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A new ambulatory system for comparative evaluation of the three-dimensional knee kinematics, applied to anterior cruciate ligament injuries

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Abstract The aim of this study was to develop an ambulatory system for the three-dimensional (3D) knee kinematics evaluation, which can be used outside a laboratory during long-term monitoring. In order to show the efficacy of this ambulatory system, knee function was analysed using this system, after an anterior cruciate ligament (ACL) lesion, and after reconstructive surgery. The proposed system was composed of two 3D gyroscopes, fixed on the shank and on the thigh, and a portable data logger for signal recording. The measured parameters were the 3D mean range of motion (ROM) and the healthy knee was used as control. The precision of this system was first assessed using an ultrasound reference system. The repeatability was also estimated. A clinical study was then performed on five unilateral ACL-deficient men (range: 19–36 years) prior to, and a year after the surgery. The patients were evaluated with the IKDC score and the kinematics measurements were carried out on a 30 m walking trial. The precision in comparison with the reference system was 4.4°, 2.7° and 4.2° for flexion–extension, internal–external rotation, and abduction–adduction, respectively. The repeatability of the results for the three directions was 0.8°, 0.7° and 1.8°. The averaged ROM of the five patients' healthy knee were 70.1°

[standard deviation (SD) 5.8°], 24.0° (SD 3.0°) and 12.0° (SD 6.3°) for flexion–extension, internal–external rotation and abduction–adduction before surgery, and 76.5° (SD 4.1°), 21.7° (SD 4.9°) and 10.2° (SD 4.6°) 1 year following the reconstruction. The results for the pathologic knee were 64.5° (SD 6.9°), 20.6° (SD 4.0°) and 19.7° (8.2°) during the first evaluation, and 72.3° (SD 2.4°), 25.8° (SD 6.4°) and 12.4° (SD 2.3°) during the second one. The performance of the system enabled us to detect knee function modifications in the sagittal and transverse plane. Prior to the reconstruction, the ROM of the injured knee was lower in flexion–extension and internal–external rotation in comparison with the controlateral knee. One year after the surgery, four patients were classified normal (A) and one almost normal (B), according to the IKDC score, and changes in the kinematics of the five patients remained: lower flexion–extension ROM and higher internal–external rotation ROM in comparison with the controlateral knee. The 3D kinematics was changed after an ACL lesion and remained altered one year after the surgery.

Keywords Gait analysis · Anterior cruciate ligament reconstruction · 3D kinematics · Outcome · Gyroscopes

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Introduction

The aim of performing an anterior cruciate ligament (ACL) reconstruction is to obtain a stable knee with a good function. This objective is attained in 80–90% of the patients operated for an isolated lesion [1]. Under these conditions, the secondary menisci lesions also decreased [1]. However, currently no study is able to prove that an ACL reconstruction prevents the development of knee osteoarthritis [2–5]. Knee osteoarthritis could be at least as frequent for operated knees as for non-operated ones [4, 5].

The persistence of a three-dimensional (3D) knee kinematics deterioration during daily activities, despite the reconstructive surgery, is one of the hypotheses formulated to explain the development of long-term chondral lesions [6]. Ligament reconstruction is a procedure that restores knee laxity and stability close to normal. But the reconstruction would be too rough to restore a function similar to that of the healthy knee. A recent study on cadaveric knees showed that three different ACL reconstruction techniques were unable to restore a physiological rotation of the tibia [7]. Thus, the stresses in the joint would be altered. In vivo, most of the studies related to the knee kinematics before and after an ACL reconstruction [8–13] have measured the range of motion in the sagittal plane (flexion–extension). The knowledge in the frontal (abduction–adduction) and transverse (internal–external) rotation planes is still incomplete [6, 14–17]. Nevertheless, the persistence of kinematics worsening in these two planes of rotation, after an ACL reconstruction [6, 14, 15], could actually contribute towards explaining an increase in the stresses exerted on the cartilage during daily activities.

Although the evaluation of the 3D kinematics appears essential, the difficulties in performing such measurements are multiple. First, there are a variety of analysis techniques [18, 36]. Most of them need specially trained staff and a long acquisition and analysis time to gather a small number of measurements. Their costs are often prohibitive for clinical studies. To be accurate, some techniques use invasive methods, which further limit the number of patients and the evaluation conditions. Usually skin markers are used. The accuracy of these methods depends on markers alignment and on their motion relative to the bone [19, 20]. Whatever the selected system is, it is necessary to use a definition to parameterize the movements measured in the space. However, no definition has been unanimously recognized and the results vary significantly from one investigator to another [21, 22]. The small amplitude of the movements in the frontal and transverse planes is even more sensitive to such definitions [23]. Moreover, the inter-subject variation of the kinematics parameters and surgical techniques [24] is an additional difficulty to

underline the kinematics criteria susceptible to explain the development of degenerative changes. Therefore, suitable tools for in vivo assessment of ACL deficient and ACL reconstructed knee are still missing.

This study proposes a new comparative knee function evaluation method using an ambulatory system based on the movement recorded on thigh and shank. It quantifies the differences of 3D kinematics of a knee from a reference value. This reference could be the healthy contralateral knee or a previous value (baseline) of the same knee. Firstly, the performances of this system were assessed. Secondly, its suitability for clinical evaluation was studied on patients with an isolated and unilateral ACL rupture, before and after surgical treatment.

Materials and methods

Patients

Five men (mean age 31 years, range 19–39) with an isolated unilateral ACL lesion have been recruited for this study. The presence of any other musculoskeletal disorder able to disrupt the gait was an exclusion criterion. These patients were professionally active and performed sport activities several times per week. None of them was a competition athlete. The first measurements were realized before surgery and after physical therapy and functional recovery (mean delay between ACL injury and reconstruction: 14 months, range 2–36). No gait asymmetry was visually detectable. All the surgeries were performed following an identical surgical technique—ACL reconstruction with bone-patellar tendon-bone autograft [25]—by the same surgeon. The follow-up data were recorded 1 year after the reconstruction. In between, the patients followed the same rehabilitation protocol [26]. No gait alteration was observed during both measurements. The characteristics of the patients are listed in Table 1.

The clinical protocol was the same for both evaluations (baseline and 1 year after ACL reconstruction) and was made by the same independent examiner. It consisted of a standard clinical evaluation and a functional dynamic analysis of the knee with our proposed ambulatory system. The clinical part included a complete evaluation according to the IKDC 2000 form [27, 28], including the subjective part and a static laxity measurement with a KT1000[®] arthrometer (MedMetric, San Diego, USA), applying the maximal manual force and calculating side to side differences. The dynamic evaluation consisted of 30 m of flat level walking. The patients executed the path at a comfortable pace and with their own sport shoes. The study was approved by the Ethics Committee of our hospital and written informed consent was given by all the patients prior to enrolment.

