Turkish Journal of Medical Sciences

http://journals.tubitak.gov.tr/medical/

Research Article

Turk J Med Sci
(2017) 47: 587-591
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doi:10.3906/sag-1601-146

Evaluation of plantar pressure distributions in patients with anterior cruciate ligament deficiency: preoperative and postoperative changes

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Received: 24.01.2016 • **Accepted/Published Online:** 02.10.2016 • **Final Version:** 18.04.2017

Background/aim: Anterior cruciate ligament (ACL) deficiency results in several kinematic changes in the lower extremities. The aim of this study is to define the plantar pressure parameters in ACL-deficient patients and to show the effect of ACL reconstruction on dynamic plantar pressure.

Materials and methods: Forty patients with unilateral ACL rupture and 40 healthy controls were included in this study. Dynamic plantar pressures of both groups were recorded by the EMED SF-2 system during level walking. Thirteen of the patients who had ACL reconstructions with hamstring autografts (HS group) were reevaluated at an average of 14.5 months following the ACL reconstructions.

Results: ACL-deficient patients had significantly lower hindfoot ($P = 0.007$) but higher midfoot pressure values ($P = 0.03$) on their ipsilateral foot compared to control group subjects. Ipsilateral hindfoot pressures were also found to be significantly lower than those of the contralateral foot ($P = 0.001$). Hindfoot pressure values of the HS group were increased in postoperative measurements ($P = 0.01$).

Conclusion: ACL-deficient patients have altered plantar pressure distributions and ACL reconstructions restore these changes to normal. Pedobarography might be used as a practical method for dynamic functional assessment of ACL-deficient patients.

Key words: Anterior cruciate ligament, reconstruction, functional evaluation, pedobarography, plantar pressure

1. Introduction

Anterior cruciate ligament (ACL) rupture is an important orthopedic problem leading to functional instability and increased risk of meniscus and cartilage damage causing early onset osteoarthritis (1). Functional assessment of patients following ACL reconstruction mainly depends on static methods, like instrumented measurement of anterior knee laxity and isokinetic measurement of extensor muscle strength, generally combined with various clinical scoring systems. However, many studies emphasized that these static methods are not sufficient to show the dynamic functions of ACL (2,3).

It was reported that ACL reconstruction not only improves knee laxity but also improves lower extremity biomechanics. Following the reconstruction procedure, biomechanical changes and abnormal gait patterns, which can cause early onset osteoarthritis and inadequate patient satisfaction, can be assessed successfully with gait analysis (4). However, the complexity of procedure and its utility in quantitative measurement of the rehabilitation process is not practical. For this reason, Mittlmeier et al. suggested dynamic pedobarography as an appropriate tool for functional monitoring following ACL reconstruction (5). This noninvasive test has been used for evaluation of plantar pressure changes during the gait cycle. Various studies exist in the literature reporting plantar pressure changes in lower extremity pathologies and also successful applications of pedobarography in functional evaluation of lower extremity reconstructive procedures (6,7).

We hypothesized that ACL-deficient patients have altered plantar pressure distributions compared to healthy individuals and ACL reconstruction may restore this condition. In this study, we aimed to determine the potential pressure distribution changes of ACL-deficient patients compared to healthy individuals. We also aimed to evaluate the effects of ACL reconstruction on pressure distribution pattern. Definition of plantar pressure distribution changes may guide us to evaluate the utility of pedobarography for dynamic functional assessment of patients following ACL reconstruction.

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2. Materials and methods

With the approval of the local ethics committee, this study was planned in two steps. In the first step, pedobarographic evaluations of ACL-deficient knees were performed and compared with both the uninvolved side and age-matched healthy controls. In the second step, pedobarographic evaluations were repeated after ACL reconstruction and the effect of the surgery was examined compared with preoperative findings. The inclusion criterion was patients with unilateral isolated ACL deficiency (confirmed by MRI and physical examination) who planned to undergo ACL reconstructions. Exclusion criteria were limited range of motion, joint effusion, accompanying ligament injury, meniscus tears greater than 25%, and body mass index (BMI) greater or less than normal (18.5–25 kg/m^2). Previous surgeries, deformities, neuromuscular diseases, and alignment problems involving the lower limb were also excluded. Out of 52 recruited ACL surgery candidates, 40 patients were included in the study. All the operations were done by the same surgeon with a transtibial technique. The average time from ACL injury to pedobarographic evaluation was 3.7 months (between 1 and 24 months). The control group consisted of 40 healthy subjects, with normal BMIs and without a history of any musculoskeletal injury or disease, with similar sex and age distributions as in the ACL-deficient patient group. Demographic data of the subjects are shown in Table 1.

The EMED SF-2 System (Novel GmbH, Munich, Germany) was used for the pedobarographic examinations. This system has a platform with 44.5 × 22.5 cm sensorial area (two capacitive transducer sensors/cm^2 with a sampling rate of 71 Hz), which was smoothly placed in the middle of a 7 × 1 m leather covered wooden walkway hiding the platform. Subjects were asked to walk barefoot at their normal walking speed. Following two walking cycles without measurements, two appropriate consecutive stance phase measurements were recorded for each foot.

