

Peak torque and knee kinematics during gait after eccentric isokinetic training of quadriceps in healthy subjects

O pico de torque e a cinemática do joelho durante a marcha após treino isocinético excêntrico do quadríceps em sujeitos saudáveis

Poletto PR¹, Santos HH¹, Salvini TF¹, Coury HJCG¹, Hansson GA²

Abstract

Objective: To evaluate the effects of eccentric isokinetic training on knee range of motion (ROM) of healthy subjects. **Methods:** The knee extensor and flexor isokinetic peak torques and ROM of flexion/extension and varus/valgus knee movements during gait of 18 healthy men (21.7±2.2 years; 1.73±0.10m; 68.7±9.4kg; body mass index: 22.6±2kg/m²) were analyzed, before and after six weeks of bilateral eccentric isokinetic training of the knee extensors at 30°/s. **Results:** The knee extensor torque increased in both limbs (right, from 229±54 to 304±53Nm; p<0.01; and left, from 228±59 to 311±63Nm; p<0.01), without any difference in torque gain between them. The knee flexor peak torque increased (from 114±30 to 123±22Nm; p<0.05), but the hamstrings/quadriceps (H/Q) ratio decreased (from 0.5±0.08 to 0.39±0.07; p<0.01) after the training. There were no differences in the flexion/extension and varus/valgus movements after the training, except for a small change (4°) in valgus for the left knee. **Conclusions:** The eccentric isokinetic training of the knee extensors increased the extensor torque and decreased the H/Q ratio, although the effect on the gait pattern seemed negligible in healthy subjects. Associated training for flexors, complementary to the extensor training, seems to be necessary for balance between knee agonists and antagonists.

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Key words: electrogoniometer; gait; torque; knee; eccentric training.

Resumo

Objetivo: Avaliar os efeitos do treino isocinético excêntrico sobre a amplitude de movimento (ADM) do joelho em sujeitos saudáveis. **Métodos:** Foram analisados os picos de torque isocinético dos extensores e flexores do joelho e a ADM de flexo/extensão e valgo/varo, durante a marcha, de 18 homens saudáveis (21,7±2,2 anos; 1,73±0,10m; 68,7±9,4kg; índice de massa corpórea: 22,6±2kg/m²) antes e após seis semanas de treino isocinético excêntrico bilateral dos extensores do joelho a 30°/s. **Resultados:** O torque extensor do joelho aumentou em ambos os membros, direito (de 229±54 para 304±53Nm; p<0,01) e esquerdo (de 228±59 para 311±63Nm; p<0,01) sem diferença de ganho de torque entre eles. O pico de torque flexor aumentou (de 114±30 para 123±22Nm; p<0,05), mas a razão isquiotibiais/quadríceps (I/Q) diminuiu (de 0,5±0,08 para 0,39±0,07; p<0,01) após o treino. Não houve diferença para os movimentos de flexo/extensão e valgo/varo após o treino, exceto uma pequena mudança (4°) no valgo para o joelho esquerdo. **Conclusões:** O treino isocinético excêntrico dos extensores do joelho aumentou o torque extensor e diminuiu a razão I/Q, entretanto o efeito sobre o padrão da marcha parece desprezível em sujeitos saudáveis. Um treino associado dos flexores, complementar ao treino dos extensores parece ser necessário para o equilíbrio entre agonistas e antagonistas do joelho.

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Palavras-chave: eletrogoniômetro; marcha; torque; joelho; treino excêntrico.

