Knee Surg, Sports Traumatol, Arthroscopy
(1997) 5 : 14–21

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Gait patterns after anterior cruciate ligament reconstruction

Received: 13 May 1996
Accepted: 28 November 1996

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Abstract The aim of this study is to analyse the changes in select gait parameters following anterior cruciate ligament (ACL) reconstruction. The study was performed on 15 subjects who underwent ACL reconstruction by the bone-patellar tendon-bone technique. Gait analysis was performed using the Elite three-dimensional (3D) optoelectronic system (BTS), a Kistler force platform and the Telemg telemetric electromyograph (BTS). Kinematic data were recorded for the principal lower limb joints (hip, knee and ankle). The examined muscles include vastus lateralis, rectus femoris, biceps femoris and semitendinosus. The results obtained from the operated subjects were compared with those of 10 untreated subjects and 5 subjects without ACL damage. In the operated subjects the knee joint angular values regained a normal flexion pattern for the injured limb during the stance phase. The analysis of joint moments shows: (a) sagittal plane: recovery of the knee flexion moment at loading response and during preswing; (b) frontal plane: recovery of the normal patterns for both hip and knee adduction-abduction moments during the entire stance phase. The examination of ground reaction forces reveals the recovery of frontal component features. The EMG traces show the normal biphasic pattern for the operated subjects as compared to the untreated subjects. The results suggest that the gait parameters shift towards normal value patterns.

Key words Gait analysis · Anterior cruciate ligament reconstruction · 3D kinematics · Kinetics · Electromyography

Introduction

Changes in the gait patterns of subjects with anterior cruciate ligament (ACL) injury have been assessed in a number of studies, all using different techniques; however, few studies have evaluated the changes in gait parameters following ACL reconstruction. Timoney et al. [32] examined the gait patterns of 10 normal and 10-ACL reconstructed (bone-patellar tendon-bone technique) subjects considering only kinetic data. Comparing these results to those of Andriacchi [1, 2, 8], it appears that ACL-reconstructed subjects show a behaviour closer to normal values than do untreated subjects.

Ciccotti et al. [12, 13] analysed the electromyographic (EMG) patterns during gait in three groups: (a) normal subjects, (b) ACL-deficient subjects undergoing rehabilitation and (c) ACL-reconstructed subjects (bone-patellar tendon-bone technique). ACL-reconstructed subjects showed EMG patterns very close to normal values, whereas subjects undergoing rehabilitation demonstrated abnormal EMG activity.

This study used a comprehensive approach (including kinematic, kinetic and EMG data analysis) for the measurement of changes in the dynamic equilibrium during gait following ACL injury and their modification following ACL reconstruction.

Patients and methods

The study was carried out with a group of 10 male subjects with ACL injury (age 27 ± 6 SD years), a different group of 15 male ACL-reconstructed subjects (bone-patellar tendon-bone technique) (age 25 ± 3 years) and 5 normal male subjects with no history of musculoskeletal pathology (age 28 ± 3 years).

The data collected for the normal group concorded with previously published results [12, 18, 19, 28]. The ACL-deficient group was examined on average 20.4 months after injury (range 8–48 months); all the subjects complained of knee instability and showed positive anterior drawer, Lachman and pivot shift tests with no associated ligament injury upon clinical examination. The mean KT-2000 arthrometer differences in excursion between knees were 3.7 ± 2.1 mm at 20 lb and 6.7 ± 3.24 mm at manual maximum. The ACL injury was always confirmed during subsequent surgical intervention.

The ACL-reconstructed subjects were examined 17 ± 5 months after the surgical intervention. All of them had resumed their normal activity, and there was no clinical evidence of instability. The mean KT-2000 arthrometer differences in excursion between knees were 1.77 ± 1.00 mm at 20 lb and 2.27 ± 1.29 mm at manual maximum. Each subject was asked to perform at least 5 trials of walking at his natural cadence (112 ± 5.1 steps/min). A 20-m distance was used to allow the subject to reach a steady state of walking.

The analysis of gait features was performed using an ELITE system (BTS, Milan, Italy) composed of the following: (a) four TV cameras for the recording of the kinematic data; (b) a force plate (Kistler, Winterthur, Switzerland) for the acquisition of ground reaction forces; and (c) a telemetric EMG system (BTS, Milan, Italy) equipped with surface electrodes for the recording of neuromuscular activity. Both ground reaction forces and EMG signals were acquired at a sampling rate of 500 Hz, whereas the four TV cameras worked at a sampling rate of 100 Hz.

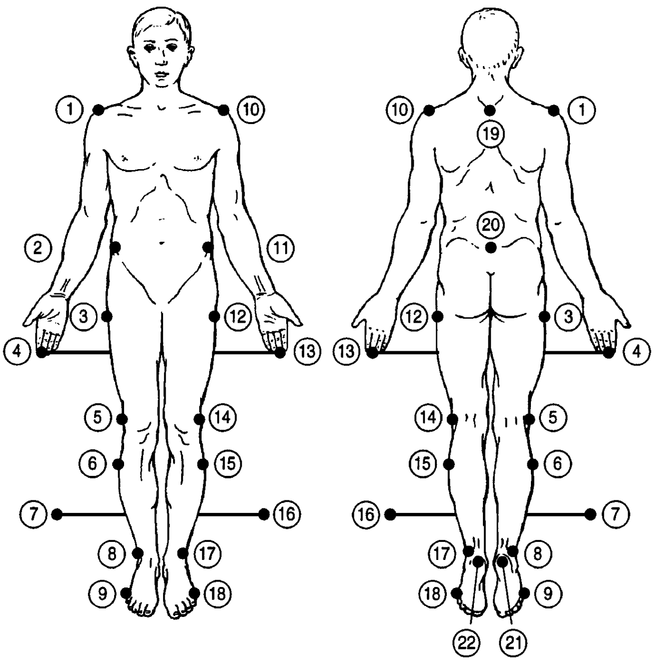

Fig. 1 Positioning of the markers, as viewed from the front and from the back (BTS, Milan, Italy). Analysis of the frame-by-frame data recorded from these markers during the gait cycle allows the determination of (a) the centre of rotation for each joint examined and (b) orientation of the coordinate systems identifying the body segments

Further elaboration of all the variables was carried out by computer.

