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Effects of open versus closed kinetic chain training on knee laxity in the early period after anterior cruciate ligament reconstruction

Matthew C. Morrissey
Zoe L. Hudson
Wendy I. Drechsler
Fiona J. Coutts
Philippa R. Knight
John B. King

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M. C. Morrissey (✉) · Z. L. Hudson
W. I. Drechsler · F. J. Coutts
Department of Health Sciences,
University of East London,
Romford Road,
London E15 4LZ, UK
e-mail: m.c.morrissey@uel.ac.uk,
Tel.: +44-020 8223-4597,
Fax: +44-020 8223-4965

P. R. Knight
Forest Healthcare Trust, London, UK

J. B. King
Department of Orthopaedics,
Royal London Hospitals,
London, UK

Abstract Knee extensor resistance training using open kinetic chain (OKC) exercise for patients recovering from anterior cruciate ligament reconstruction (ACLR) surgery has lost favour mainly because of research indicating that OKC exercise causes greater ACL strain than closed kinetic chain (CKC) exercise. In this prospective, randomized clinical trial the effects of these two regimes on knee laxity were compared in the early period after ACLR surgery. Thirty-six patients recovering from ACLR surgery (29 males, 7 females; age mean=30) were tested at 2 and 6 weeks after ACLR with knee laxity measured using the Knee Signature System arthrometer. Between tests subjects trained using either OKC or CKC resistance of their knee and hip extensors in formal physical therapy sessions three times per week. Following adjustment for site of treatment, pretraining injured knee laxity, and untreated knee laxity at post-training, the use of OKC exercise, when compared to CKC exercise, was found to lead to a 9% increase in looseness with a 95% confidence interval of –8% to +29%. These results indicate that the great concern about the safety of OKC knee extensor training in the early period after ACLR surgery may not be well founded.

Keywords Anterior knee laxity · Open kinetic chain · Closed kinetic chain · Knee Signature System · Resistance training

Introduction

In 1993, Yack et al. [26] first drew the attention of orthopaedic surgeons and physical therapists to the greater anterior tibial displacement (ATD) that occurs in open compared to closed kinetic chain resistance exercise of the knee extensors. The findings of this study were not the first to show that open kinetic chain exercise of the knee extensors may be more harmful to the torn or reconstructed anterior cruciate ligament (ACL) as this was investigated in earlier reports [1,9]. However, Yack et al. [26] were the first to directly address the question of differences between OKC and CKC exercise on ATD motion and this resulted in an increased research effort to compare these two forms of exercise. More importantly, the Yack et al. [26] study and related work led to a shift in clinical practice away from the use of knee extensor OKC training to CKC training. This shift occurred without the insight offered by a clinical trial comparing these two regimens.

In 1995, the first clinical trial comparing OKC and CKC exercise of the knee extensors in ACL-injured subjects was published [4]. Subjects in this study were recovering from ACLR and the subjects in the OKC group began to receive dynamic OKC training of the knee extensors at 6 weeks after surgery. Mean side-to-side differences in ATD (KT1000 maximum manual test) of 3.3 and 1.6 mm (variability not described) were noted in the OKC and CKC groups, respectively, although the period between surgery and testing was not specified. This difference in means was found to be statistically significant, although a smaller difference at a lower KT1000 force (20 lb) was not statistically significant. More importantly, it is difficult to conclude that the differences were due to training as no knee laxity testing was performed in the period between surgery and training initiation. To add to these inconclusive results in regards to possible differences between knee extensor OKC and CKC training on knee laxity, Beynnon and Fleming [3] have shed doubt on whether the exercises differ in their strain on the ACL.

In the ACLR knee there are two postoperative periods when the graft is believed to be most susceptible to loosening and stretching. Firstly, the graft fixation site is weakest immediately after surgery [13,14,19]. Secondly, as the fixation site become stronger, the graft tissue becomes gradually weaker until reaching its weakest point at approximately 12 weeks after surgery when strength recovery begins to occur [11,19]. It appears that Bynum et al. [4] compared CKC and OKC training in this later period of graft susceptibility. In the first of our planned clinical trials of OKC and CKC knee extensor training in patients with ACLR knees, we have endeavored to compare these two exercise regimens in the early period when the graft fixation site is weakest.

Materials and methods

Subjects

Prior to initiation of the study, a statistical power analysis was performed in order to estimate the number of subjects required to find statistically significant differences between the groups. At the time that this study was initiated there were few data in the literature that allowed satisfactory power analysis. Thus, the raw data used in this analysis was from Dr. Snyder-Mackler's work at the University of Delaware. This analysis indicated that 60 subjects would be required in order to find statistically significant differences in the groups in regards to knee stability changes.