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¹Department of Physical Therapy, Universidade Federal de São Carlos (UFSCar) – São Carlos (SP), Brazil

²Department of Occupational and Environmental Medicine, University Hospital – Lund, Sweden

Corresponding to: Tania Fatima Salvini, Universidade Federal de São Carlos, Departamento de Fisioterapia, Rodovia Washington Luis, km 235, Caixa Postal 676, CEP 13565-905, São Carlos (SP), Brazil, e-mail: tania@power.ufscar.br

Introduction

Injuries and ligament reconstructions of the knee have been associated with changes in kinematic patterns during gait¹⁻³. An altered gait, secondarily to ligament injury or reconstruction, may produce unfavorable loading of the cartilage of the knee joint⁴, and thus it may contribute to the development of arthritis⁵. Changes in gait pattern may occur as a consequence of joint tissue derangement, knee joint swelling, weakness of the quadriceps femoris muscle or muscle inhibition due to pain⁶. Atrophy of the extensor muscles is a common finding among patients undergoing anterior cruciate ligament (ACL) reconstruction⁷⁻⁹. Therefore, recovery of knee extensor strength is essential for functional rehabilitation. Previous reports have shown that the functional outcome is positively correlated with extensor strength, thus indicating that muscle strengthening is a precondition for functional recovery^{7,8}.

It has been reported that training using eccentric contractions is more effective for muscle recovery because it promotes greater changes in neural activation and muscle hypertrophy⁹⁻¹². Both force generation and stretching are major factors in activating protein synthesis, and the combination of these stimuli apparently has a pronounced additive effect¹³. Moreover, loaded eccentric exercise is a potent stimulus for hypertrophy^{14,15} and increases muscle strength¹⁶.

In a recent study¹⁷ in which we applied eccentric isokinetic training of the quadriceps muscles to subjects who had undergone ACL reconstruction, the knee extensor torque and flexion/extension range of motion (ROM) during gait increased significantly after training. However, unexpectedly increased valgus, which was most pronounced during the swing phase, along with increased valgus/varus ROM. These kinematic changes, which may imply adverse effects on the knee, were also observed in the ACL reconstructed knees when compared with the healthy untrained subjects. In this respect, it would be also important to examine the effect of isokinetic eccentric training on knee ROM in control groups (subjects with healthy knees).

Thus, this study had the objective of evaluating the effects of eccentric isokinetic training on the strength of the extensor and flexor muscles of the knee, and the sagittal and coronal knee movements during gait, in healthy male subjects. In addition, the present stride-based method for characterizing gait was compared with the method used in our previous study¹⁷.

Materials and methods

Subjects

Initially, the sample was 25 subjects, but only 18 completed the study. These 18 healthy and active males (four with right

dominance and 14 with left dominance) did not present any musculoskeletal injuries or symptoms or equilibrium disorders (age 21.7 ± 2.2 years; height 1.73 ± 0.10 m; weight 68.7 ± 9.4 kg; body mass index: 22.6 ± 2.0 kg/m²). Their occupational and recreational activities did not change, and none of them was involved in any other training program to improve muscle strength, during the present study. This study was developed with approval from the Ethics Committee for Human Investigation of the Universidade Federal de Sao Carlos (UFSCar), number 144/2004 and all the subjects signed an informed consent statement.

Eccentric training

The training was performed twice a week for six consecutive weeks, totaling 12 sessions. The extensor muscles of both the right and left knees were trained during each session. To avoid any systematic differences, the left knee was trained first in one session and the right knee first in the subsequent session. This procedure was repeated for the rest of the training. Eighteen subjects completed the training program, which had been developed in the Muscle Plasticity Unit of the Neurosciences Laboratory of UFSCar¹⁸.

The subjects warmed up for five minutes on a cycle ergometer (75W) and then the right and left quadriceps, hamstrings and calf muscles were stretched three times (30s of stretch with 30s rest). Next, the subjects were seated on the isokinetic dynamometer (Biodex Multi-Joint System 3, Biodex Medical Inc.[®], Shirley, New York, USA) with the backrest reclined 5° from vertical and straps fixing the trunk, waist and distal thigh. The lateral femoral epicondyle was used as the body landmark for matching the rotation axes of the knee joint and the lever arm of the dynamometer. The dynamometer pad was then fastened around the leg 5cm proximally to the medial malleolus, and the subjects performed a series of three submaximal contractions for familiarization. The subjects then performed three series of ten consecutive maximal eccentric isokinetic contractions; the knee was moved by the dynamometer through the ROM from 20 to 90° of knee flexion at an angular velocity of 30°/s (Figure 1). Each series was preceded by three minutes of resting, and there were no pauses between the ten contractions.