Reflective passive markers (n = 22) were positioned over specific anatomical points of both lower limbs, pelvis and trunk (Fig. 1). The data obtained from the camera recording of these markers allowed the reconstruction of internal points (centre of rotation of hip, knee and ankle joints) and segmentally embedded coordinate systems according to the model described by Davis [14]. For all trials, the joint angles were computed according to the protocol defined by Davis [14]. For the external moments, consideration was given to both the reaction force trend and the inertial parameters of each body segment. The data were normalized (both time and amplitude) prior to the calculation of the averaged values.

EMG activity of vastus lateralis, rectus femoris, biceps femoris (lateral hamstrings) and semitendinosus (medial hamstrings) muscles was recorded bilaterally. Prior to acquisition, the electrode positions were tested to control for crosstalk between different muscle groups. The raw data were highpass filtered to eliminate frequency components below 10 Hz, then rectified and filtered to eliminate the components of the signal over 200 Hz. Before calculating the average values, all EMG measurements were subject to normalization procedures. A single gait cycle (complete stride) was identified, and all the corresponding data sets were then reduced to 100 points.

Individual subject data relating to (a) the amplitude of force were normalized to subject weight, (b) the amplitude of joint moment were normalized to the subject's weight and height, and (c) the EMG were normalized to the maximum recorded signal amplitude during a single walking cycle [28].

Three different groups were defined: (a) ACL-deficient subjects, (b) ACL-reconstructed subjects and (c) control subjects. The average trend for all variables was computed for each group.

Student-Neuman-Keuls tests were adopted to determine levels of significance when comparing the groups. The tests were applied to all variables and for each stride bin.

Results

With respect to joint angles (Figs. 2–4), the injured subjects showed changes as a consequence of the ACL injury mainly at the hip and knee joints. During all phases of the gait cycle, both of these joints demonstrated reduced excursions. However, the functional pattern of the flexion-extension angle was maintained. In contrast, hip, knee and ankle angular values of the ACL reconstructed group showed behaviour similar to the normal control subjects.

Analysis of the external joint moments (Figs. 5–7) also indicated that the hip and knee joints were most affected by the injury. At heel strike the knee joint revealed a greater extension moment in the ACL-deficient subjects (Fig. 5; $P < 0.05$). During the loading response phase, a reduction of the knee flexion moment was compensated for by an increased flexion moment at the hip joint ($P < 0.05$). The joint also tended to show a reduced flexion moment during the preswing phase, but our data did not achieve statistical significance.

Both the knee and the hip indicated a decreased adduction moment during the entire stance phase (Fig. 6; $P < 0.05$). However, the internal and external rotation moments did not appear to be affected by the injury.

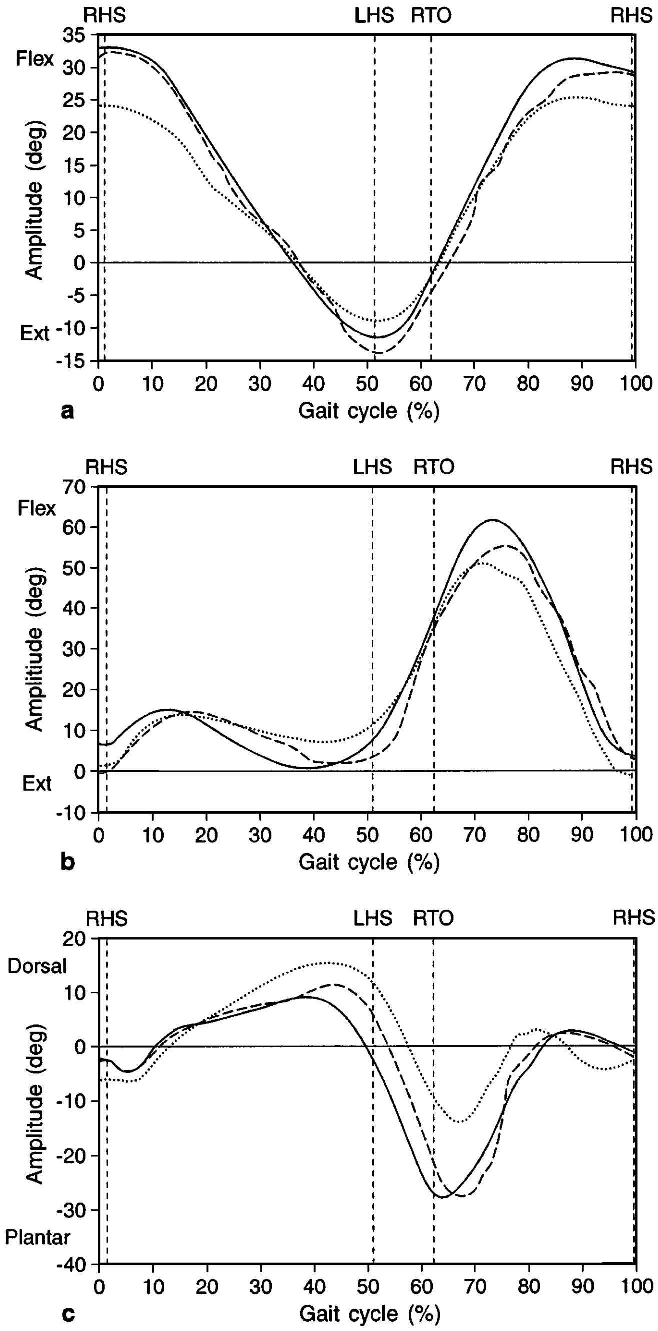

Fig. 2 Mean values of the flexion (*Flex*)-extension (*Ext*) angles of the hip (**a**), knee (**b**) and ankle (**c**) joints (——— normal subjects, ·········· ACL-deficient subjects, ——— ACL-reconstructed subjects). The amplitude of the angle is indicated in relation to the phases of the gait cycle, beginning with heel strike (*HS*). *Positive* values identify flexion (*TO* toe off)

