ANALYSIS OF ANTERIOR TIBIAL TRANSLATION, PEAK TORQUE, AND QUADRICEPS AND HAMSTRINGS COACTIVATION IN INDIVIDUALS WITH ANTERIOR CRUCIATE LIGAMENT INJURIES PERFORMING ISOMETRIC OPEN KINETIC CHAIN EXERCISES

RODRIGO ANTUNES DE VASCONCELOS[3,4], JULIANO COELHO ARAKAKI[3], ADRIANO P. SIMÃO[3], ANAMARIA SIRIANI DE OLIVEIRA[1], CLEBER JANSEN PACCOLA[2], DÉBORA BEVILAQUA-GROSSI[1]

SUMMARY

The aim of this study was to evaluate the anterior tibial translation (ATT), isometric peak torque and EMG activity in individuals with acl rupture performing isometric contraction in open kinetic chain at an angle causing substantial ATT. Twenty male subjects with acl total rupture (31.1± 7.45 years) and 20 control subjects (22.2 ± 3.15 years) were evaluated. Electromyography, arthrometric kt 1000 and isokinetic dynamometry were used to evaluate the quadriceps and hamstrings EMG activity, passive and active ATT and isometric peak torque, respectively, during three maximum isometric voluntary contractions at 30 degrees of knee flexion. The results demonstrated that the passive and active ATT is significantly greater in knees with acl rupture compared to the contralateral knees, dominant and non dominant knees of the control group. However the active ATT values were greater than the passive ATT. There is no statistically significant differences between groups concerning quadriceps and hamstring EMG activity and in the peak torque produced during the motor task requested. The results of this study demonstrated that individuals with acl rupture had similar behavior compared to normal knees regarding isometric peak torque and motor control despite the different arthrokinematics of the tibiofemural joint observed in injured knees.

Keywords: Knee; Electromyography; Anterior cruciate ligament; Exercise.

Citation: *Vasconcelos RA, Arakaki JC, Simão AP, Oliveira AS, Paccola CAJ, Bevilaqua-Grossi D. Analysis of anterior tibial translation, peak torque, and quadriceps and hamstrings coactivation in individuals with anterior cruciate ligament injuries performing isometric open kinetic chain exercises. Acta Ortop Bras. [serial on the Internet]. 2007; 15(1): 14-18. Available from URL: http://www.scielo.br/aob.*

INTRODUCTION

In the last 15 years, there was a huge growth of the number of published studies addressing researches in the areas such as anatomy, biomechanics, reconstruction surgery, and ACL rehabilitation techniques. The advancement of research in these areas of orthopaedics has considerably reduced the time required to athletes submitted to the reconstruction of that ligament to go back to sports activities.[1]

In the rehabilitation of patients with ACL rupture, studies concerning safety, effectiveness and open kinetic chain exercises (OKC) or closed kinetic chain (CKC) are most frequently found[2]. Despite OKC exercises had been through a period of total disapproval towards its inclusion on ACL rehabilitation, they are currently an important alternative for preparing specific protocols addressing such ligament. The safety in prescribing OKC exercises for patients with ACL rupture is especially due to the awareness about the close relationship between this kind of exercise, ACL and muscular reactions provoked by performing this exercise.

Several limitations were imposed for including OKC exercises on ACL rehabilitation. Those limitations were based on many published studies showing an excessive anterior tibial translation (ATT) in angles between 45° and 0°[3,4,5]. As the ACL is the primary restrictor of this movement [6], that excessive ATT can promote, during the early postoperative period, an "in situ" stress (straightly towards its fibers) on a graft at osteointegration process inside bone tunnels as well as revascularization, with deleterious effects to it, in addition to overburden secondary restrictors such as collateral ligaments, menisci, joint capsule and cartillage, leading to joint degeneration in patients who chose a conservative treatment method. With the objective of preparing safer rehabilitation protocols, many authors have used direct and indirect methods for quantifying "in situ" strengths produced on the ACL in exercises performed in OKC [3,6,7,8].

