Biomechanical Analysis of Postural Strategies over the First Two Months Following Anterior Cruciate Ligament Reconstruction

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To assess the postural strategies developed over the first 2 months following surgery by ACL patients during rehabilitation and highlight the sensory-motor impairment recovery, 21 patients were measured at three timeframes. Three two-legged standing conditions were assessed: with the eyes open, with the eyes closed either wearing or not wearing a knee orthosis. The results indicate that the weight-bearing asymmetry, initially observed (i.e., 56–44% of body-weight), disappeared progressively during rehabilitation (51–49%). The comparison of the plantar center-of-pressure displacements under both sound and operated legs demonstrated noticeable differences that also tended to decrease but without reaching a matched behavior during the last measures. These effects were seen in both eyes open and eyes closed conditions with the greatest effects in the latter condition. Wearing a knee orthosis inferred no particular changes in the postural control behaviors. These data could be used as benchmarks for highlighting the effects on undisturbed postural control of various surgery techniques and/or rehabilitation protocols.

Keywords: Anterior cruciate ligament; rehabilitation; postural control; two-legged standing; knee orthosis

Most of the clinical tests aimed at evaluating rehabilitation after anterior cruciate ligament (ACL) reconstruction are functional (Noyes et al., 1989; Höher et al., 1995; Risberg et al., 1999). More direct and objective information from a standardized laboratory protocol is therefore worth consideration. Since ACL tears are recognized to induce proprioceptive impairment in detecting passive sense of knee motion and position, one may hypothesize that repeating such measurements could reliably assess follow-up during the rehabilitation period (Reider et al., 2003). Proprioceptive input from ligaments have been shown to contribute to functional joint stability (Johansson et al., 1991).

Along with the necessity to solicit proprioceptive cues, other aspects such as loading must be considered. In most daily activities, each knee has to support at
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least half of the body weight. Several studies comparing the knee behavior under weightbearing and nonweightbearing conditions have emphasized the strain differences between these two conditions (Fleming et al., 2001). Nevertheless, too much strain in the protocol may make early testing after surgery impossible.

Therefore, postural control should be considered since it requires minimizing motions through the body joints and reasonable strain, in particular for two-legged standing. Accordingly, numerous studies in the past two decades have highlighted the deficits in postural control capacities in patients after ACL injury. Most of these studies involved patients with an old rupture of the ACL before (Okuda et al., 2005) or long after the surgery (Mizuta et al., 1992; Harrison et al., 1994; Lysholm et al., 1998; Shiraiishi et al., 1996; Henriksson et al., 2001). In addition, several studies have emphasized the deficit in proprioceptive information by comparing postural scores in both open and closed eye conditions (Okuda et al., 2005; Davids et al., 1999). The above-mentioned studies were based on one-legged standing protocols. Interestingly, some have also considered two-legged standing protocols (Okuda et al., 2005; Lysholm et al., 1998; Henriksson et al., 2001; Davids et al., 1999; O’Connell et al., 1998). However, none of these one- or two-legged protocols was able to report differentiated postural behaviors in ACL patients as compared with healthy subjects taken as reference. Interestingly, using force platform data, it was found that an impairment in weight-bearing symmetry was still present 2 months after surgery (Chmielewski et al., 2002).

Wearing a functional knee orthosis may be helpful in cases of proprioceptive impairment and muscular weakness following surgery. Beynnon et al. (2002) underlined that their application does not improve the threshold for detecting passive motions. In contrast, Birmingham et al. (2001) reported significant orthosis effects in postural control but only during their lowest constraining task consisting in one-legged standing with the eyes open. However, this latter study legitimates the use of posturography for testing knee orthotics.

Recent developments in posturographic analysis have emphasized, in particular for asymmetric postures, the benefit of separately collecting the center-of-pressure (CP) under each foot. It is indeed important to differentiate orientation (weight-bearing) from stabilization (patterns of the two plantar CP trajectories) asymmetries (Genthon and Rougier, 2005). In this train of thoughts, orientation refers to the body positioning relative to the feet while stabilization refers to the dynamic processes involved in the upright satnce maintenance. With this approach, the strategies and compensatory mechanisms between the two legs used for controlling upright quiet stance can be better understood (Genthon et al., 2008; Rougier and Bergeau, 2009; Genthon et al., 2010). In addition, a dissociation of the complex CP displacements into two basic components, the vertically projected center-of-gravity (CGv) and the difference between CP and CGv (CP-CGv), brings additional insights for describing the postural control mechanisms (Winter et al., 1996; Rougier and Caron, 2000).