The ankle joint showed significant changes only in the sagittal plane: upon loading the extension moment was reduced, and during the preswing phase, the flexion moment was increased ($P < 0.05$) with respect to the normal con-

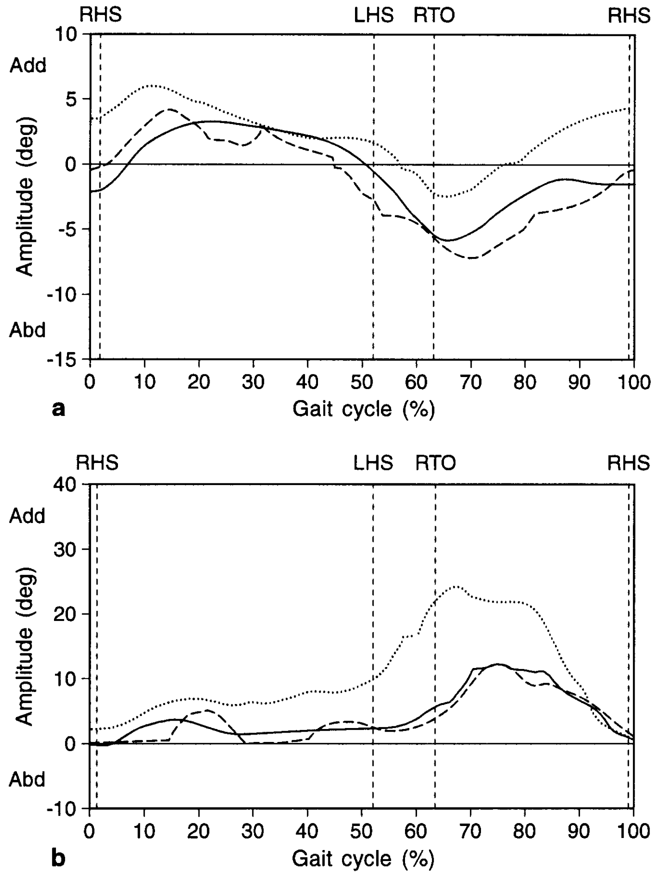

Fig. 3 Mean values of the adduction (*Add*)-abduction (*Abd*)angles of the hip (**a**) and knee (**b**) joints (——— normal subjects, ·········· ACL-deficient subjects, ––––– ACL-reconstructed subjects). The amplitude of the angle is indicated in relation to the phases of the gait cycle, beginning with heel strike. *Positive* values identify adduction

trol group. The kinetic data of the ACL-reconstructed group showed behaviour similar to that of the normal controls.

A reduced extension moment was observed at the knee upon heel strike, increased flexion moment upon loading as well as a recovery of the flexion moment during preswing.

In addition, the hip and knee adduction moment in the coronal plane were found to have regained near normal values.

In the ACL-deficient subjects the analysis of ground reaction forces (Fig. 8) demonstrated a significant reduction of the peak values of the vertical component, an altered horizontal component at the loading response and an increased anterior force at preswing ($P < 0.05$). The ground reaction force patterns of the ACL-reconstructed group were completely normal.

With reference to the analysis of EMG activity (Fig. 9), both vastus lateralis and rectus femoris showed a reduction of activity upon heel strike for the ACL-deficient group. During the stance phase these two muscles demonstrated a greater level of overall activity in the ACL-defi-

