Effectiveness of audio feedback for partial weight-bearing in and outside the hospital: a randomized controlled trial. Arch Phys Med Rehabil. 2012;93(4):565–70. doi:10.1016/j.apmr.2011.11.019.
74. Salter RB, Simmonds DF, Malcolm BW, Rumble EJ, MacMichael D, Clements ND. The biological effect of continuous passive motion on the healing of full-thickness defects in articular cartilage. An experimental investigation in the rabbit. J Bone Joint Surg Am. 1980;62(8):1232–51.
75. Piva SR, Fitzgerald GK, Irrgang JJ, Jones S, Hando BR, Browder DA, et al. Reliability of measures of impairments associated with patellofemoral pain syndrome. BMC Musculoskelet Disord. 2006;7:33.
76. Fitzgerald GK, Piva SR, Irrgang JJ. A modified neuromuscular electrical stimulation protocol for quadriceps strength training following anterior cruciate ligament reconstruction. J Orthop sports Phys Ther. 2003;33(9):492–501. doi:10.2519/jospt.2003.33.9.492.
77. 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. J Bone Joint Surg. 1995;77A(8):1166–73.
78. 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(6):653–85. doi:10.1016/j.arthro.2009.04.066.
79. Beynnon BD, Uh BS, Johnson RJ, Abate JA, Nichols CE, Fleming BC, et al. Rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind comparison of programs administered over 2 different time intervals. Am J Sports Med. 2005;33(3):347–59.
80. Escamilla RF, Macleod TD, Wilk KE, Paulos L, Andrews JR. Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: a guide to exercise selection. J Orthop Sports Phys Ther. 2012;42(3):208–20. doi:10.2519/jospt.2012.3768.
81. Ohkoshi Y, Yasuda K, Kaneda K, Wada T, Yamanaka M. Biomechanical analysis of rehabilitation in the standing position. Am J Sports Med. 1991;19(6):605–11.
82. Wilk KE, Escalmilla 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(4):518–27.
83. Shelburne KB, Pandy MG. Determinants of cruciate-ligament loading during rehabilitation exercise. Clin Biomech. 1998;13(6):403–13.
84. Toutoungi DE, Lu TW, Leardini A, Catani F, O'Connor JJ. Cruciate ligament forces in the human knee during rehabilitation exercises. Clin Biomech. 2000;15(3):176–87.
85. Escamilla RF, Zheng N, MacLeod TD, Imamura R, Edwards WB, Hreljac A, et al. Cruciate ligament tensile forces during the forward and side lunge. Clin Biomech. 2010;25(3):213–21. doi:10.1016/j.clinbiomech.2009.11.003.
86. Arms SW, Pope MH, Johnson RJ, Fischer RA, Arvidsson I, Eriksson E. The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. Am J Sports Med. 1984;12(1):8–18.
87. Irrgang JJ, Neri R. The rationale for open and closed kinetic chain activities for resotration of proprioception and neuromuscular control following injury. In: Lephart S, Fu FF, editors. Proprioception and Neuromuscular Control in Joint Stability. United States: Human Kinetics; 2000. p. 363–74.
88. Lind M, Nielsen T, Fauno P, Lund B, Christiansen SE. Free rehabilitation is safe after isolated meniscus repair: a prospective randomized trial comparing free with restricted rehabilitation regimens. Am J Sports Med. 2013;41(12):2753–8. doi:10.1177/0363546513505079.
89. Tyler TF, McHugh MP, Gleim GW, Nicholas SJ. The effect of immediate weightbearing after anterior cruciate ligament reconstruction. Clin Orthop Relat Res. 1998;357:141–8.
90. VanderHave KL, Perkins C, Le M. Weightbearing versus nonweightbearing after meniscus repair. Sports Health. 2015;7(5):399–402. doi:10.1177/1941738115576898.
91. Vascellari A, Rebuzzi E, Schiavetti S, Coletti N. All-inside meniscal repair using the FasT-Fix meniscal repair system: is still needed to avoid weight bearing? A systematic review. Musculoskelet Surg. 2012;96(3):149–54. doi:10.1007/s12306-012-0209-0.
92. LaPrade RF, LaPrade CM, Ellman MB, Turnbull TL, Cerminara AJ, Wijdicks CA. Cyclic displacement after meniscal root repair fixation: a human biomechanical evaluation. Am J Sports Med. 2015;43(4):892–8. doi:10.1177/0363546514562554.
93. Starke C, Kopf S, Lippisch R, Lohmann CH, Becker R. Tensile forces on repaired medial meniscal root tears. Arthroscopy. 2013;29(2):205–12. doi:10.1016/j.arthro.2012.09.004.
94. Park SE, DeFrate LE, Suggs JF, Gill TJ, Rubash HE, Li G. The change in length of the medial and lateral collateral ligaments during in vivo knee flexion. Knee. 2005;12(5):377–82.
95. Piva SR, Fitzgerald K, Irrgang JJ, Jones S, Hando BR, Browder DA, et al. Reliability of measures of impairments associated with patellofemoral pain syndrome. BMC Musculoskelet Disord. 2006;7:33. doi:10.1186/1471-2474-7-33.
96. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. J Orthop Sports Phys Ther. 2012;42(7):601–14. doi:10.2519/jospt.2012.3871.
97. Wilk KE, Macrina LC, Cain EL, Dugas JR, Andrews JR. Recent advances in the rehabilitation of anterior cruciate ligament injuries. Orthop Sports Phys Ther. 2012;42(3):153–71. doi:10.2519/jospt.2012.3741.