The main objective of the current study is to apply this approach to evaluating the changes in the postural control strategies used by ACL patients occurring during rehabilitation and, in particular, during the “proprioceptive” period. Because two-legged standing can be viewed as an acceptable strain for the operated knee, this task can be performed rather soon after surgery. To highlight the compensatory role played by vision in the sensory integration mechanisms,
these postural tasks were repeatedly performed in both the eyes closed and eyes open conditions.

We hypothesized that changes in both weight-bearing and plantar CP trajectory asymmetries should be seen and that these effects would be more easily seen in nonvisual conditions.

**Methods**

Twenty-one patients (14 males, 7 females; 10 and 11 with left and right knee ACL reconstructions; age = 26 ± 8 years; height = 1.72 ± 0.08; weight = 71.6 ± 12.8 kg) gave their informed consent in accordance with the guidelines of the local ethics committee and participated in this study. Sixteen and five subjects had ACL reconstruction using bone-patella-bone or hamstring muscle tendon autografts, respectively. The patients were not eligible at the onset if there was meniscal damage, if pain exceeded a level of 2 on an visual analog scale of 10, and if they had undergone ACL reconstruction less than 2 years before on the other knee.

The follow-up of their postural control strategies was assessed using a similar protocol repeated at different times during the two-part hospitalization stays of the patient: (1) at the end of the first stay when the patient was allowed autonomous gait (timeframe 1: 19 ± 3 days), (2) at the beginning (timeframe 2: 47 ± 3 days) and (3) the end of the second stay (timeframe 3: 57 ± 3 days) whose rehabilitation program was based on physical activity reconditioning. The patients stood barefoot on a double force platform (PF02, Equi+, Aix-les-Bains, France), consisting in two rectangular force platforms (20 × 35 cm) collaterally installed, and were asked to stand still with their arms at their sides. For each condition, three trials lasting 32 s (64 Hz) were recorded with rest periods between trials of similar durations. The inner borders of the feet were parallel, 6 cm apart. The plantar and resultant CP trajectories were then automatically processed, as seen below, in different ways. Three experimental conditions were randomly proposed: (1) an eyes-closed condition (EC), (2) an eyes-open (EO) condition where patients were given a vertical reference with the corner of the room, and (3) an orthosis (ORT) condition, performed the eyes closed, where a knee orthosis (Ormihl-Danet, France, stabilig X-Trem model) was installed by a single investigator around the operated knee following reproducible fitting rules. This orthosis was made of elastic foam, with two lateral joints and two Velcro fastening straps. For all conditions, the patients were required to stand motionless with no other indication.

**Computation of the Resultant Center of Pressure (CP<sub>Res</sub>) Movements**

The resultant CP<sub>Res</sub> movements were calculated, through the PROG02 software (Equi+, Aix-les-Bains, France), along each mediolateral (ML) or anteroposterior (AP) axis from the left and right plantar CP movements (CP<sub>lf</sub> and CP<sub>rf</sub>, respectively) and from the time series of the body weight distribution between the supports (Winter et al., 1996). To compare the two legs, a terminology for the plantar CP based on the operated and sound legs (CP<sub>ol</sub> and CP<sub>sl</sub>) was used throughout this study.
Estimation of the Vertically Projected Movements of the Center of Gravity (CG_v)

Since body sway is generally reduced, even for these patients, undisturbed stance maintenance inferred constant momentum of the body’s inertia. The CG_v estimation, detailed in a previous study (Caron et al., 1997), consists in multiplying the fast-Fourier transform (FFT) of the CP signal by the relation \( \frac{\Omega_o^2}{(\Omega^2 + \Omega_o^2)} \), where \( \Omega \) is angular frequency in rad/s and \( \Omega_o \) is a value determined from the anthropometric data (Brenière, 1996). We hypothesized that the body constitutes a low-pass filter, which would explain the loss in amplitude observed between CP_Res and CG_v as the frequency increases.