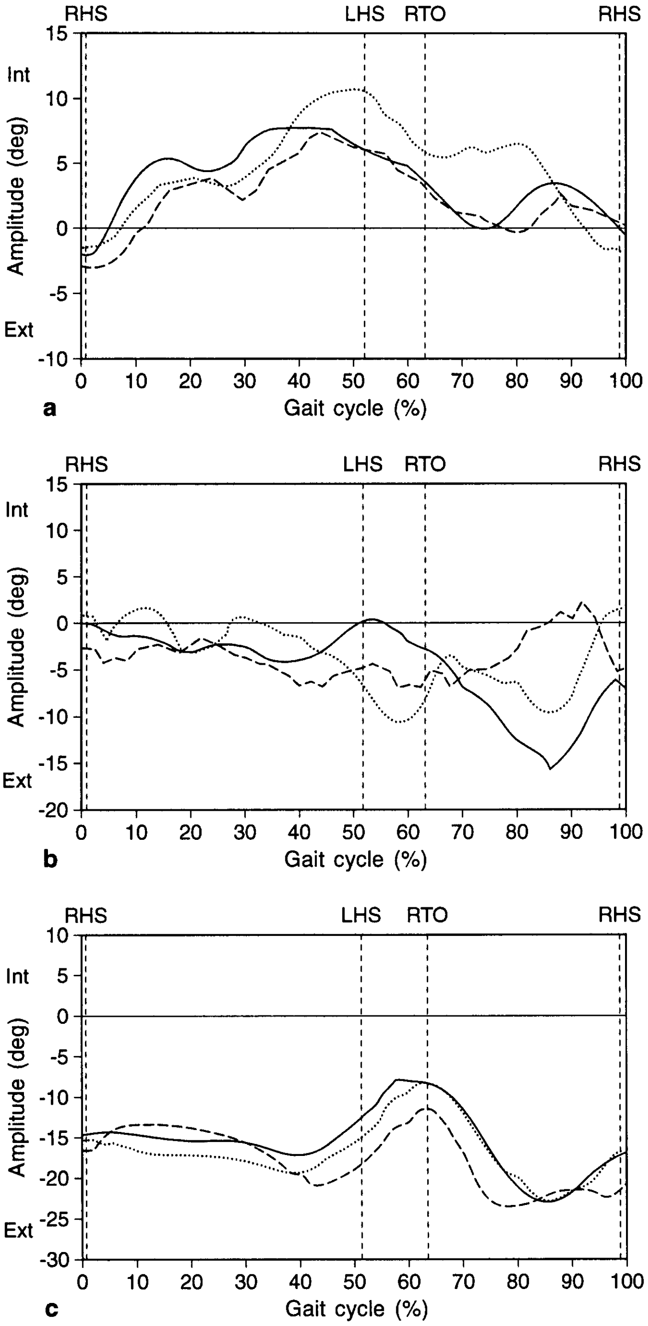

Fig. 4 Mean values of the internal (*Int*)-external (*Ext*) rotation angles of the hip (**a**), knee (**b**) and ankle (**c**) joints (——— normal subjects, ·········· ACL-deficient subjects, – – – ACL-reconstructed subjects). The amplitude of the angle is indicated in relation to the phases of the gait cycle, beginning with heel strike. *Positive* values identify internal rotation

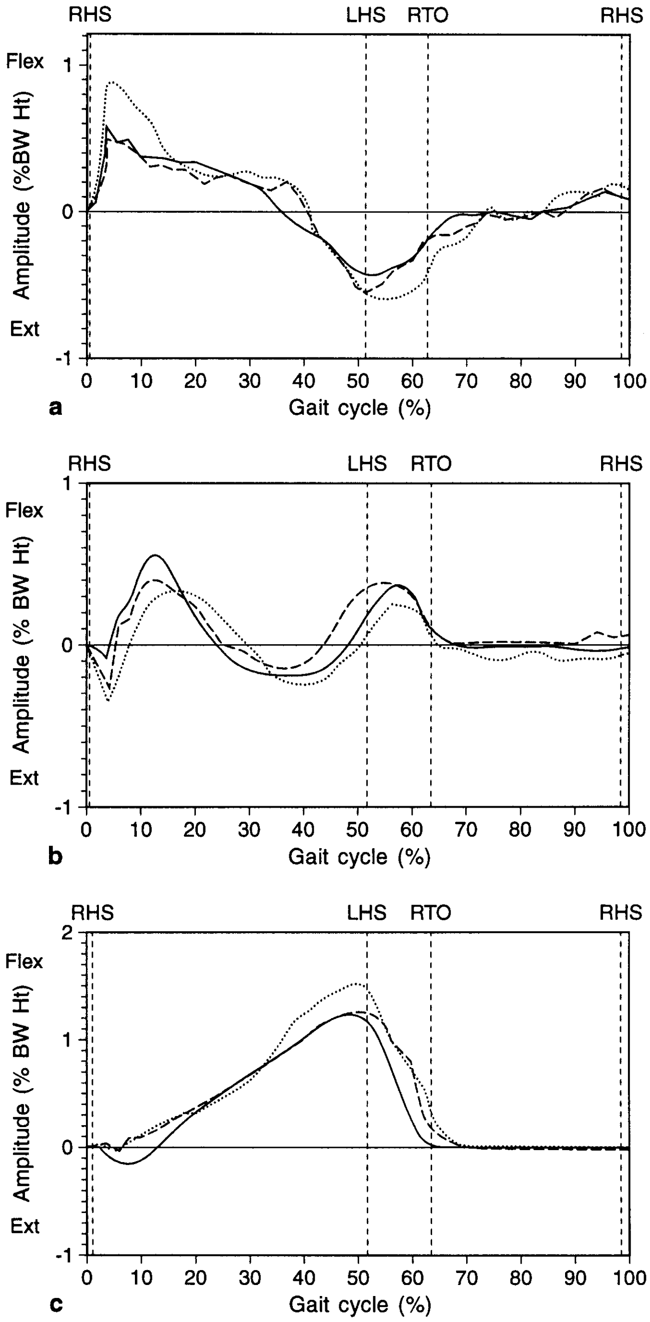

Fig. 5 Mean value of the external flexion (*Flex*)-extension (*Ext*) moments of the hip (**a**), knee (**b**) and ankle (**c**) joints (——— normal subjects, ·········· ACL-deficient subjects, – – – ACL-reconstructed subjects). The amplitude of the moment is indicated in relation to the phases of the gait cycle beginning with heel strike. Values are normalized to subject's weight and height. *Positive* values identify flexion

cient group than that observed in the control subjects. In addition, the injured subjects did not show any activity burst during the preswing phase. The hamstrings in injured subjects indicated stronger activity during the stance phase and at terminal swing (this last feature was most obvious for the lateral hamstring). The quadriceps activity of ACL-reconstructed subjects increased upon loading and decreased during the following phase of stance. The hamstring activity is reduced during the stance phase and approached closer to normal values.