Knee extensor and flexor torque

Forty-eight hours before and after the training, the peak torque of the knees was assessed, during eccentric isokinetic contractions at 30°/s. The procedure and the equipment giving peak torque data for each contraction were the same as for the training (see above), except that only one session of five contractions was performed. The peak torque was defined as the maximum value achieved during the five contractions.

To assess knee functional ability and muscle balance, the hamstrings to quadriceps (H/Q) strength was derived as the ratio between the corresponding peak torques¹⁹⁻²¹.

Knee movements

Knee flexion/extension and valgus/varus movements were recorded bilaterally using biaxial flexible electrogoniometers and acquisition units (M110, DL1001 and Datalink 2.0, Biometrics Ltd.[®], Gwent, UK). One goniometer was fixed to the shaved lateral face of each knee. The center of the inter-joint line was considered to be the common reference for the leg and thigh. The center of the sensor springs was mounted so as to coincide with this line, and the two terminals were attached on the sagittal plane of the knee and aligned with the axis of the thigh (with the additional reference point of the greater trochanter of the femur) and the axis of the lower leg (with the external malleolus as the second reference point). The sampling rate was 100Hz. The reference position (*id est* 0° of flexion/extension and valgus/varus) was derived as the mean value over a 16 seconds period, with the subject standing erect and relaxed. Positive angles denoted flexion and valgus. After familiarization with walking on a treadmill at 5km/h, knee movements were recorded for 90 seconds.

Data analysis

Knee torque and eccentric training

The knee torque and movements and the effects of training (*id est* the post-training minus the pre-training value) were calculated for both the left and right knees and evaluated by paired t-tests. The comparison between the right and left sides, both in the stride-based analysis and in the previous method used by Coury et al.¹⁷, also used paired t-Student test. The data were also tested with regard to the normality of the distribution (Shapiro-Wilk) and homogeneity of variance (Levene). All significance tests were performed at a predetermined alpha level of 0.05. Although no power calculation was made, the sample size was based on studies published in the literature (see Coury et al.¹⁷, Manal et al.²², Kurz et al.²³, Lavcanska, Taylor e Schache²⁴).

Knee movements

From the central part of the electrogoniometric recording, 50 consecutive strides were identified, independently for the right and left sides. From the flexion angles, the heel strikes were detected, defined as the first minimum occurring after the maximum flexion²⁵. The heel strike defined the beginning of the strides and, for each stride, the data were normalized to the duration of the stride. During normal gait, as seen in the present study, the first 60% of the stride represents the stance