Table 1 Characteristic data of the patients

Patient	Age (years)	Height (m)	Weight (kg)	ACL-deficient knee	Delay 1 (months)	Delay 2 (months)
1	30	1.7	59	Left	36	14
2	34	1.7	73	Left	17	15
3	39	1.9	87	Right	13	12
4	19	1.7	70	Left	3	14
5	34	1.9	77	Right	2	12

The indicated age corresponds to the patient's age at the first evaluation. Delay 1 corresponds to the time between the lesion and the first evaluation. Delay 2 corresponds to the time between the surgery and the second evaluation

Measuring device

The system was composed of two miniature sensory modules ($2.5 \times 2.5 \times 3 \text{ cm}^3$) fixed with silicone straps on the thigh and on the shank (Fig. 1). Each module contained three gyroscopes (ENC-03, Murata, Japan) perpendicularly mounted. A gyroscope is a sensor containing a vibrating element, which is sensitive to the angular velocity [29]. The ranges of the gyroscopes were set between 300 and $600^\circ/\text{s}$, in order to avoid amplitude saturation during the walk. These modules were connected to a portable data logger (Physilog[®], BioAGM, Switzerland). Signals were sampled at 200 Hz and recorded on a memory card inserted in the data logger. At the end of the measurement, the data were downloaded to a computer and analysed with a special algorithm developed under Matlab (Mathworks, Natick, MA, USA).

The modules were fixed on the patients in upright position. The 3D gyroscopes were visually oriented to align with the anatomical axes and to be collinear with each other (Fig. 1). The gyroscopic data were expressed in their segment's frame, and the joint's values in a mobile frame. The 3D knee motions were described along three directions, named flexion–extension, internal–external rotation and abduction–adduction, according to the joint's movements.

Data analysis

By subtracting the shank gyroscopic signals from the corresponding thigh ones, our algorithm calculated the 3D angular velocity of the joint. Then, after filtering and integration, it determined the 3D angles of the knee (Fig. 2).

In the framework of this study, only the flat level walking activity was tested; the 3D continuous angles were considered as three mean ranges of motion (ROM). So, for each walk the gait cycles were delimited [29]. Then, the maximal and minimal values of the three angles were localized for each cycle, in order to determine the cycles' amplitudes. Finally, the mean values were

calculated for the steady part of the walking trial, in this way removing the influence of initial acceleration and terminal deceleration.

Comparisons have been made between the 3D kinematics of the healthy and the injured knee of the same patient and between two values of the same knee obtained at different times. The Δ_h parameter was calculated to compare the 3D ROM of the pathologic knee with the controlateral healthy knee of the same patient, and the Δ_b parameter was considered as the 3D ROM

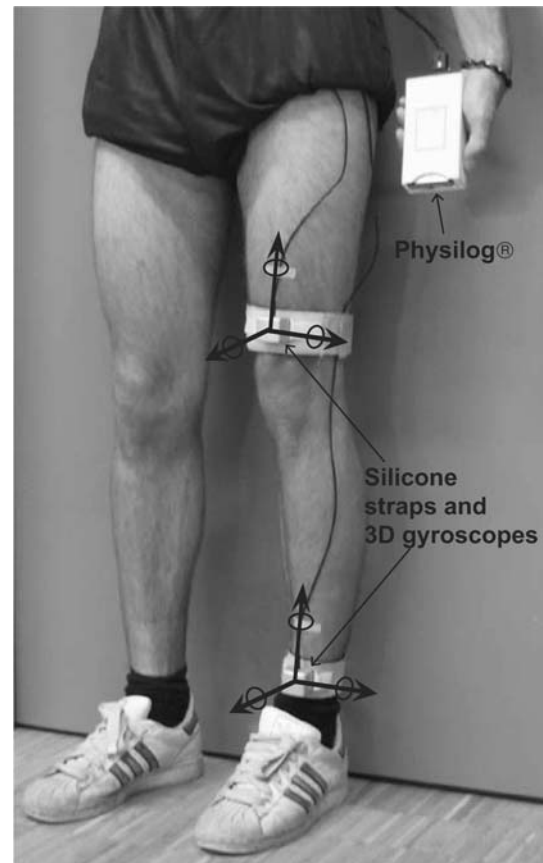


Fig. 1 The proposed system composed of two 3D gyroscopes fixed on the thigh and on the shank with silicone straps, and a Physilog[®] data logger

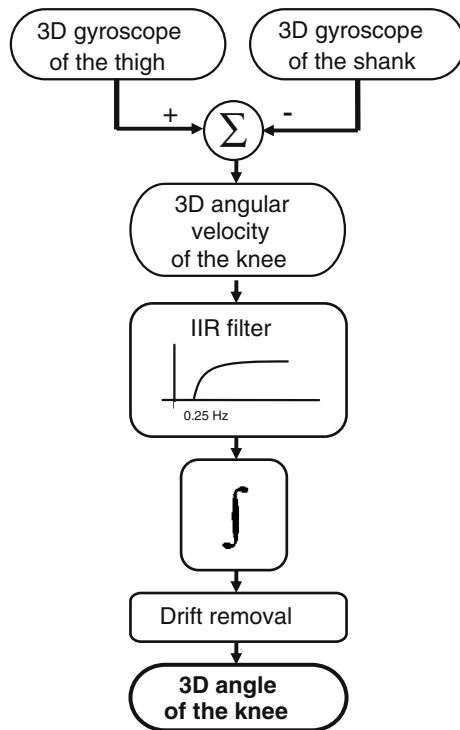


Fig. 2 Flowchart of the system

change in the postoperative knee compared to its preoperative value:

$$\Delta_h = \frac{\text{ROM of the ACL-deficient knee}}{\text{ROM of the healthy knee}} \times 100\%, \quad (1)$$

$$\Delta_b = \frac{\text{Postoperative ROM}}{\text{Preoperative ROM}} \times 100\%. \quad (2)$$

Evaluation of the measuring system

To assess the performance of the system, two series of measurements were realized. First, the precision of the system was evaluated for a healthy subject during 3 km/h walks on a treadmill (Marathon, Kettler, Germany). The 3D angles were recorded during five tests of 40 s walk by our proposed system and simultaneously by an ultrasonic system (Zebris[®], Medizintechnik, Germany). The Zebris system was used with two triplets fixed on the thigh and on the shank close to the gyroscopes. The triplets were orientated to measure the 3D rotations of the two segments along the same axes of the gyroscopes. The sampling rates were 50 Hz for the reference system and its accuracy was less than 1° [30]. An algorithm was specially realized to express the

kinematics values of the reference system according to mobile frame. Since the proposed system provides only the relative angles, the accuracy, which expresses a systematic error, is here irrelevant [33]. Therefore, only precision corresponding to the dispersion of the difference between actual and measured data was considered. So, for each sample of the five walks, the differences between both data were determined, and then, their standard deviation (SD) calculated over each walking trial. The correlation coefficients were also calculated between the angles obtained through both systems considering the signals of each walking trial (40 s).

Then, the repeatability [33] of this new evaluation technique was assessed in two different ways. First a healthy subject was asked to perform the same 30 m trial eight times while the system was removed and replaced between each trial. The 3D ROM was determined for each trial and the mean and standard deviation calculated. The standard deviation was considered as the repeatability error (RE_{sens}) due to the sensor's attachment. Secondly, the repeatability was assessed during the second measurement, performed after ACL reconstruction, by asking the patients to repeat each test three times (without removing the system). The 3D ROM was calculated independently for the three tests. Then, for each patient and parameter, the differences between the three tests and the mean value of the three tests were calculated. Finally, the SD of all patients' differences were determined for each parameter and was considered as the repeatability error (RE_{gait}) due to the gait change of the same subject from one trial to another during the same measurement.