Potential subjects were identified for this study from in-patients recovering from ACL reconstruction at five National Health Service and private hospitals in the East London area. Subjects were deemed suitable for inclusion in the study if they had no prior history of pathology requiring medical attention in the contralateral lower extremity.

Surgical procedures

Three orthopaedic surgeons participated in the study. Surgeon A (J.B.K.) performed ACL reconstruction using the technique described by Kennedy et al. [12] This technique consists of the ligament augmentation device (3M, Minneapolis, Minn., USA) with a small film of the patellar tendon. The tendon graft remains anchored at the tip of the tibial tuberosity. It is threaded through a tibial bone tunnel and then passed through the joint with an over the top technique and fixed with a lateral screw. Surgeons B (T.B.M.) and C (T.B.) performed arthroscopically assisted ACL reconstruction after harvesting a bone-patellar tendon-bone graft from the central third of the extensor mechanism via an anterior midline incision. The free graft is then inserted through tunnels in the tibia and femur with fixation using interference screws or staples.

Testing

Within the first 2 weeks following surgery, subjects were approached and given a written and verbal explanation of the study and invited to volunteer for participation in the study. The target date for test initiation was 2 weeks post-reconstruction surgery. Patients were allowed to participate in the study if their injured knee flexion passive motion was near 90° and they were able to walk without a walking aid. One of two physical therapists, at all times blinded to subject group assignment, performed knee laxity testing after subjects read and signed an informed consent form. The same examiner was used for post-testing each patient in order to avoid error due to inter-observer variability.

Knee passive laxity was tested on the Knee Signature System (KSS; Orthopedic Systems, Inc., Union City, Calif., USA). Arthrometric testing has been found to be valid relative to simultaneous radiography [23] Prior to testing of each subject, the KSS was calibrated using the "zero values function." The patient, wearing shorts, was positioned in sitting on the edge of the KSS seat. The uninjured knee was tested before testing of the injured knee. After application of the equipment to the leg using the manufacturer's recommendations, testing was performed with the knee in approximately 25° of flexion (Lachman test) and neutral rotation. The knee flexion angle was determined with a standard goniometer and the tibial rotation by observation. With the knee in this position, posterior and anterior tibial displacements were tested using 178 N of force. At least two test repetitions were performed on each leg. The first repetition was used to familiarize the patient with the procedure. The second repetition was deemed successful if displacement was recorded at 178 N and the curve describing force-displacement passed through the origin of these axes. In reliability testing, we have found that our examiners least significant difference values in test-retests of ten uninjured subjects ranged from 2.0 to 4.1 mm, which compares favourably to published data [18].

Knee laxity testing was followed by measurement of knee girth using a cloth tape and knee flexion and extension PROM using a standard goniometer. This was followed by testing the muscle strength of the: 1) hip extensors in the open kinetic chain in isokinetic concentric contractions; 2) hip and knee extensors during closed kinetic chain isotonic contractions (i.e. one repetition maximum isotonic leg press); and 3) knee flexors and extensors using isometric and concentric isokinetic tests. The dynamic muscle strength tests were performed with the knee moving from 0 to 90° flexion while the isometric test of the knee flexors and extensors occurred with the knee in 60° of flexion. Biomechanical analysis of knee function during walking and stair use was also performed using a three-camera plus force plate system [10].

Training

After initial testing, subjects were assigned to one of two treatment groups using block randomization and asked to attend physical therapy sessions three times per week for the 4-week training period of the study. Sessions occurred in the outpatient physiotherapy department at one of two National Health Service hospitals in the East London area (Mile End Hospital (MEH) or Whipps Cross Hospital (WCH). Because block randomization (four per block) was initiated prior to the inclusion of both sites, randomization was not separated for the two treatment sites.

The two treatment groups, groups C (closed kinetic chain training) and O (open kinetic chain training), differed in the type of isotonic resistance training used for their hip and knee extensors. Their training is summarized in Table 1. Group C subjects performed unilateral closed kinetic chain resistance training of the hip and knee extensors on a leg press machine (Horizontal Leg Press, Technogym UK, Bracknell, UK) with all these subjects using the same device for this exercise regardless of treatment site. The leg press machine was set so that the patient was supine with the hip

Table 1 Exercises excluded in the training groups. *OKC* Open kinetic chain, *CKC* closed kinetic chain

Exercise	Group C exclusions	Group O exclusions
OKC knee extensor exercise	X	
OKC hip extensor exercise	X	
Step-ups	X	X
Squats	X	X
Leg press		X
Plantar flexor exercise	X	X

and knee in approximately 90° of flexion for the start of each lift and the trunk slightly inclined from a parallel-to-floor position. A small block of wood was placed under the heel of the exercise leg and the patient was instructed to perform the exercise without making contact between the forefoot and the leg press platform. This was done to prevent the subjects from using their plantarflexors during this exercise.