Interestingly, CG_v and CP–CG_v movements can be used to assess the body motions and the neuromuscular means called into play for their control, respectively. Even though these two movements are related biomechanically, they may fluctuate independently (Rougier et al., 2007). Accordingly, a specific index (deadening ratio), based on the ratio between the variances of CP–CG_v and CG_v movements, was computed for each ML (R_ml) and AP (R_ap) axis (Rougier et al., 2007). The larger the ratio, the more deadening the postural control. For instance, an increased deadening ratio means that, despite increased CP–CG_v movements (i.e., horizontal accelerations communicated to the CG), the CG_v movements do not increase in comparable proportions or, even, decrease.

Signal Processing

The various CP_rf, CP lf, CP_Res, CG_v, CP–CG_v movements were studied through several parameters, including the mean body-weight distribution, the variances of the successive positions and deadening ratios along both ML and AP axes, the surface (Tagaki et al., 1985), and mean velocity (total path lengths divided by trial duration). With Gaussian distributions of the various parameters (assessment through Kolmogorov-Smirnov tests), two-factor (rehabilitation timeframe and condition) ANOVA with repeated measures were computed to assess the role played by these factors on CG_v and CP–CG_v movements. Three-factor (leg, rehabilitation timeframe, and condition) ANOVA were also performed to assess the role played by each leg. These factors included the leg (sound/injured), the timeframe (1/2/3), and the condition (EO/EC/ORT). Dunnett’s multiple comparison tests were performed as post hoc analysis with the EC condition or timeframe 1 taken as references. For all tests, the first level of significance was set at \( p < .05 \).

Results

Mean Bodyweight Distribution and Mean CP Positions

During the first recording session, the patients distributed their bodyweight asymmetrically with the main load on the sound leg (56% ± 5). As the rehabilitation advanced, this asymmetry was decreased to reach normal postural behavior when entering (52% ± 4) or departing (51% ± 4) the second in-patient care (Figure 1). This effect was underlined by the two-factor ANOVA \([F(2,180)=21.66; p < .01]\) and the post hoc Dunnett test, which highlighted the differences between timeframes 1 and 2 \((p < .01)\) and between timeframes 1 and 3 \((p < .01)\).
Figure 1 — Bar charts representing mean (+ s.d.) of bodyweight distribution, surface and mean velocity for plantar CP movements. OL: operated leg; SL: sound leg.

The ANOVA test also revealed the effects on the mean positions along the AP axis [F(2,180)=5.27; \( p < .01 \)]. The CP\textsubscript{Res} displacements were progressively forwarded (i.e., toward the toes) during rehabilitation. The Dunnett tests demonstrated significant differences between timeframes 1 and 2 (\( p < .02 \)) and between timeframes 1 and 3 (\( p < .01 \)). As seen by the three-factor ANOVA [F(2,360)=7.86; \( p < .01 \)] and post hoc analysis (between timeframes 1 and 2: \( p < .01 \) and between timeframes 1 and 3: \( p < .01 \)), the forward CP\textsubscript{Res} shift also involved the sound and injured legs.

CG\textsubscript{v} and CP–CG\textsubscript{v} Movements

The two-factor ANOVA revealed significant effects for the condition factor and for various parameters characterizing the CP–CG\textsubscript{v} movements (Figure 2): the variances
Figure 2 — Bar charts representing mean (+ s.d.) of surface, mean velocity, variances, and deadening ratios along ML and AP axes for CG_v and CP–CG_v movements.
along ML \( [F(2,180)=3.35; p < .04] \) and AP axes \( [F(2,180)=14.44; p < .01] \), surface \( [F(2,180)=7.98; p < .01] \) and mean velocity \( [F(2,180)=8.25; p < .01] \). The post hoc analysis indicated significant differences between EO and EC conditions for AP variance, surface, and mean velocity (\( p < .01 \) in all cases). Significant trends were also found for the CG\textsubscript{v} movements with the ANOVA computed from the AP variance \( [F(2,180)=7.47; p < .01] \), surface \( [F(2,180)=3.19; p < .04] \) and mean velocity \( [F(2,180)=14.48; p < .01] \). Post hoc effects involving vision were found for AP variance and mean velocity (\( p < .01 \) in all cases).