Those methods require laboratories counting on expensive infrastructure and equipment, of high technical supply, and, in many of them, the use of cadavers as models, turning their reproduction in a clinical environment impossible. The arthrometer KT 1000 (MEDmetric,San Diego,CA) was developed by Daniel [9] in order to assess ATT through Lackman's standard test position, manual maximum test, and active test of the quadriceps intending to differentiate knees with ACL injuries from normal knees. The three mentioned tests evaluate patients at dorsal decubitus, relaxed, or just performing a voluntary quadriceps contraction strong enough to lift the calcaneus up from test table. Howell [10] was the first to publish a modified active test of the quadriceps (MATQ) for measuring ATT using the KT 1000 arthrometer as a simpler method. In the MATQ, the investigator collects ATT values during maximum

Study conducted at the Department of Biomechanics, Medicine and Locomotive Apparatus Rehabilitation, Hospital das Clínicas, Medical College, University of São Paulo – Ribeirão Preto, SP, Brazil

Correspondences to: Débora Bevilaqua-Grossi - Departamento de Biomecânica, Medicina e Reabilitação do Aparelho Locomotor - Hospital das Clínicas da Faculdade de Medicina de Ribeirão Preto da Universidade de São Paulo - Avenida Bandeirantes, nº 3900, Campus da USP, CEP 14049-900 - Ribeirão Preto, São Paulo, Brasil - E-mail address: deborabg@fmrp.usp.br

1. Ph.D. Professor, Department of Biomechanics, Medicine and Locomotive Apparatus Rehabilitation FMRP-USP
2. Chairman, Department of Biomechanics, Medicine and Locomotive Apparatus Rehabilitation FMRP-USP
3. Physical Therapist, Master in Medical Sciences - FMRP-USP
4. Knee Surgery Group, Department of Orthopaedics, Hospital Celso Pierro - PUCC