Group O subjects exercised the same leg muscle groups in the open kinetic chain using either ankle weights or on machines designed for isolated resistance of these muscle groups (i.e. knee and hip extension machines) with various types of this equipment used throughout the study. The attending therapist decided whether to use ankle weights or machines for hip and knee extensor exercise and was urged to use machines as early as possible in the subjects' training in order to allow greater standardization of the resistance loads.

For the hip and knee extensor muscle resistance exercises, regardless of kinetic chain training type, three sets of 20 repetitions maximum (RM) were used in each session. No other resistance training exercises of these types was allowed. Attempts were made to equalize the training range of motion (ROM) and velocity in the training groups. The training ROM for both hip and knee extensors in both groups was 90 to 0°. To control velocity, subjects used Right Weigh (Baltimore Therapeutic Equipment, Baltimore, Md., USA) timing feedback devices. These machines give immediate feedback to the subjects about the speed of their weight lifting as they train relative to a target speed. The target speed setting used, denoted as level 3 on the machine, was 1.5 s for the concentric phase and 3.0 s for the eccentric phase of a training repetition with a 1.0-s interval between phases. These represent average angular velocities of 60°/s for the concentric phase and 30°/s for the eccentric phase.

The following resistance training exercises were excluded in group C: OKC exercise of the hip and knee extensors, step ups and squats. Group O subjects were not allowed to perform squats, step-ups and leg press exercises. Resistance training of other leg muscles was not controlled except the exclusion of exercise of the plantarflexors. For the most part, these additional exercises were of the hip adductors and abductors and knee flexors. Endurance training of the leg muscles was allowed in both groups using a stationary cycle. The decision as to the use of cycling and the intensity, frequency and duration of this exercise was left to the discretion of the attending therapist. Neuromuscular electrical stimulation and EMG-biofeedback of the hip extensors, knee flexors and extensors and ankle plantarflexors was not allowed during the training period.

No controls were placed on methods used to treat pain, swelling and hypomobility. In addition, training to enhance lower extremity balance and proprioception, which consists of minor resistance to the lower extremity muscles, [17] was not restricted or controlled in either group though guidance was offered so that the two training sites were roughly using the same exercise types, frequencies and durations. No study restrictions were placed on the patient's treatment before and after the study training period.

Data and statistical analyses

Because injured knee ATD measurements are positively skewed in their frequency distribution, logarithmic transformation of the injured knee ATD was performed and geometric means will be presented as summary statistics for the data. In clinical trials of intervention, it is vital that the treatment groups are compared for the status of the dependent variable at the pre-intervention point. This is especially true for analysis of knee laxity data, as we have found a significant correlation between starting laxity and change in laxity in the early period after ACLR [16]. In this study, analysis of covariance (ANCOVA) was used to examine differences between the two exercise groups in post-training laxity in the treated knee after adjustments had been made for: laxity in the untreated knee at post-training; pretraining difference in laxity between the two knees; and any overall difference in outcomes achieved between the two hospital sites. This model is easily extended to allow investigation of whether or not the relative effectiveness of the two exercise regimes differs between the two hospitals.

The laxity measurements in the treated knee are standardized to the uninjured knee at both pretraining and post-training. For pretraining measurements this is first achieved by subtracting the uninjured knee ATD from the injured. This method, commonly cited in the literature [2,4,6,8,20,21,25], is used because this is likely to be the most meaningful method of expressing this data for the clinician. This gives a single value that could meaningfully be included as a covariate in the ANCOVA model. For post-training measurements, standardization was achieved by having the uninjured knee ATD as a covariate. Such standardization helps to reduce unexplained variation in laxity measurements due to, for example, day-to-day variability in the performance of the examiner and of laxity in the knee (e.g. due to changes in body temperature).