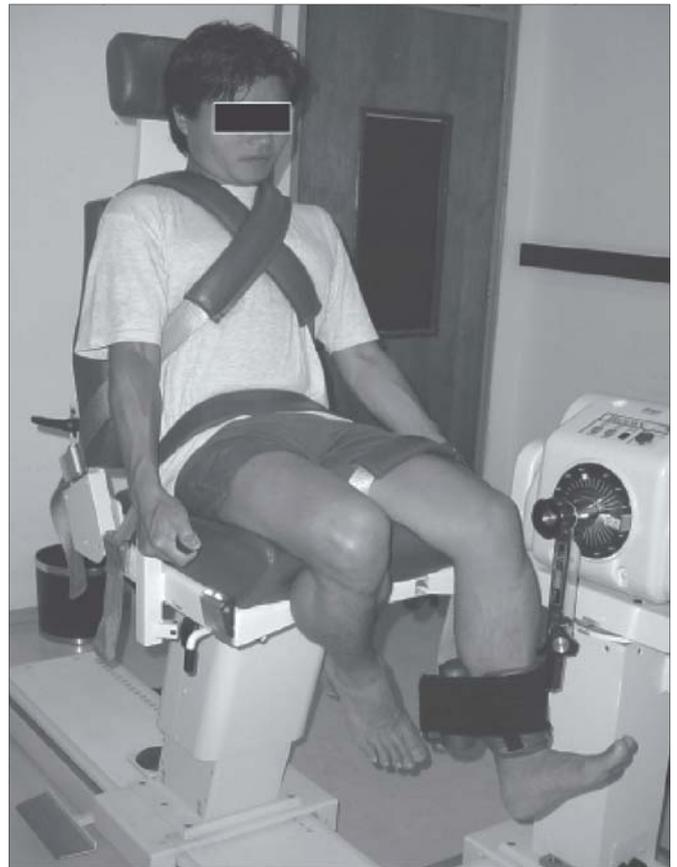


Figure 1. Positioning of the subject in the isokinetic dynamometer during eccentric training of the knee extensor (note the isometric contraction of the flexor in the contralateral limb).

phase and the subsequent 40%, the swing phase²⁵. For each stride, the maximum and minimum angles and the ROM (*id est* the maximum minus the minimum angle) were derived for flexion/extension and valgus/varus. The mean values of these measurements for the 50 strides were used to characterize the knee movements for each subject. In addition, for each subject and knee, graphs of the mean values for the 50 strides were derived. This analysis was performed using software developed from MatLab 6.5 (MathWorks Inc.[®], Natick, MA, USA).

Comparative analysis of the electrogoniometric method

A comparative analysis was made between the present method and the previous method¹⁷ of electrogoniometric records. For this, the 1st and 99th percentiles, and the 99th minus the 1st percentile of the angle distributions, were calculated for 60s of the central part of the gait (the same method as used in our previous study¹⁷), for 81% of the recordings (29 out of 36). The reference position was derived in the same way, and for the same time period, for both methods. We then compared this percentile analysis with the new method used in the present study.

Results

Peak torque

After the isokinetic eccentric training, both the right and the left limb presented increased knee extensor peak torque (38 and 41% greater, respectively). The right limb increased from 229 ± 53 to 304 ± 53 Nm ($p < 0.01$) and the left limb increased from 228 ± 59 to 311 ± 63 Nm ($p < 0.01$). Although, unexpectedly, the training increased the knee flexor peak torque by 8% (from 114 ± 30 to 123 ± 22 Nm, $p < 0.05$), there was a natural decline in the H/Q ratio of 22% (from 0.5 ± 0.08 to 0.39 ± 0.07 , $p < 0.01$).

Kinematic analysis

Means and standard deviations for the maximum, minimum and ROM angles are shown in Table 1, for before and after the training. Regarding the minimum flexion/extension values, there was

no noticeable hyperextension during walking, while the average maximum flexion/extension during the swing phase was between 53 and 54° , independent of knee and training. Figure 2, which presents the mean ensemble curves with their standard deviations, for the 18 subjects, shows that the symmetry between the knees and the lack of any effect from the training on the flexion/extension angles applied to all parts of the gait cycle.

There was no significant difference (right knee: $p = 0.2$; left knee: $p = 0.54$) in valgus/varus ROM between pre and post-training measurements, for both knees (Table 1). The maximum and minimum values, as presented in Figure 2, show that the valgus/varus angles, except for the left knee after training, were fairly symmetrically distributed around the reference position. After the training, the left knee displayed a general shift towards valgus, which was most pronounced during the swing phase (the average difference between the mean ensemble curves was 4.1°). The increased valgus is also shown by the increased minimum and maximum angles.