Received in: 11/21/05; approved in: 07/30/06

voluntary isometric contractions (MVIC) performed in an isokinetic dynamometer in order to study indirect OKC effects on ACL at different flexion angles and subjects groups. The author compared the ATT produced during isometric contraction of the quadriceps to the ATT produced by the standard test with strength of 89N performed at rest position.
Subsequently, Jenkins et al.[11] using the same test (MATQ) compared the ATT produced during isometric exercises in OKC (extensor table) and in CKC (leg press 180). Those authors used different methodologies, producing conflicting results and limiting conclusions. One of the greatest limitations in both studies was the failure to investigate the electromyographic activity between quadriceps and hamstrings simultaneously when collecting data on the ATT produced by OKC exercise, because the differences on translation values may have been biased by the contraction of the muscles around knee during required task, especially on hamstrings action [12].
This mechanism of dynamic stability would be primarily influenced by hamstrings counteracting tibial anteriorization to the femur[7].
The theory suggesting that hamstrings could protect the ACL was raised after the publication of studies by Gruber et al.[13] who described ACL reflex range. The ACL reflex range is characterized by an increased electromyographic activity of femoral biceps and semitendinous muscles when the ACL is stimulated by electricity or mechanical deformation. This protective mechanism occurs due to an influence of the rich nervous supply possessed by the ligament[14]. The existence of that reflex-range was shown both in animals and in human beings[15,16].
The analysis of muscular co-activation in rehabilitation exercises has a critical importance for understanding the behavior of knees with and without ACL injuries, especially regarding their protective role or the potential to cause ligament injury.
The active extension of the knee performed with the aid of pulleys or advanced mechanotherapy equipment cause high shear forces that are transmitted to the ACL in a normal knee, and allows for an over normal ATT when ACL is absent. However, hamstrings activation during these exercises may reduce ATT, since those muscles are inserted on the posterior portion of the tibia and promote posterior traction or shear to the tibia[12]. This posterior traction would increase joint stiffness resulting from the activity of agonists and antagonists[17].
Several studies used the electromyography for investigating muscular co-activation and the resultant interaction between quadriceps and hamstrings in knee active extension exercises.
Solomonow et al.(15) , in their classic study, assessed the EMG activity of quadriceps and hamstrings in normal subjects and in those with ACL rupture, where these performed 6 isokinetic contractions at 15°/s in a Cybex II isokinetic dynamometer at angles ranging 0 - 90°. In a patient with ACL injury, the authors demonstrated the mechanism of tibial sub dislocation to the femur, which occurred at approximately 46° causing a dramatic reduction of the extensor torque with a resultant increase of the range of electromyographic signal of hamstrings and a reduced range of signal of the quadriceps, justifying the fact that joint stability in extension is not a role played uniquely by ACL, but also by the antagonist muscle – in this case, the hamstrings – avoiding ATT. Taking this study as a reference, many authors with various methodologies showed an increased electromyographic activity of hamstrings at angles close to end extension in OKC, stressing the consensus about hamstrings working as synergists to the ACL [18-21].
Nevertheless, most of the studies do not include patients with total ACL injury and did not assess anterior tibial translation simultaneously with quadriceps and hamstrings electromyographic activity correlating this to performance angles that produced more significant ATT to a similar increase of the range of electromyographic signal. Furthermore, few studies have investigated co-activation in isometric activities. There is a shortage of studies in literature using and investigating the co-activation between quadriceps and hamstrings in a larger number of volunteers with ACL injuries during isometric contractions of knee extension in OKC comparing these individuals to normal subjects.
The simultaneous analysis of muscular co-activation, ATT and torque peak evaluation enables us to correlate hamstrings behavior during angles producing more extensive tibial translation identifying potential changes influenced by ACL injury when performing this specific motive task.
By identifying those changes, OKC exercises in rehabilitation programs for patients with ACL injury may be introduced in a more grounded way.
The objectives of this study were to assess anterior tibial translation (ATT), isometric torque peak, and electromyographic activity of individuals with anterior cruciate ligament (ACL) injuries by performing isometric contractions in open kinetic chain at 30° knee flexion angle.

MATERIALS AND METHODS

Sample characterization

Two groups involving a total of 40 male volunteers, ages ranging from 18 to 40 years, were enrolled in the study. The first group consisted of 20 volunteers (mean age 31.1 $\pm$ 7.45 and mean height 174 cm $\pm$ 6.65) with unilateral ACL injury occurred at least 6 months previously to the beginning of the study. The volunteers with injured ACL were further divided into two groups: knee with injured ACL (IACL) and healthy contralateral knee (HCLK). The Lysholm's subjective evaluation was used(22). The average score achieved on Lysholm scale for volunteers in group ACL was 69.45 $\pm$ 17.34 points.
The second group named as control was constituted of 20 volunteers (mean age 22.2 $\pm$ 3.15 SD and mean height 175cm $\pm$ 8.55 SD) with no previous history of knee injuries whatsoever or neuromuscular disorders, and they could not present with ligament laxity differences $\geq$ 3mm between knees. Subsequently, similarly as happened with the injured subjects group, the control group was further divided into dominant knee (DK) and non-dominant knee (NDK).
All volunteers signed a formal informed consent term for taking part of the research, which was approved by the committee on ethics of Ribeirão Preto Medical College.