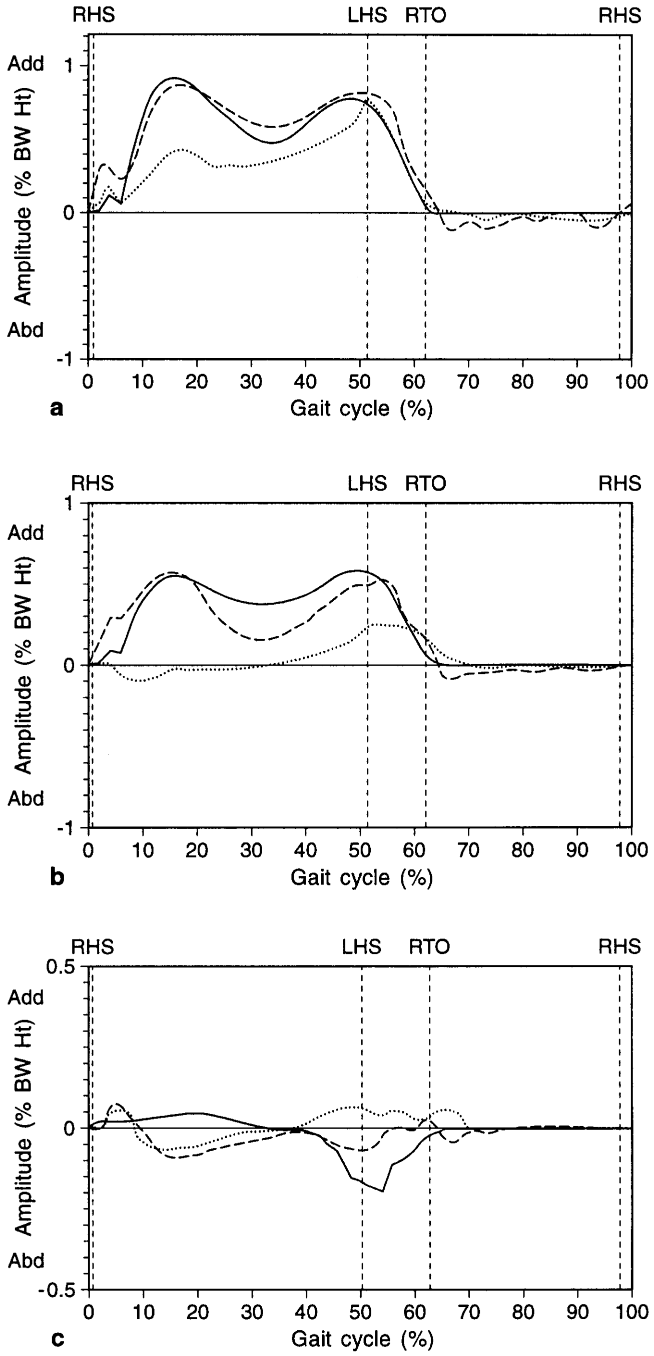

Fig. 6 Mean value of the external adduction (*Add*)-abduction (*Abd*) moments of the hip (**a**), knee (**b**) and ankle (**c**) joints (——— normal subjects, ·········· ACL-deficient subjects,——— ACL-reconstructed subjects). The amplitude of the moment is indicated in relation to the phases of the gait cycle beginning with heel strike. Values are normalized to subject's weight and height. *Positive* values identify adduction

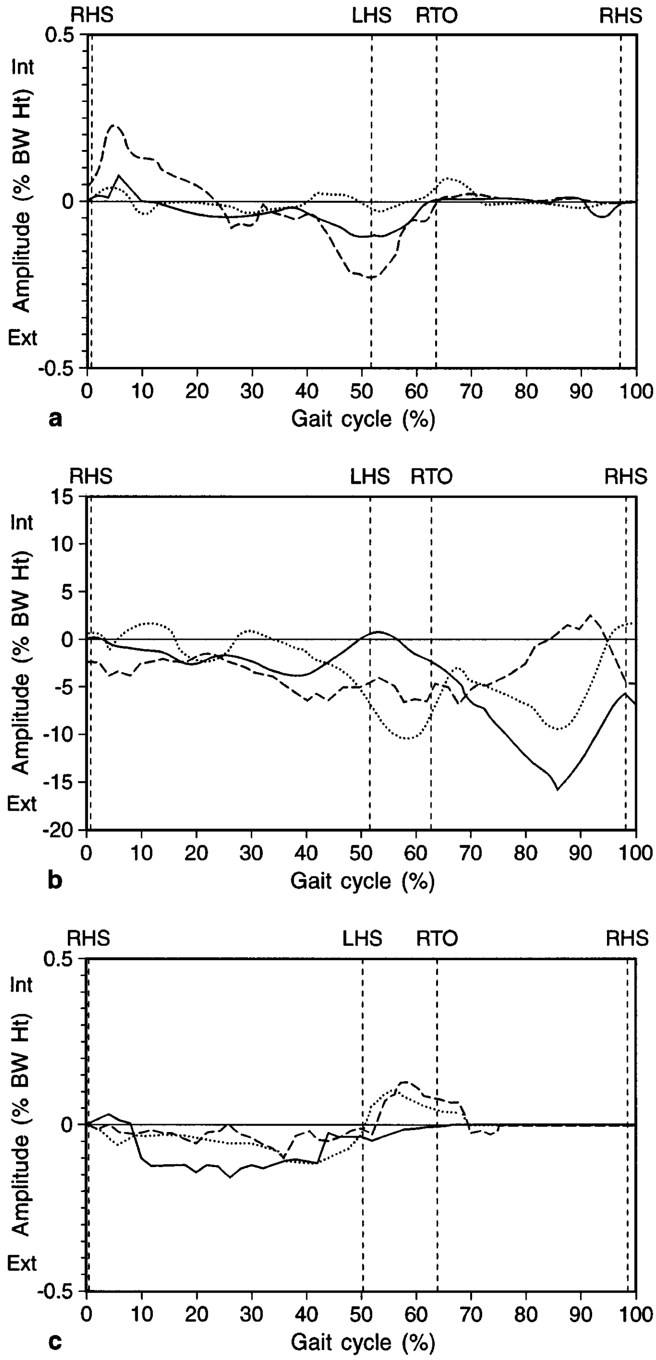

Fig. 7 Mean value of the external internal (Int) external (Ext) rotation moments of the hip (**a**), knee (**b**) and ankle (**c**) joints (——— normal subjects, ·········· ACL-deficient subjects,——— ACL-reconstructed subjects). The amplitude of the moment is indicated in relation to the phases of the gait cycle beginning with heel strike. Values are normalized to subject's weight and height. *Positive* values identify internal rotation