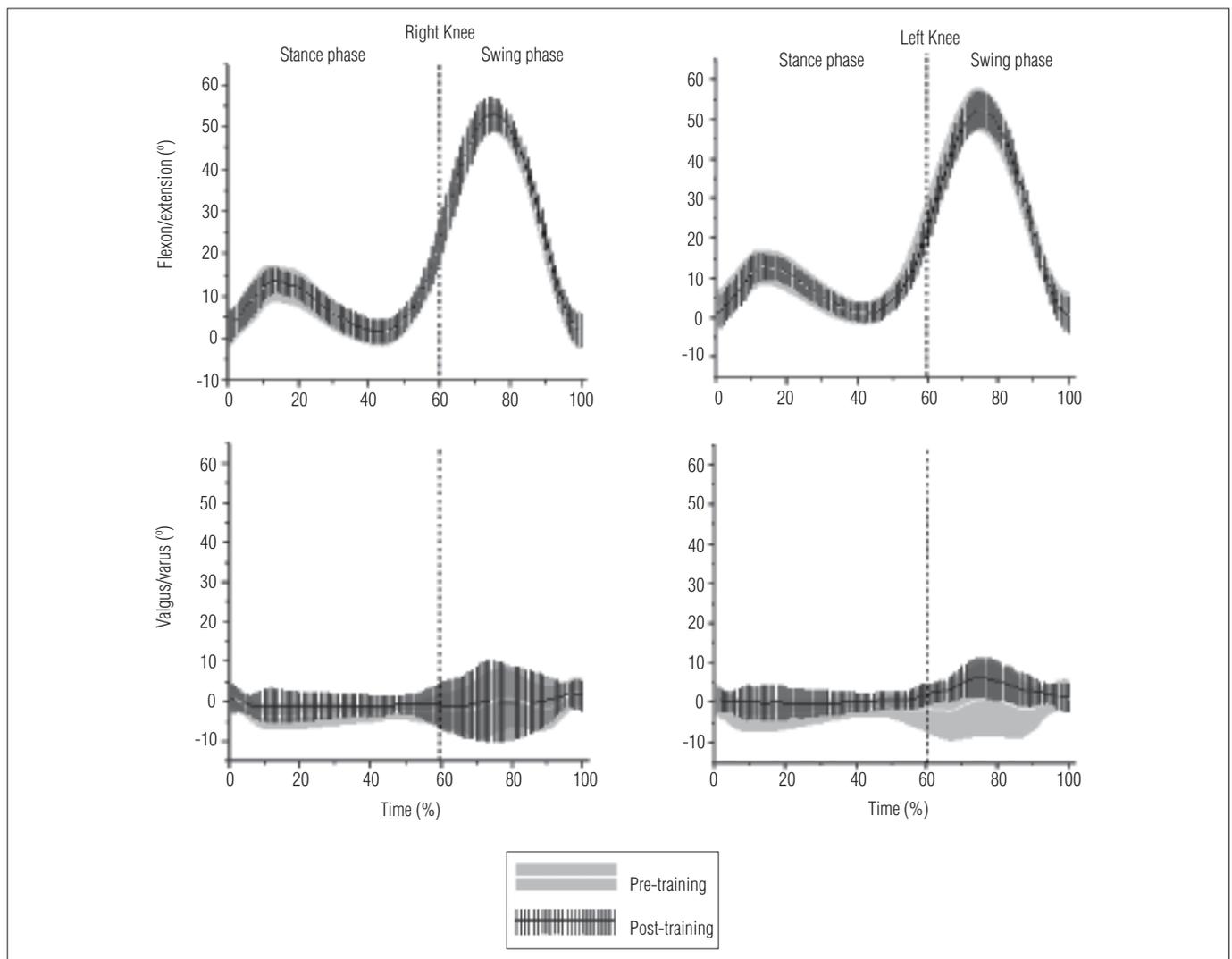


Figure 2. Mean amplitudes and standard deviations of flexion/extension and valgus/varus movements during 100% of consecutive strides, depicted in the stance and swing phases of gait for both knees before and after training, among 18 healthy male subjects. Positive angles denote flexion and valgus.