Instrumentation

For measuring ligament laxity in the ACL group and control group, the manual maximum test (MMT) was performed using the KT1000 tm arthrometer (MEDmetric , San Diego,CA) where the patient was positioned at test standard position totally relaxed, stabilized, and with knee positioned at 30° flexion (Figure 1A). Following MMT, the KT 1000 tm was used for collecting ATT data during the Modified Active Test of the Quadriceps (MATQ) during three Maximum Voluntary Isometric Contractions with knees flexed at 30° (Figure 1C). The reliability test intra-investigators (ICC) intra-days and inter-days for the investigator who performed the tests with the KT 1000 on MMT and MATQ were previously performed before each data collection. Reliability (ICC) for MMT ranged from 0.79 to 0.98, and from 0.93 to 0.98 for MATQ[23].
For performing the three MVIC and collect the isometric peak at the angle above mentioned, an isokinetic dynamometer (Biodex multi-joint system 3 pro) belonging to the Department of Physical Therapy, Federal University of São Carlos, was used, which was previously set up by means of its specific software for operating in the isometric mode in order to precisely measure desired angle and to provide visual feedback to the volunteer regarding strength at extensor moment that was produced during the test.
For electromyographic assessment, electromyography equipment (Myosystem Br 1, Prosecon®) was employed. Electric activity of rectus muscle of the thigh (RT), oblique vastus medialis (OVM), long lateral vastus (LLV), femoral biceps (FB) and Semitendinous

(ST) muscles were captured by simple differential active surface electrodes (EMGsystem), low and high bypass filter with frequency cutoffs at 1000 Hz and 20 Hz. The gross captured signals were subsequently processed by using Myosystem – BR 1(version 2.5) software at a sampling frequency of 2000 Hz , which transformed the gross signal of the motor units action potentials into numeric values of the RMS (root mean square).
For normalizing electromyographic data correspondent to hamstring muscles signal, the volunteers performed MVIC with knees flexed at 30^o during 5 seconds. For normalizing electromyographic data correspondent to quadriceps muscles signal, the volunteers performed MVIC with knees extended at 90^o during 5 seconds.
Following, the subjects were asked to perform MATQ by making three MVIC with knees extended for 5 seconds for each contraction with knees at a flexion angle of $30\,^o$ where ATT and the isometric torque peak were simultaneously collected (Figure 1B). Two-minute intervals between MVICs at each angle were employed to avoid muscular fatigue. The order of the exercises at each angle was randomly assigned. The tests were first made on the contralateral knee for the injured group, and on the non-dominant knee for control group.

Statistical Analysis

The variance analysis method (ANOVA) with repeated measurements, if required, was used for assessing ATT during MATQ and isometric torque peak between groups. $P \leq 0.05$ was the significance level adopted in this study.
For assessing the range of quadriceps muscle electromyographic signal (RT + OVM + LLV) among groups, the ANOVA method was employed with repeated measurements, and, if required, the contrasts formation technique for the analysis of data. $P \leq 0.05$ was the significance level adopted. For assessing hamstrings muscles electromyographic signal (FB + ST), the Wilcoxon's non-parametric test was used for paired data when a comparison was made between IALC x HCLK and NDK x DK, and the Mann-Whitney's non-parametric test for independent samples. $P \leq 0.05$ was the significance level adopted.

RESULTS

Manual maximum test (MMT) and modified active test of the quadriceps (MATQ)

On the manual maximum test, significant higher ATT values were found for IACL group (15.91 ± 2.82 SD) when compared to the other HCLK (7.74 ± 2.04 SD), DK (7.42 ± 2.18 SD), and NDK (7.39 ± 2 SD) groups ($p \leq 0.001$). No significant differences were found between HCLK X DK (p=0.63), HCLK x NDK (p=0.58) and DK x NDK (p=0.85) groups (Figure 2).
During MATQ, significantly higher ATT values were found for IACL group (11.21 ± 2.4 sd) when compared to the other HCLK (7.13 ± 2.3 SD), DK (7.08 ± 2.3 SD), NDK (7.04 ± 2.1 SD) ($p \leq 0.05$) (Figure 2).

Quadriceps and Hamstrings electromyographic activity

The analysis of the EMG activity by normalized RMS values for the quadriceps (RT + OVM + LLV) and hamstrings (FB + ST) muscular groups showing contraction strength at proposed angle (30o) are expressed as a percentage of the MVIC. Results show that there is no statistically significant difference on the electromyographic activity of the quadriceps between IACL X HCLK (p =0.11), (IACL x DK) (p =0.14), (IACL x NDK) (p =0.14) groups (Figure 3). Similarly, no statistically significant difference was found between IACL x HCLK (p =0.18), IACL x DK (p =0.70), and IACL x NDK (p =0.95) groups for hamstrings electromyographic activity. Hamstrings electromyographic activity remained low, ranging from 9 to 13 % of the MVIC (Figure 3).