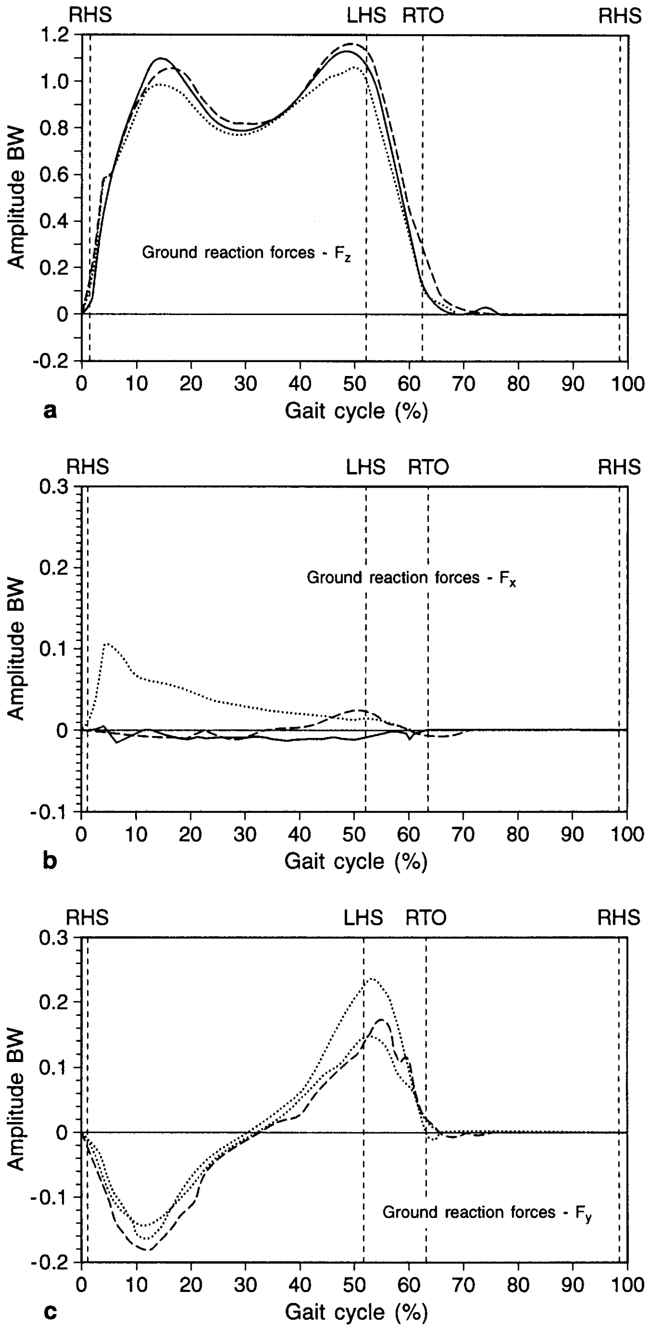

Fig. 8 Mean values of the ground reaction forces (——— normal subjects, ·········· ACL-deficient subjects, – – – ACL-reconstructed subjects). The amplitude of the force is indicated in relation to the phases of the gait cycle beginning with heel strike. Values are normalized to subject's weight

Discussion

The results of this study indicate that relevant gait parameters tend to approach normal values following ACL reconstruction. The most significant changes concern the hip and knee external moments in the sagittal plane.

The ACL-deficient subjects showed an increased knee extension moment at heel strike and a reduced flexion moment upon loading and during the preswing phase. This behaviour was compensated for by an increase in the external hip flexion moment.

Berchuck et al. [8] illustrated a reduction of knee external flexion moment upon loading which derived from the necessity of a reduction of the net internal extension moment caused by the quadriceps activity which affects the anterior displacement of the tibia. This behaviour is more important upon loading than at toe-off since the anterior displacement of the tibia due to the quadriceps contraction is more significant when the knee is close to maximum extension, which takes place immediately following heel strike.

In our study the synchronised analysis of kinetic and EMG variables verified how the external moment is balanced by the internal one. It is obvious that the net internal moment is a result of the combined action of various muscle groups and ligaments.

As for the role of the muscles, the additional information obtained by the EMG signals allowed for quantification of the relative intervention of flexors and extensors at each time point. Analysing these data, we see that the global decrease in the internal extension moment is not due to a reduction of extensor activity (quadriceps), but rather to a more complex neuromuscular mechanism which brings about an increase in both extensor and flexor activity (most prominent in the hamstrings) in order to assure joint stability.

In the sagittal plane the ACL-reconstructed subjects show a pattern closer to that of the normal subjects. The external knee flexion moment upon loading is increased (as already stated by Timoney et al. [32]), and the knee flexion moment at toe-off is completely recovered. Upon loading, the increase in the net internal extension moment was due to the predominant quadriceps activity and the reduced hamstring co-contraction. At preswing, the normal peak activity of the quadriceps returns, confirming the net internal extension moment.

In the coronal plane, throughout the stance phase the external adductor moment of both the hip and knee was reduced in the ACL-deficient subjects.

Absence of the ACL implies that the centre of knee joint rotation is displaced medially and backwards, and this results in an increased external rotation instability. The new behaviour of the knee joint could be the consequence of a need for increased stability of the external compartment. In any case, further studies investigating this particular finding are required in order to clarify its significance.