The decrease during rehabilitation was stronger for the CP–CG\textsubscript{v} than for the CG\textsubscript{v} movements (Figure 2). Accordingly, the deadening ratios, rather high at timeframe 1, tended to decrease afterward. This was confirmed by the ANOVA for the ML \( [F(2,180)=6.14; p < .01] \) and AP axes \( [F(2,180)=5.21; p < .01] \). The post hoc analysis indicated significant differences between timeframes 1 and 2 (ML: \( p < .00; AP: p < .01 \)) and between timeframes 1 and 3 (\( p < .01 \) for both ML and AP axes). The capacity to counteract the horizontal accelerations communicated to the CG\textsubscript{v} movements was thus progressively increased throughout the rehabilitation program. Lastly, a condition factor effect is worth mentioning but was found only along the ML axis \( [F(2,180)=4.77; p < .01] \). This effect principally stems from the EC/EO comparison (\( p < .02 \)), which showed higher ratios for the EC condition (Figure 2), showing that the larger CP–CG\textsubscript{v} movements for the EC condition do not infer concomitant increases in CG\textsubscript{v} movements.

**Plantar Movements Under Operated and Sound Legs**

When comparing the CP under the sound and operated legs, surface and mean velocities always appear larger for the former than for the latter (Figure 1). This observation was confirmed with the two significant ANOVA tests involving the leg factor for both surface \( [F(1,360)=57.93; p < .01] \) and mean velocity \( [F(1,360)=39.06; p < .01] \). Even though the gap between the surface values from both legs tended to decrease with time for all conditions, no significant effect was seen for EO, EC, and ORT conditions. Lastly, wearing a knee orthosis on the injured leg did not infer any gap reduction.

**Discussion**

The results of this study have emphasized a number of short-term postural effects resulting from ACL reconstruction. On the whole, our data confirm that postural control can be a good means to highlight the sensorimotor impairment resulting from ACL reconstruction and the effects induced by rehabilitation programs. Although most of the past studies were based on patients with chronically deficient knees, the current study reports the progression over the first 2 months following surgery and the rehabilitation influence. We believe that two main results should be pointed out: (1) the orientation (weightbearing) asymmetry returns to normal when the second rehabilitation in-patient care (timeframe 2) begins and (2) despite a slight tendency to progressively decrease, the stabilization asymmetry (assessed by the surface difference between the two plantar CP displacements) remains substantial at the end of the rehabilitation in-patient care (timeframe 3).
ACL Reconstruction Impairs Upright Quiet Stance Control

The biomechanical analysis of upright standing emphasizes the use of two distinct mechanisms to perform CP displacements (Winter et al., 1996; Rougier, 2007). If the feet are positioned side by side, the ML displacements are achieved by loading/unloading mechanisms involving the hip joints, whereas AP displacements result from pressure variations mobilizing the ankle joints. Despite a low theoretical contribution, the postural dysfunction presently observed may underline a major role for the knees in this organization. As highlighted by the data reported herein, postural impairment is observed along both the ML and AP axes. For the first axis, it can be hypothesized that sensory information from the knees’ receptors are involved in the legs’ loading/unloading mechanisms, this view being in line with a noticeable contribution of load receptors in that control (Dietz et al., 1992). In parallel, the impairment of the extensor muscles due to the ACL surgery may explain the difficulty controlling the body’s motions along the AP axis. These control deficits also reinforce the idea of a modular approach for postural control in humans and therefore also challenge inverted pendulum modeling (Massion, 1992). With the separate measurement of the two plantar CP displacements, one can see compensatory mechanisms between the two legs for controlling the CP movements along the AP axis, inferring rather constant CG movements.