The standard deviations for the maximum and minimum valgus/varus angles were relatively large, compared with the standard deviations for the flexion/extension angles, thus indicating a higher inter-individual variation for valgus/varus than for flexion/extension (Table 1). The standard deviations in Figure 2 also show this relatively large inter-individual variation, and that it was most pronounced during the swing phase. It is interesting to observe that, for valgus/varus, the standard deviation decreased, *id est* the movement pattern of the subjects became more uniform during the swing phase for the left knee after training.

The kinematic analysis used in our previous study¹⁷ identified values that were almost identical to those from the present method. The differences in the results from the two methods (previous method minus present method) were: peak flexion 0.5° (IC95%=0.4°-0.6°), peak extension 0° (-0.5°-0.4°), range of flexion/extension 0.5° (0.1°-1°), peak valgus -0.5° (-0.7°--0.4°), peak varus -0.5° (-0.8°--0.3°) and valgus/varus range 0° (-0.3°-0.3°).

Discussion

The eccentric training increased both the peak extensor torque (by 40%) and the peak flexor torque (by 8%), but it decreased the H/Q ratio (from 0.5 to 0.39). These changes had no significant effect on the gait kinematics of the knee, especially for the valgus/varus ROM, except for a small shift towards valgus for the left knee after the training.

Methodological considerations

The training in the present study was similar to the training in our previous study¹⁷, except for shorter duration (six versus 12 weeks in the previous study). In spite of this, the torque gain was higher in the present study (39 versus 25% in the previous study). The lower efficiency in extensor torque gain during the training in the previous study¹⁷ was probably because the quadriceps muscle had an abnormal pattern of motor unit recruitment after ACL reconstruction¹³.

One limitation of the present study was that the flexor peak torque was only measured for the nondominant limb, which was done for technical reasons. However, future studies that evaluate both the dominant and the nondominant limb are necessary, since a difference in valgus/varus during gait was found only on the left side.

The use of a stride-based analysis is more relevant for gait evaluation than the more general analysis of amplitude distributions that we have previously used. For technical reasons, only the 29 gait recordings that were recorded using the DL1001 data logger were used for comparing the methods. For

Table 1. Means and mean differences of the flexion/extension and valgus/varus angles of the right and left knees before and after training, among 18 healthy male subjects during gait.

| Movement | Angle (°) | | |
|--------------------------|-----------|----------|-----------|
| | Maximum | Minimum | ROM |
| Flexion/extension | | | |
| Right side | | | |
| Before training | 52.6±3.7 | -0.9±3.4 | 53.8±4.8 |
| After training | 53.5±4.2 | 0±2.7 | 53.4±4.4 |
| Difference | 0.9±3.3 | 0.9±3 | -0.4±4.7 |
| p-value | 0.27 | 0.22 | 0.72 |
| Left side | | | |
| Before training | 53±5.8 | -0.7±2.8 | 53.6±5.9 |
| After training | 52.5±4.7 | -1.4±2.6 | 53.9±5.4 |
| Difference | -0.5±3.3 | -0.7±2.3 | 0.2±3.2 |
| p-value | 0.55 | 0.23 | 0.79 |
| Valgus/varus | | | |
| Right side | | | |
| Before training | 5.5±3.9 | -6±5.3 | 11.6±5.2 |
| After training | 6.4±6.2 | -6.5±5 | 12.9±5.5 |
| Difference | 0.9±8.9 | -0.5±7.9 | 1.4±4.3 |
| p-value | 0.68 | 0.8 | 0.2 |
| Left side | | | |
| Before training | 5.9±4.9 | -6.3±5.3 | 12.2±3.6 |
| After training | 8.3±4.1 | -3.1±2.1 | 11.4±3.4 |
| Difference | 2.3±5 | 3.2±5.3 | -0.8± 5.5 |
| p-value | 0.06 | 0.02 | 0.54 |

Note: Results are means±standard deviations; positive angles denote flexion and valgus; range of motion=ROM.

the derived measurement, the differences between the two methods were surprisingly small, for both flexion/extension and valgus/varus. The very small and physiologically non-significant differences enabled direct comparisons of the results obtained using the two methods. Moreover, when these methods are used for quantifying the effect of training, as in both the present study and our previous one, differences between pairs of measurements made using the same method are calculated, thus virtually eliminating even the minute differences between the methods. Hence, methodological considerations can be disregarded when comparing the results from the present study and our previous study.