Another element which supports the hypothesis that such a strategy exists is the change observed in the position of the mediolateral component of the ground reaction force. This component is clearly more lateral during the

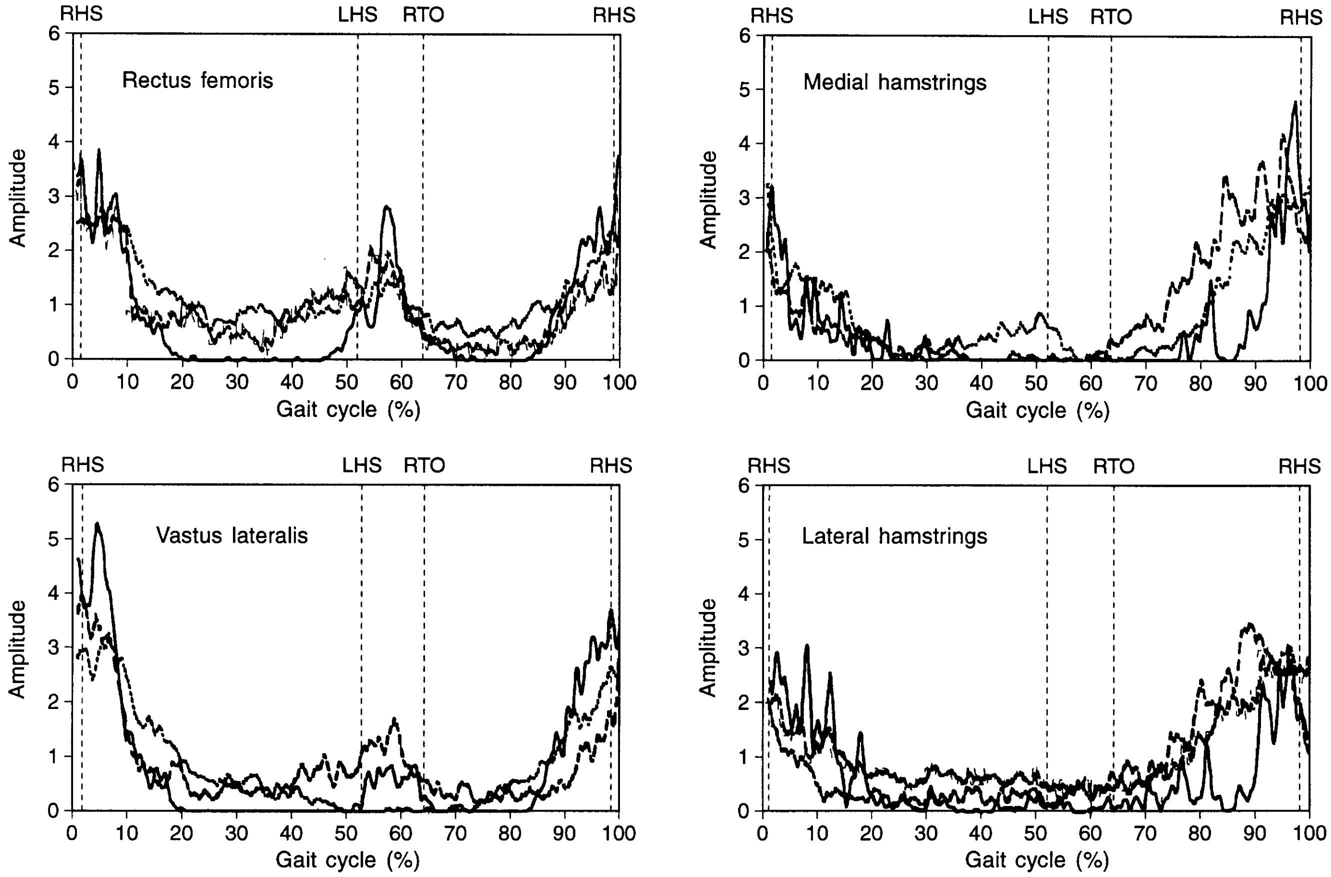

Fig. 9 Electromyography (EMG) activity of knee joint extensor and flexor muscles (——— normal subjects, ·········· ACL-deficient subjects, – – – – – ACL-reconstructed subjects). The amplitude of the EMG activity is indicated in relation to the phases of the gait cycle beginning with heel strike. Values are normalized to the mean activity value over the entire stride

entire stance phase. This behaviour is no longer required after ACL reconstruction, which could explain the return to normal values of adductory moment and ground reaction forces medio lateral component patterns. Also, the vertical component of the ground reaction forces in this group approaches normal values, suggesting that this protective scheme of walking used by the pathological group is being overcome.

The EMG patterns are altered due to joint instability. For example, and as reported by Limbird et al. [21], the vastus lateralis and the rectus femoris showed lower activity during the loading response. Ciccotti et al. [13] described an increased activity of vastus lateralis used as a strategy to prevent pivoting of the knee, but their patients had undergone intensive physical therapy prior to assessment.

Other changes in EMG patterns observed in the injured group included the following: (a) greater quadriceps and hamstrings activity during the entire stance phase; this probably reflects an attempt to increase knee joint stability; (b) the quadriceps muscle does not show an activity peak at terminal swing as it does in the control group; this reduction would explain the reduction of the knee flexion moment during this phase; and (c) greater hamstring activity at terminal swing. This finding supports the results from previous studies [13] and can be attributed to a compensatory strategy which acts to increase the knee stability at heel strike so that internal rotation (pivoting) at the knee joint is prevented or minimised.

In accordance with the findings of Ciccotti et al. [13], the EMG patterns of ACL-reconstructed subjects appear to approach the values observed in normal subjects. The quadriceps activity is increased during the loading response, but is reduced during the subsequent stance phase and shows a peak at preswing, as observed in normal subjects. Also, co-contraction of the hamstrings during the stance phase is greatly reduced in this group with respect to the injured subjects.