Results

Instrumentation

The results for angle estimation are compared to the reference system in Fig. 3. The precision (minimum; maximum) obtained for the five walks were, respectively (2.5°; 4.4°), (2.1°; 2.7°) and (2.7°; 4.2°) for the flexion–extension, the internal–external rotation and the abduction–adduction. The corresponding correlation coefficients were, respectively, between (0.98; 0.99), (0.92; 0.96) and (0.75; 0.9).

The mean 3D ROM obtained with the healthy subjects over eight repeated walking trials were 69.9°, 25.8° and 11.6° and the RE_{sens} were 0.8°, 0.7° and 1.8°, respectively. Table 2 contains repeatability errors RE_{gait} for the 3D ROM and Δ parameters during the tests with the five patients. Figure 4 presents the 3D ROM for a typical patient for three postoperative walks. This figure also reports RE_{gait} (Table 2).

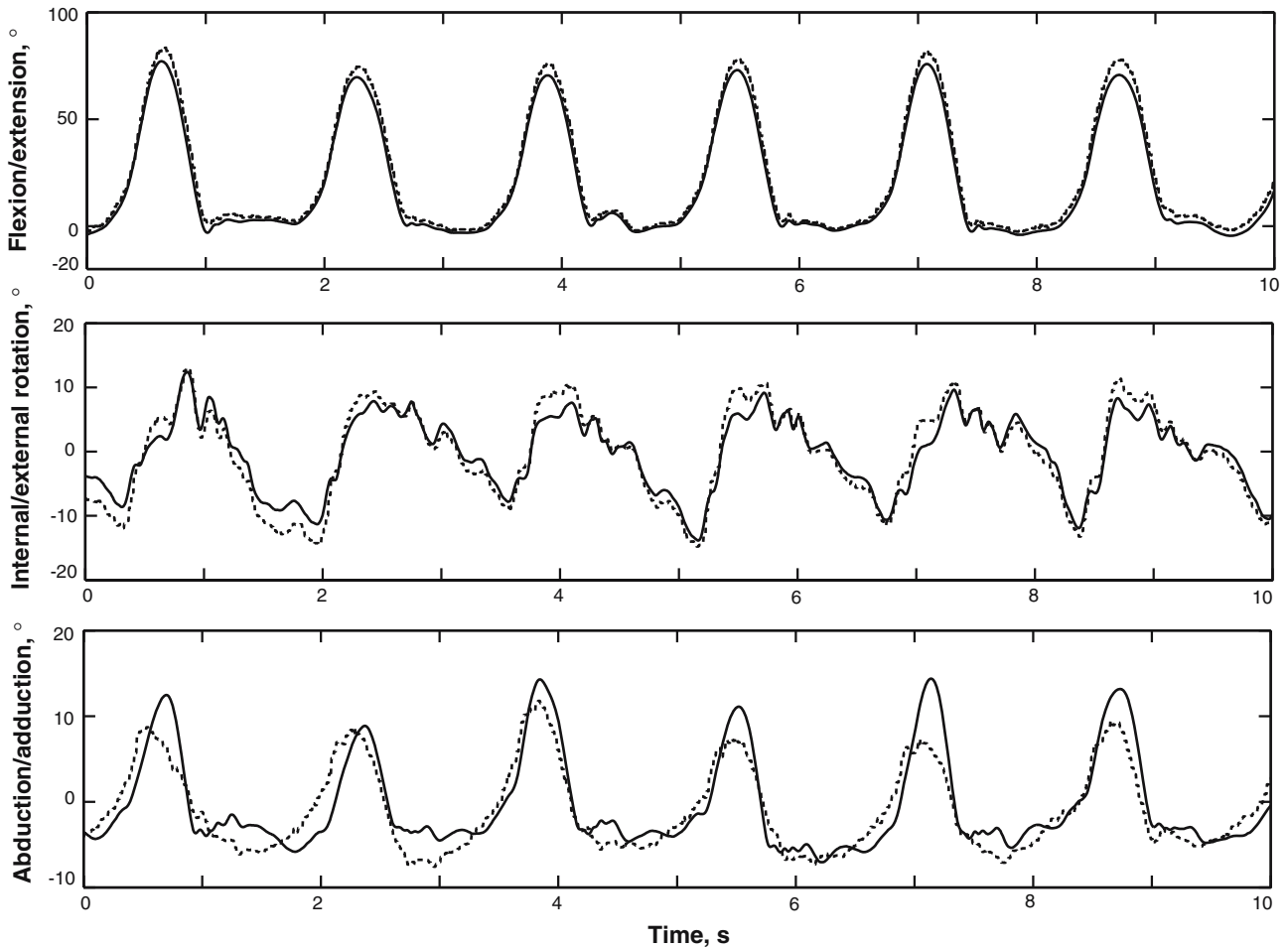


Fig. 3 3D angles for ten typical seconds of treadmill walking of a healthy subject. *Continuous line* corresponds to the reference system angles, and *dotted line* to the proposed system

Clinical study

The results of the IKDC score (2000 form), of the IKDC subjective score and of the laxity measurement, before and after the surgery, are listed in Fig. 5. One year after the reconstruction, all the patients improved their IKDC score: four knees were classified “normal” (A) and one “almost normal” (B). The subjective IKDC score improved by 17.1 units in average (range 12.6–22.1). The laxity decreased by 6.2 mm in average (range 4–9).

Table 3 contains the 3D ROM measured for the healthy and the pathologic knee of the five patients prior to surgery and a year after it.

Figure 6 shows the three Δ_h graphs illustrating the modification of the 3D ROM of the deficient knee compared to the controlateral healthy knee, before and after the ACL reconstruction. The 100% value corresponds to the value measured for the healthy knee considered as the reference. The results are expressed as a percentage of this value. In flexion–extension, the

deficient knee showed a decrease of the ROM compared to the healthy knee, which persisted postoperatively. In internal–external rotation, the deficient knee showed a decrease in ROM. However, after the ACL reconstruction, an increase was measured for all the patients. In abduction–adduction, no tendency was found. Patients 1, 3 and 4 walked with an increase in ROM; while patient 5 showed a decrease and patient 2 did not demonstrate any dissymmetry. However, after the surgery, those patients who showed an ROM

Table 2 Repeatability (RE_{gait}) calculated on three walks of five patients

		Flexion/ extension	Internal/ external rotation	Abduction/ adduction
ROM	Amplitude (°)	0.8	0.6	0.7
	Δ_h and Δ_b (%)	1.6	4.5	21

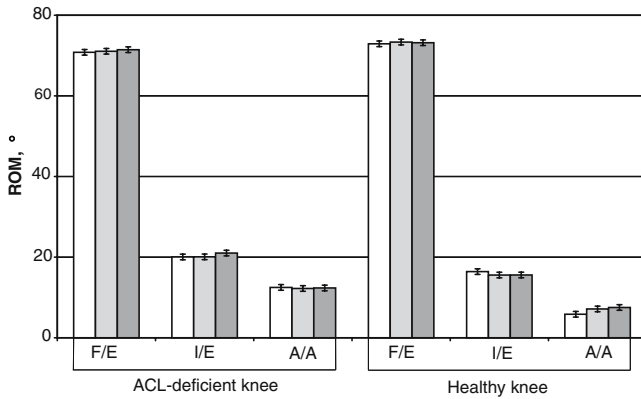


Fig. 4 3D ROM for three postoperative walks of a typical patient. The hooks (\square) indicate the repeatability (RE_{gait}) calculated on five subjects. *F/E* corresponds to flexion/extension, *I/E* to internal/external rotation, and *A/A* to abduction/adduction

variation went closer to the reference value (healthy knee).