Physiological effects

As expected, the eccentric training increased the extensor torque of the knees, similarly to what was found in the previous study using a similar training protocol for subjects who had undergone ACL reconstruction¹⁷. However, the unexpected gain in flexor torque was probably due to isometric contraction in the contralateral limb, performed by the subjects during eccentric actions of the extensors (Figure 1), since muscle strengthening of this group was not in the training program used. Among other factors, the increased flexor

torque may be due to the hemispheric dominance of the task itself²⁶, the size and uniformity of the sample, sex²⁷, age²⁸, functional asymmetry²⁹, motor experience and type of strategies developed during practice²⁶.

Nevertheless, the decline in H/Q ratio, after the training, indicates that the flexors presented reduced capacity for knee stabilization. This could be considered to be an increased risk of injury. Normal values for H/Q ratio of 0.4 to 0.5 have been reported based on peak moments, independent of contraction mode and velocity^{19,30}. The approximate values for H/Q ratio (≈ 0.3) suggest that the flexors muscles have a reduced capacity for dynamic knee joint stabilization during forceful knee flexion movements with simultaneous eccentric quadriceps muscle contraction^{31,32}. This may reflect predisposition to injury³³.

The quadriceps muscle contraction may create significant anterior tibial translation or shear, especially at high contraction forces with the knee towards full extension³⁴⁻³⁶, and this may produce substantial internal rotation of the tibia relative to the femur^{34,37}. The co-activation of the hamstring muscles, in addition to the ACL tension, will significantly contribute towards counterbalancing the tibial shear^{32,37} or rotation³⁰. Therefore, the H/Q ratio may be used to indicate the extent to which the hamstring muscles are capable of counteracting the anterior tibial shear induced by maximal quadriceps muscle contraction¹⁹. The results from the present study show that when eccentric training is applied exclusively to the quadriceps muscles, it alters the forces involved in knee joint stabilization.

The decline in the H/Q ratio found in this study was a consequence of the higher torque gain of the knee extensor (about 40%), compared with the torque gain of the knee flexor (8%). However, this result seems to only marginally affect the gait pattern in normal subjects. Specifically, no increase in valgus/varus ROM was observed, while such an increase was the main finding in our previous study on ACL reconstruction patients. Such patients are probably more susceptible to alterations in gait kinematics due to eccentric training, and also present higher values in the H/Q ratio. If the decline in H/Q ratio is the same as in the present study, the mechanical

properties of the ligaments may be more sensitive to increased extensor torque, even when partly balanced by antagonistic torque of the flexors. Thus, to prevent ACL reconstruction patients from developing degenerative complications, secondary to the primary injury, rehabilitation that restores functional knee kinematics during gait seems important. Since eccentric exercise is an effective method for strengthening the knee extensors, complementary eccentric training of the knee flexors may be required, in order to maintain a normal H/Q ratio and avoid possible abnormalities in the gait kinematics.

The comparison between the results from this study and our previous report¹⁷ indicates that some aspects of the effects of eccentric training on knee gait parameters in normal and ACL reconstruction subjects still remain to be considered in future studies. For example, it would be interesting to assess the effect of bilateral eccentric training of knee flexors and extensors on the gait pattern of normal and ACL reconstruction subjects, and also the effects of different combinations of frequency and duration of training.

Conclusions : : : .

Isokinetic eccentric training of knee extensors increased the torque of the knee extensor and decreased the H/Q ratio, but the effect on the gait pattern seems negligible in healthy subjects. Associated training of knee flexors, complementary to the training of the extensors, might be necessary in order to maintain the balance between knee agonists and antagonists.

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