Figure 1 - *(A) Individual being positioned for performing the maximum manual test (MMT) at rest. (B) Volunteer being positioned for performing the modified active test of the quadriceps (MATQ) with knee flexed at 300. (C) KT1000 arthrometer positioned for MATQ test.*

Isometric torque peak

There was no statistically significant difference between IACL (100.32 ± 20.36), HCLK (112.17± 24.65), DK (111.54 ± 28.80), NDK (109.77± 32.66) groups for torque peak produced with knee flexed at 30^o ($p > 0.05$) (Figure 4).

DISCUSSION

One of the objectives of this study was to assess if the KT 1000 tm is able to differentiate knees with ACL injuries from those with intact ACL on both proposed tests, the MMT and the MATQ. Results showed a significantly higher ATT values during MMT in knees with ACL injury included on IACL group when compared to other groups ($p \leq 0.001$).

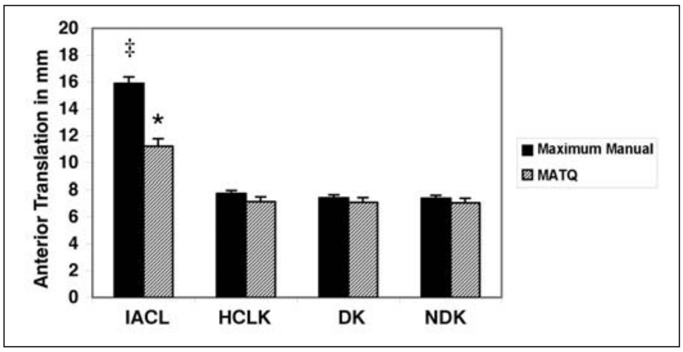

Figure 2 – *Values for anterior tibial translation collected during maximum manual test (MMT) and modified active test of the quadriceps (MATQ)*
‡ Significant difference between IACL group compared to other groups at MMTp≤0.05.
** Significant difference between IACL group compared to other groups at MATQ p ≤ 0.05.*
IACL – Injured ACL group; HCLK – healthy contralateral knee; DK – dominant knee control group; NDK – non-dominant knee control group.

Bach et al.(23) using the MMT assessed ATT in volunteers with acute and chronic ACL injuries and compared them to normal subjects. The mean ATT in acute and chronic injuries were similar, with no statistically significant differences, was 13.0 and 13.5 mm, respectively; however, they were almost twice the ATTA values in normal knees: 7 mm. The authors conclude that MMT was the strongest variable for discriminating the ATT difference between a normal knee and a knee with ACL rupture. Similarly, Rangger et al. (24) concluded that the highest translation values and the biggest displacement differences between injured knees and normal knees

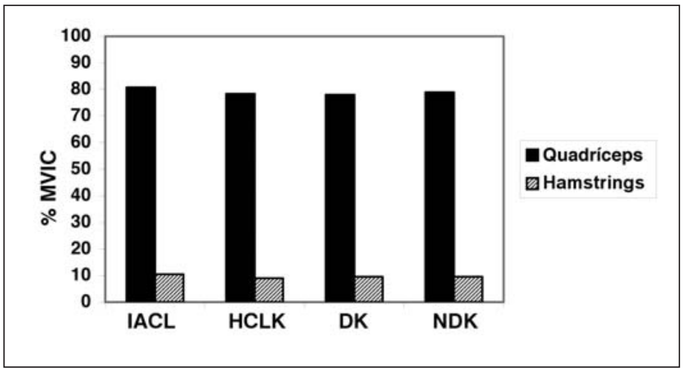

Figure 3 – *Electromyographic activity of the quadriceps (RT + LLV + OVM) and hamstrings (FB + ST) normalized and shown as a percentage of the maximum voluntary Isometric Contraction during the modified active test of the quadriceps with knee flexed at 30º. There are no statistically significant differences between groups p>0.05. Injured ACL (IACL) n=20, contralateral knee (HCLK) n=20, dominant knee control group (DK) n=20, non-dominant knee control group (NDK) n=20.*