The three Δ_b graphs of Fig. 7 illustrate the postoperative evolution of the 3D ROM of both, the injured and the healthy knees, in comparison with their preoperative value. The 100% value corresponded to the preoperative value of each knee. The results were expressed in percentage compared to this value. In flexion–extension, after the surgery, a ROM increase was measured for the operated knee. The same was observed for the healthy knee. For the internal–external rotation, an ROM gain was measured for the operated knee, with the exception of patient 1, in whom the change was not noticeable for the healthy knee. In abduction–adduction, the operated knees rather showed an ROM decrease. No general tendency was noticed for the ROM of the healthy knee.

Discussion

Instrumentation

The results of the proposed system were close to those of the reference system presenting small standard deviation (2° – 4°), reflecting precise estimations of angles for the three directions. Although the internal–external rotation angle showed a lower error, the system works identically for the three directions. This difference could be due to a better matching of the two systems (reference and proposed) for this direction of rotation. Actually, the alignment of gyroscopes axis was easier for internal–external rotation. The correlation coefficients were all superior to 0.9 for the flexion–extension and the internal–external rotation. They varied between 0.75 and 0.9 for the abduction–adduction. This lower correlation could be explained by

the smaller rotation amplitudes occurring along this axis, as reported by Marin et al. [34].

The important aspect concerning the performance of our system is the repeatability of the results, which is essential to determine if two knees function similarly or not. First, we assessed the repeatability of the system by measuring eight walks of the same subject (RE_{sens}). These values reflect the sensitivity of the system to the orientation of the sensors at the installation. But it also considered (at least for one subject) the differences in the way of walking from one

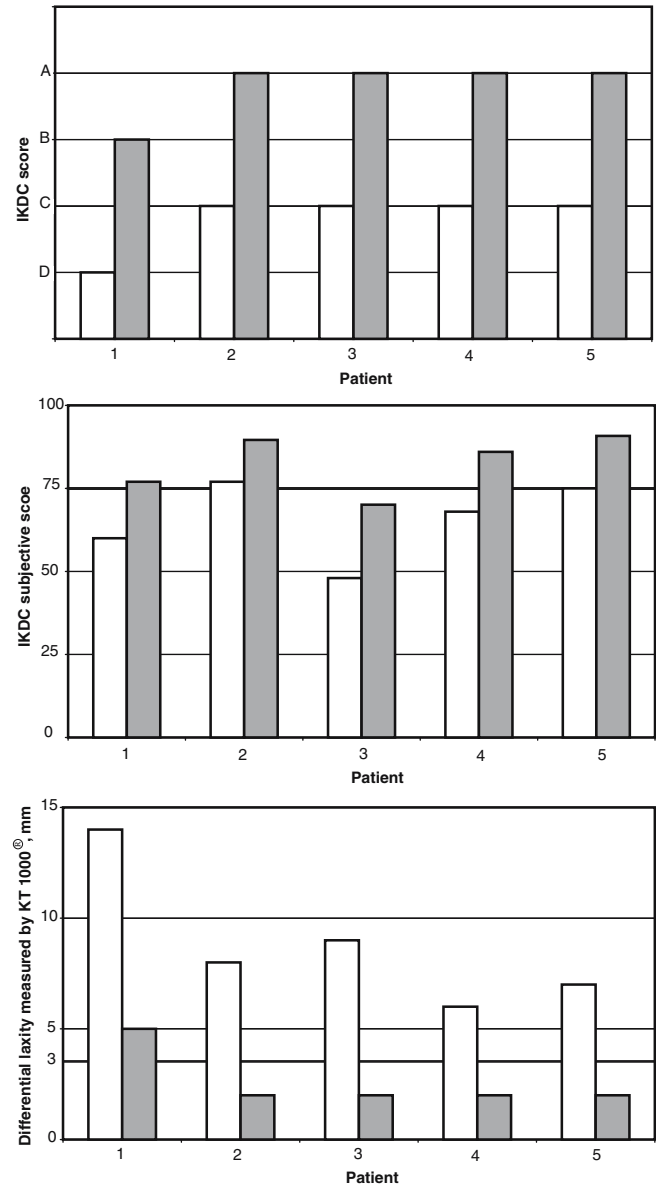


Fig. 5 IKDC score, IKDC subjective score and differential laxity measured by KT1000[®] applying the maximal manual force for the five patients. *Open square* corresponds to preoperative results, and *filled square* to postoperative results

Table 3 3D ROM of the five patients healthy and pathologic knee before (BR) and after (AR) the ACL reconstruction

Movement	Patient	Healthy BR	Healthy AR	Pathologic BR	Pathologic AR
Flexion–extension	1	66.1	73.3	64.2	71.1
	2	79.5	78.4	75.6	75.1
	3	67.5	82.4	65.1	74.7
	4	71.9	76.2	57.4	69.7
	5	65.6	72.1	60.5	71.0
Internal–external rotation	1	24.0	15.6	17.6	20.1
	2	28.9	29.0	25.9	34.8
	3	20.6	19.8	15.9	21.5
	4	23.6	22.5	20.3	30.6
	5	23.0	21.9	23.4	22.5
Abduction–adduction	1	5.7	7.2	13.6	12.2
	2	18.6	11.1	21.8	8.8
	3	11.5	6.4	30.9	12.8
	4	5.8	8.6	22.3	14.9
	5	18.1	17.9	9.9	13.5

trial to another. The second repeatability (RE_{gait}) values only reflected variations (for the same patient) in the way of walking (gait). For flexion–extension and internal–external rotation both values (RE_{sens} and RE_{gait}) were close and less than one degree. For abduction–adduction RE_{sens} was low (1.8°) in comparison with the ROM occurring in this direction. As previously stated, the alignment of the sensors was more difficult for the abduction–adduction, which can explain the lower repeatability.

The error of repeatability was less than the precision. This is due to the fact that the precision was estimated based on the instantaneous values of angles whereas the repeatability concerned the ROM. Moreover the precision considered a reference system as actual value while in repeatability the error was obtained through the same system.

When comparing the ROM obtained through this system with those of the devices presented in the literature [15–17, 35], we obtained physiological values for flexion–extension and internal–external rotation. But for the abduction–adduction (Table 3) some ROM are too large. This can be explained by the fact that, though the sensors were oriented very carefully during the measurements, this was not sufficient to get good results for the abduction–adduction. Figure 8 shows the results of a simulation where the sensing module of the thigh was virtually misaligned from -10° to 10° in the horizontal, frontal and the sagittal planes. This figure represents the difference for both legs of the five patients in the post-operative trials in comparison with the results obtained without virtual misalignment. This simulation confirms that this system is sensitive to the orientation of the sensors during the attachment. In comparison with the repeatability results obtained when the system was removed several times (RE_{sens}), visual orientation of the sensors seems to be reproducible within a few degrees. Therefore, the high abduction–adduction ROM could come from crosstalk error caused by a particular gait or

from skin motion. One can notice that the performance obtained through this system has been sufficient to reveal changes during its clinical utilisation.