We could also have standardized post-training knee laxity measurements by subtracting the uninjured knee ATD, consequently using this difference as the outcome variable in the ANCOVA model. However, knee laxity measurements expressed as side-to-side differences also have a positively skewed distribution. Side-to-side knee laxity differences can be transformed appropriately for use as the outcome variable in an ANCOVA analysis, but because the differences can be negative in value a simple log transformation cannot be used. It is highly desirable to use a simple logarithm transformation, as this is the only transformation that allows the results of the analysis to be back-transformed to give meaningful estimates of the magnitude of the difference between the two exercise techniques. By using the injured knee ATD as the outcome variable, which is always positive in value, and standardizing by the inclusion of uninjured knee ATD as an extra covariate, we can use the natural logarithm transformation. Meaningful estimates of standard deviation cannot be obtained once the data has been transformed.

By transforming the outcome data using a natural logarithm, performing the analysis on this transformed data and then back-transforming the estimate of the difference between the two groups, we can obtain an estimate of the ratio of geometric means of the injured knee ATD measurements taken in the two exercise groups and a 95% confidence interval for the ratio. The ratio will be expressed as Group O ATD/Group C ATD. Statistical analysis was performed using Stata [version 5; StataCorp (1997) Stata Statistical Software: Release 5.0, College Station, Tex., USA: Stata Corporation].

Results

Subjects were included in data analysis if all of the following criteria were met: 1) number of days between surgery and pre-test was less than 20; 2) number of days be-

Table 2 Means (±SD) of subject characteristics and knee laxity data. *Group C* Closed kinetic chain training group, *group O* open kinetic chain training group, *F* female, *M* male, *ATD* anterior tibial displacement under a load of 178 N using the knee ligament arthrometer

Variable	Group C	Group O
Body weight (kg; post-test)	76±13	77±12
Height (cm; pretest)	174±13	179±7
Gender	6F/12M	1F/17M
Age (years)	31±8	28±9
Period from injury to surgery (months)	45±61	31±28
Patients having previous arthroscopic knee surgery	15	14
Patients having partial meniscectomy prior to ACLR	4	6
Patients having ligament augmentation device	4	5
Patients having partial meniscectomy with ACLR	3	6
Period from surgery to pre-test (days)	15±1	14±1
Pretest injured knee ATD (geometric mean in mm)	9.87	9.46
Post-test injured knee ATD (geometric mean in mm)	9.98	10.25

tween pre- and post-test was less than 35; and 3) number of treatment sessions was between 9 and 13. Thirty-six patients successfully participated in the study and their characteristics are summarized in Table 2. Only three subjects had non-ACL ligament injuries in the ACLR knee and these were all noted in the arthroscopic surgery that was performed prior to the ACLR surgery. Two of these three subjects had PCL injury and the third had an MCL injury. All were in group C.

Crosstabulating training regime with physical therapy treatment site, we found that patients at WCH were more likely to receive OKC training and that patients at MEH were more likely to receive CKC training. Of the 18 subjects in group C, therapy occurred equally at both sites, while of the 18 group O subjects, 13 had therapy at WCH and the other five subjects were trained at MEH. This introduces the possibility that any observed difference between the two training methods is confounded by any overall difference in outcome between the two hospitals. Such potential confounding was controlled during the statistical analysis.

The data in Table 2 indicate that injured knee laxity prior to and after training is similar in the two groups with the geometric means, which are less susceptible to distortion by positive skew, presented in this Table. The results of the ANCOVA with transformed data indicate that there is no evidence that the relative effect of the two exercise regimes on knee laxity differs between the physical therapy treatment sites (t=0.41, P=0.68). The important result of this investigation is that subjects in group O displayed higher laxity scores in the post-training examination but it was not possible, with the data in this study, to reject the possibility that this difference between the two exercise regimes was due to chance [ratio of geometric means (O/C)=1.09; 95% confidence interval: 0.92, 1.29; t=1.01, P=0.32]. In other words, the OKC group was estimated to be 9% looser than the CKC group at the post-training assessment but the 95% confidence interval indicates that the data are consistent with both greater and lesser laxity in the OKC group. That is, the data indicates that the two exercise regimens did not differ in their effects on knee laxity.

Discussion

The results of this investigation, showing no statistically significant difference between open and closed kinetic chain training of the knee and hip extensors on knee anterior tibial displacement in the early period after ACLR, can be explained in a number of ways. First of all, one explanation for the lack of differences in laxity change between these two training regimens concerns the question of whether these exercises actually differ in their strain on the ACL. That is, despite the prevailing opinion of physical therapists and orthopaedic surgeons that OKC training of the knee extensors is more stressful for the ACL than CKC exercise, the possibility exists that this is not so or that this increased strain is not sufficient to cause increased knee laxity, at least in this subject population. The early studies that compared ACL strain in CKC and OKC exercise of the knee extensors consistently found OKC exercise either offered more strain on the ACL or caused greater anterior tibial displacement during the exercise [1,9]. However, more recent work by Beynnon and Fleming [3] found that the ACL strain in the two exercises is similar.