were produced by MMT. Another test modality in which the KT 1000 tm arthrometer was used was the modified active test of the quadriceps (MATQ). The results of the present study showed that ATT was significantly higher at 30º (11.21 ± 2.4) in the IACL group when compared to the other groups. These results show that the use of the KT 1000 tm arthrometer in MATQ is able to reproduce results similar to other studies using various instruments for measuring ATT and, as a result, the "in situ" forces on the ACL showing higher ATT values between 30º and 0º of knee flexion(5,6,25,26).

Only two studies used the KT 1000 tm as the method of choice for

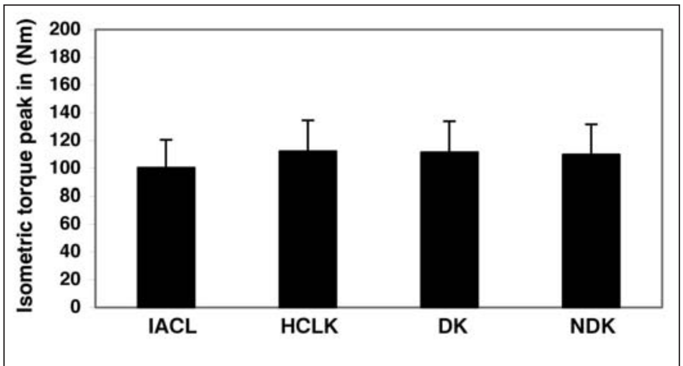

Figure 4 - *Isometric torque peak (Nm) collected during modified active test of the quadriceps (MATQ) with knee flexed at 30º. There are no statistically significant differences between groups p > 0.05. Injured ACL (IACL), contralateral knee (HCLK), dominant knee control group (DK), non-dominant knee control group (NDK).*

assessing ATT during OKC exercises, showing conflicting results between them.

Howell(10) did not find any significant ATT differences during MATQ at angles ranging from 15o to 60º of knee flexion. These results may have been influenced by factors concerned to the methodology employed for preparing the study. Inclusion criteria for volunteers to be assigned to the group with injured ACL have not been described in the study, and the intra-investigator reliability test for the KT 1000 tm during MATQ has not been conducted, what may cause a high level of variability between measurements and repetitions.

Jenkins et al.(11) found lower ATT values produced by the group with ACL injury when performing MATQ on the extensor chair at 30º (8.10 mm) and 60º (2.17mm). Those results disagree with the values found in this study, once the IACL showed higher values at 30º (11.21± 2.4). The difference between those values may have been biased by methodological differences, once the authors used 25% of each individual's body weight to perform MATQ, while, in this study, the maximum voluntary isometric contraction was employed. As a result, lower levels of quadriceps contraction and the activation of a lower number of motor units may have been produced in the study by Jenkins et al.[11] leading to a lower ATT during task effort.

Another objective of this study was to assess the ATT in OKC; however, although results show a significant ATT increase with knees flexed at 30º for IACL group, limited conclusions can be drawn regarding the stress imposed to the ACL during these exercises, especially regarding the suggestion that this excessive translation found could cause deleterious effects to the graft after this ligament is surgically reconstructed.

Although the present study disagrees with the findings by Howell(10) regarding ATT non-differentiation between injured and normal knees using the KT 1000 tm as a measuring instrument, one of the conflicting results shown by that author was that the MVIC performed by volunteers did not exceed ATT values provoked by a standard test with the kt 1000 tm performed at rest with an anteriorization force of 89 N.

Howell(10) in his study, explains that the anterior shear Component caused by quadriceps contraction is reduced as tibia slides anteriorly as a result of patellar tendon angle reaching to a more perpendicular alignment versus tibial plateau with an anteriorized tibia.