Compared to optic, magnetic or ultrasonic motion capture systems using laboratory setting [36, 37], the proposed system showed lower precision, but allowed autonomous and non-constrained measurements. Since this system was based on body fixed sensors, it was fully ambulatory and can be used outside a laboratory. Another aspect which makes gyroscopes attractive for this study is the fact that gyroscopes can be attached anywhere on a body segment; the angular rotation is still the same along this segment. The system was easy-to-use and its manipulation (attachment, withdrawal, transfer and data analysis) takes only a few minutes. Since the patients do not need any assistance during the measurements and the capacity of the memory is large enough to record many hours, this system could be used for long-term monitoring of daily activities. However, for more rigorous activities, errors due to skin and muscle motion, as well as slippage of the straps and sliding due to sweat must be considered.

The main advantage of the proposed system in comparison with other ambulatory devices using body fixed sensors is its ability to provide 3D evaluation of knee kinematics. For example Williamson et al. [38] and Dejnabadi et al. [39] combined one gyroscope and two accelerometers on the thigh and on the shank to get the absolute knee angle in the sagittal plane, but those systems were unable to measure internal–external rotation. Giansanti et al. [40] investigated the possibility of using six or nine accelerometers to obtain the position and orientation of a body segment. Their simulations concluded that none of the two systems was suitable for body position and orientation estimation. Although 3D motion analysis systems using gyroscopes, accelerometers and magnetometers [41, 42] have been designed, they have not been applied to 3D ambulatory evaluation of knee kinematics.

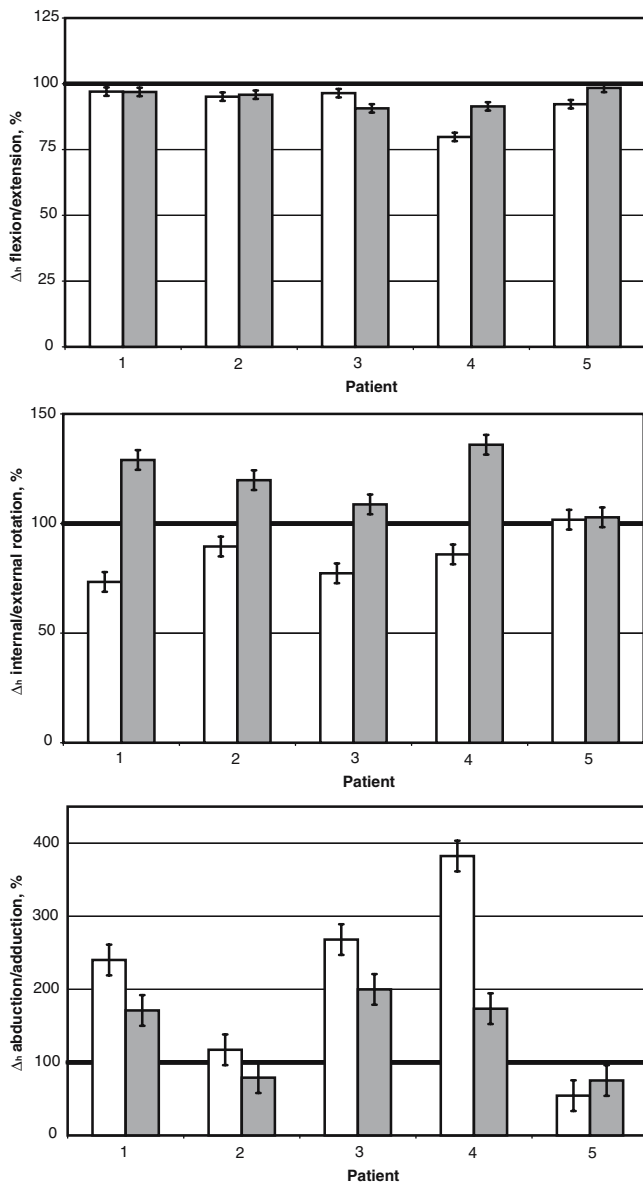


Fig. 6 Δ_h for flexion/extension, internal/external rotation and abduction/adduction for the five patients. The 100% value represents the ROM of the healthy controlateral knee. *Open square* corresponds to preoperative results and *filled square* to postoperative results. The hooks (\pm) indicate the reproducibility (RE_{gait}) calculated on five subjects

The proposed system is a simple alternative to gait laboratory systems for the 3D knee kinematics evaluation. During this study, the angular values have been evaluated as ROM, but a more detailed analysis of the patterns of movement [43, 44] during the gait cycles would probably enhance the comparisons. The present system does not give absolute angular values, but a new sensors combination, including accelerometers, should

enable it to get these values [39]. Moreover, using more sensors should also permit insensitivity to the initial orientation of the sensors and crosstalk errors. In addition, the realization of a wireless system [45] should improve the patient's comfort and the quality of the results.

Gait kinematics after an ACL lesion

In comparison with the healthy knee, our data showed that, for the studied patients, the 3D knee kinematics was modified after an ACL lesion. In flexion–extension, ROM decreased for the deficient knee compared to the healthy knee (Fig. 6). This parameter was previously underlined by many publications [9, 13, 46–52]. However, other authors did not find it [8, 11, 16, 52]. Many reasons could be advanced to explain this discordance. Firstly, this parameter varies from individual to individual and depends on their more or less successful adaptation to the ACL deficiency [53, 54]. Secondly, the time passed since the lesion also influences the amplitude measured in flexion–extension. For example Knoll et al. [8] found a decrease in flexion–extension only in patients with an acute lesion (mean delay after the lesion: 12 days). A flexion–extension decrease was present in 57% of Wexler's patients [49] and in 80% of Briac's patients [32]. This discordance underlines that the study of the kinematics only in the sagittal plane is not sufficient.

In internal–external rotation, an ROM decrease was also shown (Fig. 6). The comparison with the data from the literature is here tricky since the maximum angle of the tibial rotation is generally measured. For instance, some authors have underlined an increase of the external rotation [35, 55]; others an increase of the internal rotation [16]. Jonsson [56] did not underline any significant differences, although this last study did not include any dynamical measurements. The increase of the external rotation has been interpreted as a possible adaptation to the knee instability [35]. Our method does not give absolute angles, it calculates the mean ROM. The kinematics alteration could correspond to a modification of the muscular control during walking. The EMG data precisely suggest that the muscular activity is different after an ACL lesion [57–59]. The activity of the hamstring muscles, especially of the biceps femoris, would be extended. The hamstring muscles are agonists of the ACL and take part in the knee internal–external rotation. So, the ROM decrease measured in this study could be a consequence of the muscular system adaptation to the ACL deficiency.