Recovery of Normal Quiet Stance Control Needs Time

One interesting feature of the two-legged stance is that it places less stress on the ACL graft, hence contrasting with one-legged stance protocols. Even though, the one-legged stance protocol may be viewed as more functional, one of the main advantages of the two-legged is that the test can be performed rather rapidly after the ACL reconstruction. Despite the lower loading of the leg, at the onset patients distribute their bodyweight asymmetrically (about 45% on the operated leg). This level of asymmetry is likely too low to explain the postural control impairment alone (Genthon and Rougier, 2005). Factors such as apprehension, swelling and residual pain might explain the reluctance to overload the operated leg and to exert appropriate plantar CP displacements. In particular, even though pain was among our criteria of inclusion, it is possible that some higher or lower values might be experienced by the patients all along the follow-up.

A normal weightbearing symmetry is reached 6–7 weeks after surgery and before physical activity reconditioning during the second in-patient care. In contrast, stabilization asymmetry, involving the CP displacements under each foot, persists at the time of the last measurements, i.e., 2 months after surgery. In healthy adults, these CP displacements usually display similar longitudinal patterns along the main axes of the feet and reflect the major role of the flexor/extensor muscles on AP postural control. Modifying this symmetry complicates the control since it generally necessitates compensatory displacements under one of the legs, as seen for instance in amputees (Rougier and Bergeau, 2009). Stabilization symmetry would therefore require more time for the ACL patients, which contradicts a previous study (Chmielewski et al., 2002). Differences in the instructions given to the patients (in this case “put equal weight on both legs”) and shoe wearing may explain the discrepancies in our results. A much longer period was also observed.
by Zatterstrom et al. (1994) since comparable balance parameters for the two legs, in one-legged protocols, were found after 12 months. However, as demonstrated recently (Burdet and Rougier, 2007), one-legged standing capacity is poorly related to two-legged standing capacity.

**The Sensorimotor Deficit Is Better Highlighted in Nonvisual Conditions**

A priori, the sensory deficiency resulting from ACL reconstruction is better highlighted by reducing or removing the other available cues, explaining why previous experiments on this topic have been based on the nonvisual condition. The greater differences, observed in the EC condition at timeframe 1, between the two plantar CP displacements and the larger CP–CGv movements (in turn inferring larger deadening ratios) clearly confirm this view. In contrast, the weightbearing asymmetry seems unaffected by the vision factor.

Bringing to light the more interesting EC condition allows us also to justify the two-legged stance protocol. Compared with the one-legged protocol, which induces twice as much strain on the knee, the two-legged protocol determines less variable postural behavior, and, more importantly, allows much earlier measurement after surgery.

**Wearing a Knee Orthosis Does Not Allow ACL Patients to Improve Their Postural Control**

Regarding the knee orthosis, one might think at the onset that a test time closer to the surgery might have produced more significant results. These data confirm the previous reports demonstrating that a knee orthosis is not useful (Beynnon et al., 2002). On the contrary, it is worth noting that several studies have however shown that elastic compression sleeves (as opposed to hinged knee orthoses) have been positively evaluated in regards to balance performance (Kuster et al., 1999; Chuang et al., 2007). Taken together, this would indicate that the sensory component, i.e., the capacity of the orthosis to increase the sensory cues would be real and counterbalanced when an increased mechanical stability, due to the rigid hinge, is present. Our results should also be discussed with the only study, to our knowledge, testing a rigid knee orthosis using a postural task (Birmingham et al., 2001). In that study, wearing a knee orthosis improved postural control. To be more precise, this effect was observed during one-legged standing and only during the EO condition. More importantly, the tested patients had undergone ACL reconstruction at least 6 months before. The type of postural task and the clinical profile of the tested patients make the two studies incomparable.

This study has brought out new insights into the postural control strategies developed by ACL patients in the early postoperative period. Nonvisual conditions and two-legged protocols seem relevant to describe the recovery time required for regaining orientation and stabilization symmetries. Measurements over longer periods of time and in chronic patients might complete this follow-up description. These data could also be used as benchmarks for further specifying the rehabilitation effects induced by various parameters such as the surgical techniques and the rehabilitation methods used to recover physical fitness. The relationship between
the postural control parameters described in this study to patients’ self-reported functional ability is also needed to fully comprehend and appreciate the importance of the postural control deficits on patient outcomes.

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References