In order to investigate the influence of quadriceps and hamstrings in ATT, the electromyographic activity of 5 thigh muscles were collected. The results of this study show significant higher ATT values at 30º for the IACL group when compared to the ATT produced at the same angle for other groups; however, there were no changes on the EMG activity of the quadriceps and hamstrings among groups during the demanded motor task, thus not showing differences on motor control strategy between subjects with ACL injury and normal knees performing isometric contractions of the quadriceps with knees flexed at 30º. Another factor showing a similar muscle activation pattern among groups was the absence of significant differences on isometric torque peak, showing similar recruitment of motor units of the quadriceps, once this would be the key muscular group generating the collected isometric torque. Therefore, even with this research being reproduced in a similar way, the results of this study do not corroborate the theory of the mechanism of reflex range shown by Solomonow et al.[15] as a result of the increased electromyographic signal range of the hamstrings and the inhibited EMG activity of the quadriceps at angles provoking high ATT as a result of a neuromuscular response started after an increase of load and mechanical deformation speed of joint mechanoreceptors located at the ACL or capsule and other ligamentar structures with the objective of preventing excessive ATT.

Few studies investigated the co-activation between quadriceps and hamstrings in isometric tasks performed in OKC by individuals with ACL injury. Grabiner et al.[27] did not find significant differences on hamstrings activity at angles close to total extension.

Kubo et al.[28] assessed the electromyographic activity of agonists (femoral quadriceps) and antagonists (femoral biceps) during isometric torque measurements at 10º intervals at angles ranging from 40o to 110º of knee flexion. Although the authors found a greater femoral biceps activity at the highest flexion angles, no significant differences were found in terms of co-activation patterns with knee flexed at 40º e 90º. Both researchers included only normal subjects in the study, recording results similar to ours for control group. Therefore, results have not evidenced differences in the response of quadriceps and hamstrings electromyographic activity and isometric torque peak in volunteers with ACL injury, although they presented with a higher ATT when compared to the other groups. A probable explanation for this may be that the imposed motor task does not promote high levels of instability and the mechanism of reflex range between ACL and hamstrings have been shown to occur only in dynamic tasks imposing a greater challenge to dynamic stabilizers, as, for example, rotational movements[21].

CONCLUSION

In the present study, individuals with and without anterior cruciate ligament injuries do not show changes on electromyographic co-activation patterns between quadriceps and hamstrings and on isometric torque and peak production, even at angles producing greater ATT in isometric contractions. By using the KT 1000 we were able to differentiate the behaviors of knees with ACL injuries from normal knees performing maximum voluntary isometric contraction with knees extended at 30º.