In abduction–adduction no systematic modification has been underlined (Fig. 6). Three patients showed an

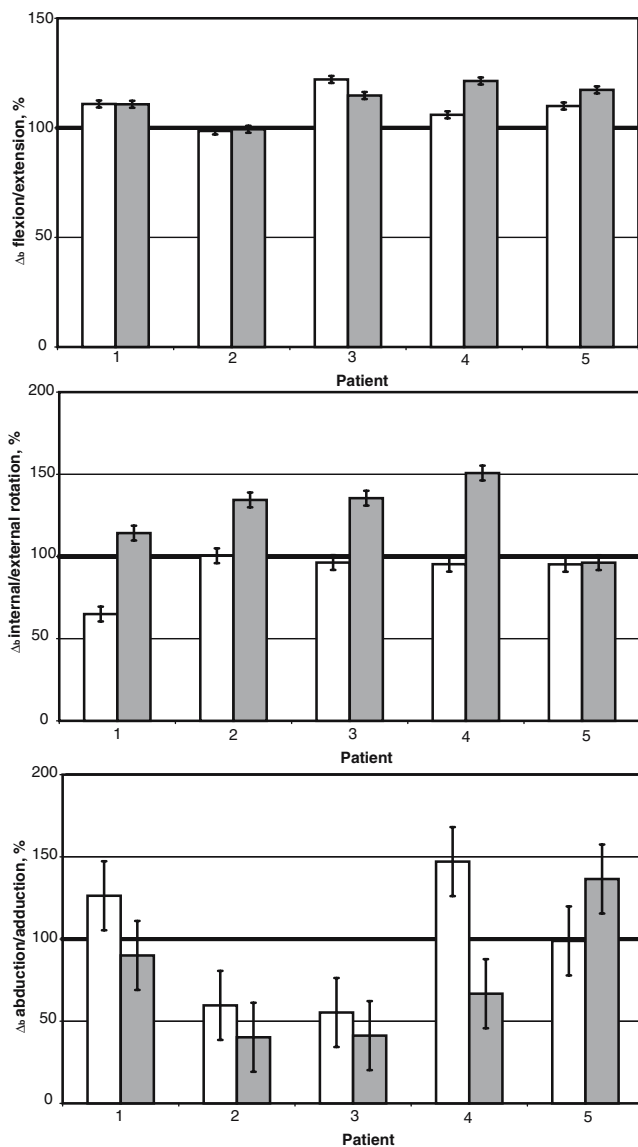


Fig. 7 Δ_b for flexion/extension, internal/external rotation and abduction/adduction for the five patients. The 100% value represents the preoperative ROM of the knees. *Open square* corresponds to the healthy knee and *filled square* to the ACL-deficient knee. The hooks (\pm) indicate the reproducibility (RE_{gait}) calculated on five patients

ROM increase while one patient presented a decrease. The data from the literature are especially slight. Jonsson [56] did not find any modification in comparison with the healthy knee. Georgoulis [16] and Brandsson [6] did not underline any significant differences. Zhang [35] measured an increase in the abduction. Other studies are necessary to better understand the kinematics in the frontal plane and the role of potential alterations of the functioning of the deficient knee.

Gait kinematics after an ACL reconstruction

A year after an ACL reconstruction, an improvement in knee function and clinical score can be observed in all patients (Fig. 5). According to the IKDC's criteria, four knees were classified A (normal) and one was classified B (almost normal). The IKDC subjective score was improved and the laxity was physiological (normal) for four patients. The laxity was still high (5 mm) for one patient. All patients did not resume their sportive and professional activities; two patients still limit their sport participation. These results are in concordance with those from the literature [1].

Contrarily, a year after the ACL reconstruction, the 3D kinematics was still perturbed. In flexion–extension, an ROM limitation persisted for the operated knee (Fig. 6). However, a gain compared to the preoperative values was measured (Fig. 7). This improvement was present for both knees, which explains the permanence of differences between the healthy and the operated knee. The studies of Gokeler [9] and of Hooper [12] also showed the persistence of this difference in flexion–extension, respectively 6 and 12 months after the surgery. Bulgheroni [17] found a tendency to the normalization of the kinematics parameters 17 months after the ACL reconstruction, in comparison with healthy controls. This suggests that the necessary time for the ROM normalization in flexion–extension could be more than one year. In our study, the patients with the highest subjective scores (>75 points) presented the closer ROM regarding their healthy side. The perception of knee functioning that the patient has could also influence the evolution of this kinematics parameter. Georgoulis [16] did not underline any difference 30 weeks after the ACL reconstruction, in comparison with healthy subjects. All the patients enrolled in this study presented an excellent function of the operated knee, but the lack of objective score limits the comparison.

In internal–external rotation, an ROM increase was measured after the surgery (Figs. 6, 7). A study of Brandsson [6] suggested that the internal–external rotation was not restored after the ACL reconstruction. Georgoulis [16] did not initially underline any rotational disorder during walking, in comparison with healthy subjects. But in another study of the same group [15], an increase of the ROM for the operated knee was observed compared to the healthy one. This observation was realized when the patients were asked to go a few steps down and then to pivot, at the bottom of the stairs. An ROM increase, during a light downward run, was also underlined by Tashman et al. [14] a year after the surgery. As for our patients, the operating technique used for these three studies was an ACL reconstruction with bone-patellar tendon-bone autograft, with the exception of four patients between the six patients of Tashman et al. (reconstruction with hamstring tendons autograft).