References

1. Andriacchi TP (1993) Functional analysis of pre and post knee surgery: total knee arthroplastic and ACL reconstruction. J Biomech Eng 115:575–581
2. Andriacchi TP, Birac D (1993) Functional testing in the ACL deficient knee. Clin Orthop 288:40–47
3. Andriacchi TP, Micosz RP (1991) Musculoskeletal dynamics, locomotion and clinical application. In: Mow C, Hayes WC (eds) Basic orthopaedics biomechanics. Raven Press, New York, pp 51–92
4. Andriacchi TP, Kramer GM, Landon GC (1985) The biomechanics of running and knee injuries. In: Finerman G (ed) American Academy of Orthopaedic Surgery Symposium on Sports Medicine: the knee. Mosby, St Louis, pp 23–32
5. Arms SW, Pope MH, Johnson RJ, et al (1984) The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. Am J Sports Med 12:8–18
6. Baratta R, Solomonow M, Zhou BH, et al (1988) Muscular coactivation. The role of antagonist musculature in maintaining knee stability. Am J Sports Med 16:113–122
7. Barrack RL, Burkner JD, Kneisl J, et al (1990) The outcome of nonoperatively treated complete tears of the anterior cruciate ligament in active young adults. Clin Orthop 259:192–199
8. Berchuck M, Andriacchi TP, Beach BR, et al (1990) Gait adaptations by patients who have a deficient anterior cruciate ligament. J Bone Joint Surg [Am] 72:871–877
9. Boyd IA (1954) The histological structure of the receptors in the knee joint of the cat correlated with their physiological response. J Physiol 124:476–488
10. Branch TP, Hunter R, Donath M (1989) Dynamic EMG analysis of anterior cruciate deficient legs with and without bracing during cutting. Am J Sports Med 17:35–41
11. Carlson S, Nordstrand A (1968) The coordination of the knee muscles in some voluntary movements and in the gait in cases with and without knee injuries. Acta Chir Scand 134:423
12. Ciccotti MG, Kerlan RK, Perry J, et al (1994) An electromyographic analysis of the knee during functional activities. I. The normal profile. Am J Sports Med 22:645–650
13. Ciccotti MG, Kerlan RK, Perry J, et al (1994) An electromyographic analysis of the knee during functional activities. II. The anterior cruciate ligament deficient and reconstructed profiles. Am J Sports Med 22:651–658
14. Davis RB III, Ounpuu S, Tyburski D, et al (1991) A gait analysis data collection and reduction technique. Hum Movement Sci 10:575–587
15. Draganich LF, Jaeger RJ, Kralj AR (1989) Coactivation of the hamstrings and quadriceps during extension of the knee. J Bone Joint Surg [Am] 71: 1075–1081
16. Eckhardt R, Scharf HP, Puhl W (1994) The importance of neuromuscular coordination for athletic stress of the knee joint after ACL injuries. A gait and locomotion analysis with EMG on treadmill. Sportverletz Sportschäden 8:16–24
17. Freeman MAR, Wyke B (1967) The innervation of the knee joint: an anatomical and histological study in the cat. J Anat 101:505–532
18. Kadaba MP, Ramakrishnan HK, Wootten ME, et al (1989) Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. J Orthop Res 7:849–860
19. Kadaba MP, Ramakrishnan HK, Wooten ME (1990) Measurement of lower extremity kinematics during level walking. J Orthop Res 8:383–392
20. Lass P, Kaalund S, LeFevre S, et al (1991) Muscle coordination following rupture of the ACL. Electromyographic studies of 14 patients. Acta Orthop Scand 62:9–14
21. Limbird TJ, Shiavi R, Fraser M, et al (1988) EMG profiles of knee joint musculature during walking: changes induced by anterior cruciate ligament deficiency. J Orthop Res 6:630–638
22. Noyes FR, Matthews DS, Mooar PA, et al (1983) The symptomatic anterior cruciate deficient knee. II. The long-term functional disability in athletically active individuals. J Bone Joint Surg [Am] 65:163–174
23. Noyes FR, Mooar PA, Mattheus DS, et al (1983) The symptomatic anterior cruciate deficient knee. I. The long-term functional disability in athletically active individuals. J Bone Joint Surg [Am] 65:154–162
24. Noyes FR, Schipplein OD, Andriacchi TP, et al (1992) The ACL deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. Am J Sports Med 20:707–716
25. Renström P, Arms SW, Stanwyck TS, et al (1986) Strain within the anterior cruciate ligament during hamstring and quadriceps activity. Am J Sports Med 14:83–87
26. Schultz RA, Miller DC, Kerr CS, et al (1984) Mechanoreceptors in human cruciate ligaments. J Bone Joint Surg [Am] 66:1072–1076
27. Schutte MJ, Dabezies EJ, Zimmy ML, et al (1987) Neural anatomy of the human anterior cruciate ligament. J Bone Joint Surg [Am] 69:243–247
28. Shiavi R, Bugle HJ, Limbird T (1987) Electromyographic gait assessment. Part 1. Adult EMG profiles and walking speed. J Rehabil Res Dev 24:13–23
29. Solomonow M, Baratta R, Zhou BH, et al (1987) The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. Am J Sports Med 15:207–213
30. Solomonow M, Baratta R, Zhou BH, et al (1989) The role of the hamstrings in the rehabilitation of the anterior cruciate ligament-deficient knee in athletes. Am J Sports Med 7:42–48
31. Tibone JE, Antich TJ, Fanton GS, et al (1986) Functional analysis of anterior cruciate ligament instability. Am J Sports Med 14:276–284
32. Timoney JM, Inman WS, Quesada PM, et al (1993) Return of normal gait pattern after anterior cruciate ligament reconstruction. Am J Sports Med 21: 887–889
33. Vailas JC, Tibone JE, Perry J, et al (1990) The effects of functional knee bracing on the dynamic biomechanics of the cross-cut maneuver. J Sports Traumatol Rel Res12:197–206