REFERENCES

1. Bollen S. Advances in the management of anterior cruciate ligament injury. Curr Orthop. 2000; 14:325-8.
2. Fitzgerald GK. Open versus closed kinetic chain exercises: issues in rehabilitation after anterior cruciate ligament reconstruction surgery. PhysTher. 1997; 77:1747-54.
3. Hirokawa S, Solomonow M, Lu Y, Lou ZP, D´ambrosia R. Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction Am J Sports Med. 1992; 20:299-306.
4. Beynnon BD, Johnson RJ, Fleming BC, Stankewich CJ, Renstrom PA, Nichols CE. The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension. A comparison of an open and a closed kinetic chain exercise. Am J Sports Med. 1997; 25: 823-9.
5. Escamilla RF, Fleisig GS, Zheng N, Barrentine SW, Wilk KE, Andrews JR. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc. 1998; 30:556-69.
6. Woo Sl, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu Fh. The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon . A cadaveric study comparing anterior tibial and rotational loads. J Bone Joint Surg Am. 2002; 6:907-14.
7. 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; 12:8 -18.
8. Nisell R, Erickson MO, Nemeth G, Ekholm J. Tibiofemoral joint forces during isokinetic knee extension. Am J Sports Med. 1989;17:49-54.
9. Daniel DM, Stone ML. Instrumented Measurement of anterior knee laxity in patients with acute ACL disruption. Am J Sports Med. 1985;13:401-7.
10. Howell SM. Anterior tibial translation during a maximum quadriceps contraction: is it clinically significant? Am J Sports Med. 1992;18:573-8.
11. Jenkins WI, Munns SW, Jayaraman G, Wertzberger KI, Neely KA . Measurement of anterior tibial displacement in the closed and open kinetic chain. J Orthop Sports Phys Ther. 1997; 25:49-56.
12. Yanagawa T, Shelburne K, Serpas F, Pandy M. Effect of hamstrings muscle action on stability of the ACL-deficient knee in isokinetic extension exercise. Clin Biomech. 2002; 17: 705-12.
13. Gruber J, Wolter D, Lierse W. Anterior cruciate ligament reflex (LCA reflex). Unfallchirurg. 1986; 89:551-4.
14. Poulsen PD, Krogsgaard MR. Muscular reflex elicited by electrical stimulation of the anterior cruciate ligament in humans. J Appl Physiol. 2000; 89:2191-5.
15. Solomonow M, Baratta R, Zhou Bh, Shoji H, Bose W, Beck C, D´ambrosia R. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. Am J Sports Med. 1987; 15:207-13.
16. Johansson H, Sjolander P, Sojka PA. Sensory role for the cruciate ligaments. Clin Orthop Rel Res.1991; 268:161-78.
17. Basmajian JV, Deluca CJ. Muscle alive: their functions revealed by electromyography. 5th ed. Baltimore: Wiliams & Wilkins 1985. p.223-27
18. Baratta R, Solomonow M, Zhou Bh, Letson D, Chuinard R, D´ambrosia R. Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. Am J Sports Med. 1988; 16:113-22.
19. Draganich LF, Jaeger RJ, Kralj AR. Coactivation of the hamstrings and quadriceps during extension of the knee. J Bone Joint Surg Am. 1989; 71:1075-81.
20. Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Bojsen-Moller F, Dyhre-Poulsen P. Antagonist muscle coactivation during isokinetic knee extension. Scand J Med Sci Sports. 2000; 10: 58-67.
21. Kingma, I, Aalbersberg S, Van Dieen JH. Are hamstrings activated to counteract shear forces during isometric knee extension efforts in healthy subjects? J Electromyogr Kinesiol. 2004; 14:307-15.
22. Lysholm J, Gilquist J. Evaluation of knee ligament surgery results with especial emphasis on use of a scoring Scale. Am J Sports Med. 1982; 10:150-4.
23. Bach BR, Warren RF, Flynn WM, Kroll M, Wickiewiecz TL. Arthrometric evaluation of knees that have a torn anterior cruciate ligament .J Bone Joint Surg Am. 1990; 72:1299-306.
24. Rangger C, Daniel DM, Stone Ml, Kaufman K. Diagnosis of an ACL disruption with Kt-1000 Arthrometer Measurements. Knee Surg Sports Traumatol Arthrosc. 1993; 1:60-6.
25. Vasconcelos RA. Análise da translação anterior da tíbia e co-ativação do quadríceps e isquiotibiais em indivíduos com lesão do ligamento cruzado anterior em cadeia cinética aberta [Mestrado]. Ribeirão Preto: Universidade de São Paulo; 2005.
26. Zavatsky AB, Beard DJ, O´Connor JJ. Cruciate ligament loading during isometric muscle contractions. A theoretical basis for rehabilitation. Am J Sports Med. 1994; 22:418-23.
27. Grabiner MD, Campbell KR, Hawthorne Dl, Hawkins DA. Electromyographic study of the anterior cruciate ligament-hamstrings synergy during isometric knee extension. J Orthop Res. 1989; 7:152-5.
28. Kubo K, Tsunoda N, Kanehisa H, Fukunaga T. Activation of agonist and antagonist muscles at different joint angles during maximal isometric efforts. Eur J Appl Physiol. 2003; 91:349-52.