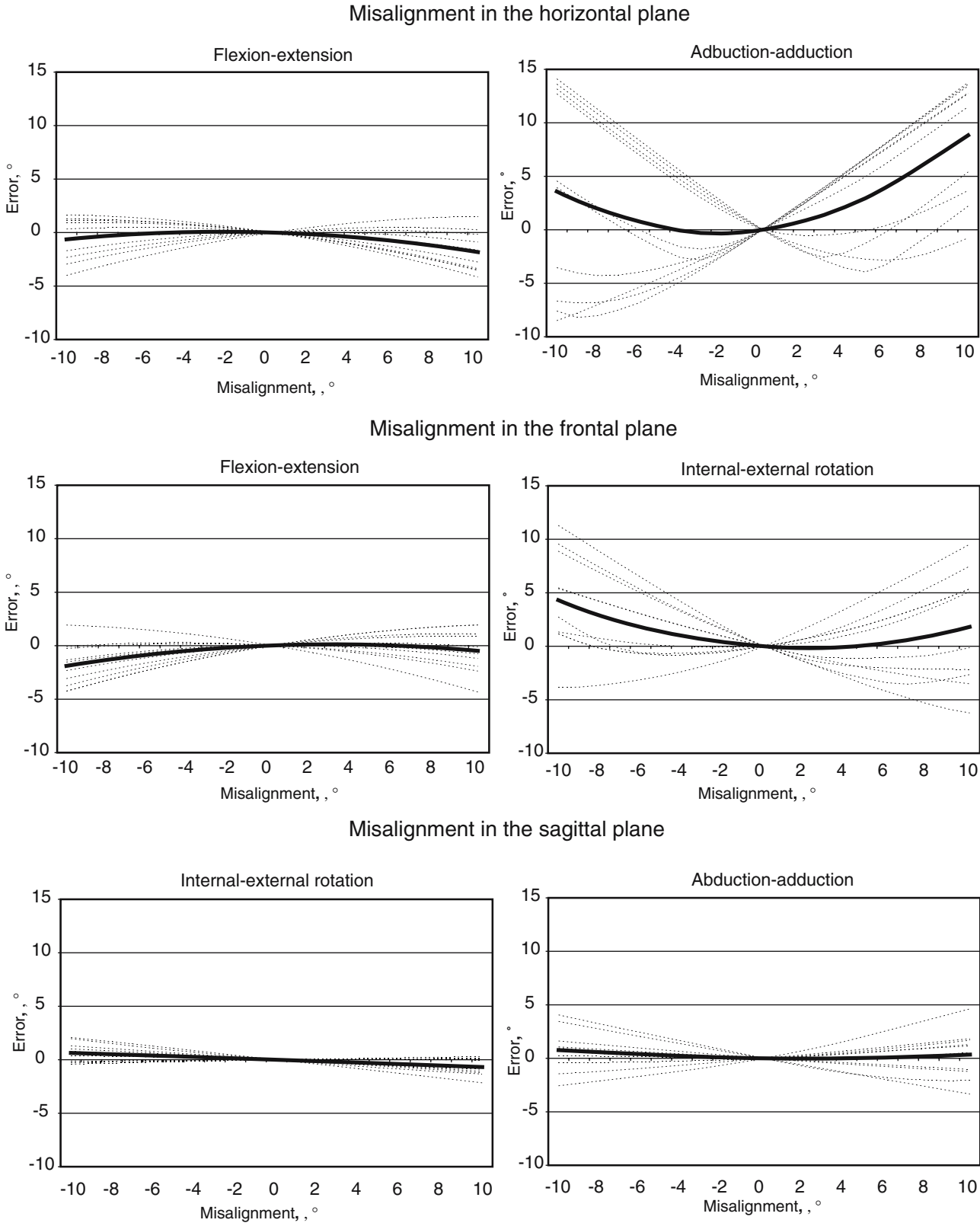


Fig. 8 Simulation of the ROM error in function of the misalignment of the sensory module of the tight in the horizontal, frontal and sagittal plane. *Dotted line* corresponds to the five postoperative walks of both knees and *continuous line* to the mean value

In abduction–adduction, the ROM of the operated knees had a tendency to get closer to the value of the healthy knee. A decrease was observed after surgery for three patients where an increase was present before the surgery. The inverse was observed for one patient (no 5). (Figs. 6, 7). With the exception of Tashman et al. [14], who showed an increase of the abduction, others' investigations did not underline any differences [6, 15, 16]. Further studies are also needed to better understand the kinematics evolution of the operated knee in the frontal plane.

This study had some limitations. The population was small since the framework of the study was limited to underlying the effectiveness of a new measuring system for 3D knee function evaluation after ACL reconstruction. Actually a larger population is needed to evaluate the improvement of laxity after this ACL reconstruction. Moreover, our analysis was focused on the 3D ROM of knee angles. Nevertheless, the results are coherent with the literature. Firstly, this study confirmed that knee kinematics was modified after an ACL lesion [9, 13, 16, 32, 35, 46, 47, 51, 55]. It also showed that an instrumented gait analysis in the sagittal plane is not sufficient [16, 35, 55]. But particularly, this study suggested that the 3D kinematics remained still altered a year after the surgery, in the studied population. A decrease of the ROM persisted in flexion–extension a year after the surgery. This parameter probably depends on multiple factors. The time period from the surgery and the

patient's adaptation after the reconstruction are likely to modify it [9, 12, 16, 17]. For the postoperative evaluation, limiting the analysis to the sagittal plane was also inadequate. The persistence of internal–external rotational disorders was especially well underlined in this study. This kinematics parameter could be particularly interesting: the ACL not only controls the sagittal translation of the knee, but also the internal–external rotation. The agreement of these results with *in vitro* [7, 60, 61] and *in vivo* [6, 14, 15] studies suggests that the reconstruction techniques with bone–patellar tendon–bone autograft and with hamstring tendons autograft do not restore the control of the internal–external rotation. The persistence of such disorders could contribute towards modifying the stresses on the cartilage during daily activities. The proposed gait analysis does not currently permit to relate to the development of knee osteoarthritis. But it represents a promising tool for the evaluation of surgical techniques susceptible to improve the internal–external rotation (graft's positioning, ACL two bundles reconstruction). Moreover, the development of analysis tools like these, easy to position and ready to handle by physicians, therapists, or nurses, allows a longitudinal follow-up of large populations. Long time measurements of various activities (walking, uphill–downhill walking, climbing, etc.), in outdoors and without supervision, could also be envisaged. Such prospects are susceptible to improve the knowledge of the gradual change of patients with an ACL lesion.

References

- Shelbourne KD, Gray T (2000) Results of anterior cruciate ligament reconstruction based on meniscus and articular cartilage status at the time of surgery. Five- to fifteen-year evaluations. *Am J Sports Med* 28:446–452
- Chol C, Ait Si Selmi T, Chambat P, Dejourdagger H, Neyret P (2002) Seventeen year outcome after anterior cruciate ligament reconstruction with a intact or repaired medial meniscus. *Rev Chir Orthop Reparatrice Appar Mot* 88:157–162
- Gillquist J, Messner K (1999) Anterior cruciate ligament reconstruction and the long-term incidence of gonarthrosis. *Sports Med* 27:143–156
- Fink C, Hoser C, Hackl W, Navarro RA, Benedetto KP (2001) Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture—is sports activity a determining variable? *Int J Sports Med* 22:304–309
- Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR (1994) Fate of the ACL-injured patient. A prospective outcome study. *Am J Sports Med* 22:632–644
- Brandsson S, Karlsson J, Sward L, Kartus J, Eriksson BI, Karrholm J (2002) Kinematics and laxity of the knee joint after anterior cruciate ligament reconstruction: pre- and postoperative radiostereometric studies. *Am J Sports Med* 30:361–367
- Hagemeister N, Long R, Yahia L et al (2002) Quantitative comparison of three different types of anterior cruciate ligament reconstruction methods: laxity and 3D kinematic measurements. *Bio-med Mater Eng* 12:47–57
- Knoll Z, Kocsis L, Kiss RM (2004) Gait patterns before and after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 12:7–14
- Gokeler A, Schmalz T, Knopf E, Freiwald J, Blumentritt S (2003) The relationship between isokinetic quadriceps strength and laxity on gait analysis parameters in anterior cruciate ligament reconstructed knees. *Knee Surg Sports Traumatol Arthrosc* 11:372–378
- Lewek M, Rudolph K, Axe M, Snyder-Mackler L (2002) The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clin Biomech (Bristol, Avon)* 17:56–63