Another possible explanation for the lack of differences between the treatment groups in this study concerns the intensity of the training in the OKC group. Concerns about the questionable safety of OKC knee extensor resistance training through the extended ROM are prevalent and profound in physical therapy and orthopaedic medicine. This was evident in the number of our associates outside of the study who made comment about the questionable wisdom of using this exercise in this patient population. Concern over this effect on the aggressiveness of our therapists applying OKC knee extensor treatment led to discussion of this 'problem' at team meetings. The study principal investigator (MCM) also made monthly visits to the training sites to observe treatment of the subjects. The principal investigator attempted to convince the therapists that the worse case scenario would consist of unassertive OKC knee extensor training in this study leading to a false conclusion that OKC knee extensor training is safe. Furthermore, it was explained that this false conclusion could lead to increased, unsafe OKC use in the profession after the study results are reported. In sum, the principal investigator was satisfied that the therapists accepted this argument and were as aggressive in their training of the knee extensors in the OKC as they were in using CKC exercise. This conclusion was mainly based on the observation of the training sessions and the fact that the attending therapists continued to use OKC training with all study subjects after the subjects had completed study participation (indicating their lack of fear of using knee extensor OKC exercise). Future studies may be able to avoid this potential problem with the use of isokinetic or isometric training where the resistance loads are largely independent of the therapist. We chose to use isotonic resistance because this is the most commonly used method in present clinical practice.

A third explanation for the lack of a significant difference in knee laxity change between groups concerns the stresses placed on the knee outside of physical therapy. It is possible that the groups differed in the stresses they placed on the passive restraints to ATD during activities outside of therapy and that this may have clouded the results. In the future, we intend to account for activity levels outside of therapy.

Another explanation for the non-significant differences between the treatment groups concerns the threshold for graft fixation site loosening or graft lengthening. It is possible that the knee extensor OKC and CKC exercises may differ in the loads they place on the graft but both loads may be below the load threshold necessary to cause increased ATD. This highlights the need to compare the training regimens at different periods after ACLR when the threshold for increased ATD may be lower or the resistance loads greater. This type of analysis is also required for ACL-deficient knees.

A fifth explanation for the lack of significant differences between treatment groups concerns a possible type II error. That is, this study may have lacked the subject numbers and related statistical power to detect a real difference in knee laxity changes between the groups. However, even if a larger sample was used to find statistically significant differences between the means found in this investigation, the difference in means is of questionable clinical significance. Additionally, the laxity changes in both groups are arguably not clinically significant.

A final possible cause for finding no differences between the treatment groups concerns the overall training load used in this study. Nine to 13 treatment sessions each containing 60 cycles of knee extensor concentric and eccentric contractions over a 1-month period may not be sufficient to cause training effects sufficient to show differences in the kinetic chain types. However, this overall training load is likely to be more than what is presently used for OKC knee extensor training in the early ACLR rehabilitation period and is a starting point for future studies comparing the effects of these regimens on knee laxity.

Regardless of the eventual conclusions drawn in regards to the effects of knee extensor OKC and CKC resistance training on knee laxity, it is important to consider the relative importance of knee anterior tibial displacement. On one side of this argument are papers such as that of Daniel et al. [5] that have found significant correlations between ATD, when tested immediately after ACL injury, and later need for meniscal surgery and development of osteoarthritis. In contrast, others [7,22,24] have found that ATD is not significantly correlated to function. We tend to give both of these arguments importance with the suspicion, not yet borne out by extensive study, that the amount of ATD may not determine functional loss but could lead to later injuries (e.g. of the meniscus) and the development of osteoarthritis. We know of no studies that investigate whether there is an ATD change threshold for later problems. We can say that we have been following the patients in this study with 6- and 12-month testing and have not found that subjects who had significant increases in laxity during the study period have developed problems within 12 months of surgery. We intend to perform further analysis of possible long-term effects.

Recognizing that ATD is only one consideration in determining which type of kinetic chain resistance to use after ACLR, additional analysis has been performed to address concerns about knee pain and function changes that may differ as a result of OKC and CKC knee extensor training. In these studies, the treatments do not appear to differ in their effects on knee pain [15] or function [10]. Considering all of these results, it is suggested that, until there is evidence that open kinetic chain training offers an advantage over closed kinetic chain knee extensor training after ACLR, closed kinetic chain training be the treatment of choice.

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