11. Ferber R, Osternig LR, Woollacott MH, Wasielewski NJ, Lee JH (2002) Gait mechanics in chronic ACL deficiency and subsequent repair. *Clin Biomech* (Bristol, Avon) 17:274–285
12. Hooper DM, Morrissey MC, Drechsler WI, Clark NC, Coutts FJ, McAuliffe TB (2002) Gait analysis 6 and 12 months after anterior cruciate ligament reconstruction surgery. *Clin Orthop* 168–178
13. DeVita P, Hortobagyi T, Barrier J. (1998) Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation. *Med Sci Sports Exerc* 30:1481–1488
14. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. *Am J Sports Med* 32:975–983
15. Ristanis S, Giakas G, Papageorgiou CD, Moraiti T, Stergiou N, Georgoulis AD (2003) The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs. *Knee Surg Sports Traumatol Arthrosc* 11:360–365
16. Georgoulis AD, Papadonikolakis A, Papageorgiou CD, Mitsou A, Stergiou N (2003) Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. *Am J Sports Med* 31:75–79
17. Bulgheroni P, Bulgheroni MV, Andriani L, Guffanti P, Giughello A (1997) Gait patterns after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 5:14–21
18. Van Bogart J (2000) Motion analysis technologies. *Pediatric Gait*, IEEE CNF
19. Fuller J, Liu LJ, Murphy MC, Mann RW (1997) A comparison of lower-extremity skeletal kinematics measured using skin- and pin-mounted markers. *Hum Mov Sci* 16:219–242
20. Sati M, de Guise JA, Larouche S, Drouin G (1996) Quantitative assessment of skin-movement at the knee. *Knee* 3:121–138
21. Woltring HJ (1994) 3D attitude representation of human joints: a standardization proposal. *J Biom* 1399–1414
22. Ramakrishnan HK, Kabada MP (1991) On the estimation of joint kinematics during gait. *J Biom* 969–977
23. Cheze L (2000) Comparison of different calculations of three-dimensional joint kinematics from video-based system data. *J Biomech* 33:1695–1699
24. Yagi M, Wong EK, Kanamori A, et al. (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med* 30:660–666
25. Chambat P, Chaker M (2004) Technique de la ligamentoplastie du ligament croisé antérieur au tendon rotulien (tunnel fémoral de dehors en dedans). In: Landreau P, Christel P, Djian P (eds) *Pathologie ligamentaire du genou*. Paris, pp 365–390
26. Jacquot L, Ratchet O, Chambat P (2001) La rééducation du genou après greffe du ligament croisé antérieur. In: Chambat P, Neyret P, Bonnin M, Dejout D (eds) *Sport et Rééducation du membre inférieur*. Montpellier, pp 31–50
27. Irrgang JJ, Ho H, Harner CD, Fu FH (1998) Use of the International Knee Documentation Committee guidelines to assess outcome following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 6:107–114
28. Irrgang JJ, Anderson AF, Boland AL (2001) Development and validation of the international knee documentation committee subjective knee form. *Am J Sports Med* 29:600–613
29. Aminian K, Najafi B, Bula C, Leyvraz PF, Robert PH (2002) Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes. *J Biom* 35:689–699
30. Chateau H, Girard D, Degueurce C, Denoix JM (2003) Methodological considerations for using a kinematic analysis system based on ultrasonic triangulation. *ITBM-RBM*, pp 69–78
31. Della Croce U, Camomilla V, Leardini A, Cappozzo A (2003) Femoral anatomical frame: assessment of various definitions. *Med Eng Phys* 25:425–431
32. Birac R, Andriacchi TP, Bach BR (1991) Time related changes following ACL rupture. *Trans Orthop Res Soc* 1:231
33. Webster JG (2004) *Bioinstrumentation*. Wiley, NJ, ISBN 0-471-26327-3
34. Marin F, Allain J, Diop A, Maurel N, Simondi M, Lavaste F (1999) On the estimation of knee joint kinematics. *Hum Mov Sci* 18:613–626
35. Zhang LQ, Shiavi RG, Limbird TJ, Minorik JM (2003) Six degrees-of-freedom kinematics of ACL deficient knees during locomotion-compensatory mechanism. *Gait Posture* 17:34–42
36. Richards JG (1999) The measurement of human motion: a comparison of commercially available systems. *Hum Mov Sci* 18:589–602
37. Milne AD, Chess DG, Johnson JA, King GJW (1995) Accuracy of an electromagnetic tracking device: a study of the optimal operating range and metal interference. *J Biom* 791–793
38. Willemsen ATM, Frigo C, Boom HBK (1991) Lower extremity angle measurement with accelerometers—error and sensitivity analysis. *IEEE Trans Biomed Eng* 38(12):1186–1193
39. Dejnabadi H, Jolles BM, Aminian K. A new approach to accurate measurement of uniaxial joint angles based on a combination of accelerometers and gyroscopes. *IEEE Trans Biomed Eng* (in press)
40. Giansanti D, Macellari V, Maccioni G, Cappozzo A (2003) Is it feasible to reconstruct body segment 3D position and orientation using accelerometric data. *IEEE Trans Biomed Eng* 50(4):476–483
41. Zhu R, Zhou Z (2004) A real-time articulated human motion tracking using tri-axis inertial/magnetic sensors package. *IEEE Trans Neural Syst Rehabil Eng* 295–302
42. Mayagoitia RE, Nene AV, Veltink PH (2002) Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. *J Biom* 35:537–542
43. Stokes VP, Lanshammar H, Thorstensson A (1999) Dominant pattern extraction from 3D kinematic data. *IEEE Trans Biomed Eng* 46:100–106
44. Deluzio KJ, Wyss UP, Zee B, Costigan PA, Sorbie C (1997) Principal component models of knee kinematics: normal vs. pathological gait patterns. *Hum Mov Sci* 16:201–217
45. Aminian K, Najafi B, Gramiger J, Morel P (2002) Body movement monitoring device, PCT no CH02/00075
46. Andriacchi TP, Birac D (1993) Functional testing in the anterior cruciate ligament-deficient knee. *Clin Orthop* 40–47
47. Berchuck M, Andriacchi TP, Bach BR, Reider B (1990) Gait adaptations by patients who have a deficient anterior cruciate ligament. *J Bone Joint Surg Am* 72:871–877
48. Hurwitz DE, Andriacchi TP, Bush-Joseph CA, Bach BR Jr (1997) Functional adaptations in patients with ACL-deficient knees. *Exerc Sport Sci Rev* 25:1–20
49. Wexler G, Hurwitz DE, Bush-Joseph CA, Andriacchi TP, Bach BR Jr (1998) Functional gait adaptations in patients with anterior cruciate ligament deficiency over time. *Clin Orthop* 166–175
50. Shiavi R, Limbird T, Frazer M, Stivers K, Strauss A, Abramovitz J (1987) Helical motion analysis of the knee—II. Kinematics of uninjured and injured knees during walking and pivoting. *J Biomech* 20:653–665

51. Patel RR, Hurwitz DE, Bush-Joseph CA, Bach BR Jr, Andriacchi TP (2003) Comparison of clinical and dynamic knee function in patients with anterior cruciate ligament deficiency. *Am J Sports Med* 31:68–74
52. Timoney JM, Inman WS, Quesada PM et al (1993) Return of normal gait patterns after anterior cruciate ligament reconstruction. *Am J Sports Med* 21:887–889
53. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L (1998) Basmajian student award paper: movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol* 8:349–362
54. Houck J, Yack HJ (2003) Associations of knee angles, moments and function among subjects that are healthy and anterior cruciate ligament deficient (ACLD) during straight ahead and crossover cutting activities. *Gait Posture* 18:126–138
55. Brandsson S, Karlsson J, Eriksson BI, Karrholm J (2001) Kinematics after tear in the anterior cruciate ligament: dynamic bilateral radiostereometric studies in 11 patients. *Acta Orthop Scand* 72:372–378
56. Jonsson H, Karrholm J, Elmqvist LG (1989) Kinematics of active knee extension after tear of the anterior cruciate ligament. *Am J Sports Med* 17:796–802
57. Limbird TJ, Shiavi R, Frazer M, Borra H (1988) EMG profiles of knee joint musculature during walking: changes induced by anterior cruciate ligament deficiency. *J Orthop Res* 6:630–638
58. Ciccotti MG, Kerlan RK, Perry J, Pink M (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
59. Imran A, O'Connor JJ (1998) Control of knee stability after ACL injury or repair: interaction between hamstrings contraction and tibial translation. *Clin Biomech (Bristol, Avon)* 13:153–162
60. Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL (2003) Knee stability and graft function following anterior cruciate ligament reconstruction: Comparison between 11 o'clock and 10 o'clock femoral tunnel placement. *Arthroscopy* 19:297–304
61. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH (2002) 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* 84-A:907–914