Stance phase plantar pressure distribution data, in terms of peak pressures, were analyzed using a software program (Novel-Win software, Novel GmbH). This program automatically divides the foot into eleven anatomical parts (masks) as shown in the Figure so that peak pressure values in different parts of the foot can be calculated. Peak pressure values for the whole foot, forefoot, midfoot and hindfoot and also medial, middle, and lateral columns of the forefoot were calculated from the mask data. Finally, the mean of the two measurements for each foot were saved for later statistical analysis.

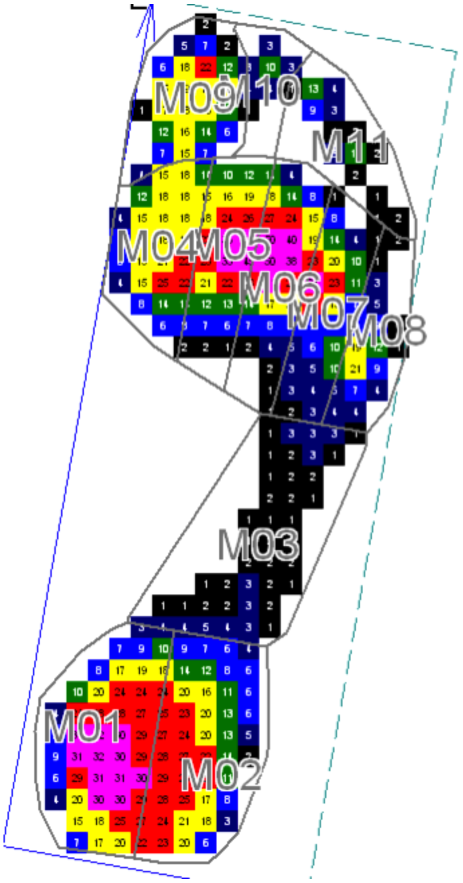

Figure. Pressure distribution of the foot in the stance phase of the gait, divided into eleven anatomical parts (masks) with Novel-Win Software. Masks: M1–2: medial and lateral heel, M3: midfoot, M4–8: metatarsal areas of forefoot, M9: big toe, M10: second toe, M11: lateral toes.

Table 1. Demographic data of the subjects: mean (standard deviation) [minimum, maximum].

Parameters	ACL-deficient group	Control group	P-value
Sex	34 males, 6 females	30 males, 10 females	0.269
Age (years)	27.25 (7.95) [17–47]	24.00 (3.39) [20–38]	0.070
Weight (kg)	71.08 (7.76) [50–88]	69.58 (8.37) [52–90]	0.409
Height (m)	1.74 (0.06) [1.62–1.88]	1.74 (0.08) [1.55–1.92]	0.872
BMI (kg/m^2)	23.42 (1.67) [18.82–24.98]	22.86 (1.74) [20.01–24.96]	0.143

Patients underwent ACL reconstructions with hamstring autografts 1 week after the pedobarographic examinations and a standardized physical therapy protocol, 6 months in duration, was applied for each patient at the same center.

Postoperatively patients' anterior knee laxities were measured with the Kneelax 3 (Biodex) arthrometer device. Besides pedographic measurement, subjective functional results were evaluated with the Lysholm knee scoring system and IKDC-2000 (International Knee Documentation Committee 2000) subjective evaluation forms. Thirteen patients who had ACL reconstructions with hamstring allografts and fixation with interference screws and staples, whose anterior knee laxity differences were smaller than 5 mm (average: 2.1 mm), and who had perfect-good Lysholm scores (average: 97.77) and IKDC-2000 subjective knee evaluation scores close to normal (average: 89.64) were evaluated by pedobarography at an average of 14.5 months postoperatively.

For statistical analysis, we randomly chose one foot of the control subjects, depending on the knowledge that there is not any plantar pressure difference between the right and left foot (8,9). ACL-deficient patients' feet were grouped as ipsilateral foot (ACL-deficient side) and contralateral foot (ACL-intact side) without right/left side distinction. SPSS 16.0 for Windows (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Two-tailed t-tests were conducted to analyze the differences between control group and ACL-deficient patient group data. Paired t-tests were performed to analyze the differences between preoperative and postoperative data and patients' ipsilateral and contralateral feet.

3. Results

ACL-deficient patients had significantly lower hindfoot peak pressure (PP) values (27.05 ± 5.84 N/cm^2) in their ipsilateral foot according to the control group subjects (30.86 ± 6.49 N/cm^2) (P = 0.007), but higher midfoot PP values (12.48 ± 6.73 N/cm^2) than the controls (9.45 ± 5.47 N/cm^2) (P = 0.03), as shown in Table 2. Contralateral foot PP differences were not found to be statistically different (P > 0.05). Intragroup analysis showed that ipsilateral hindfoot PP (27.06 ± 5.84 N/cm^2) was significantly lower than the contralateral PP (29.70 ± 6.00 N/cm^2) (P = 0.001). There was no significant pressure difference between other anatomic parts of the foot.

Hamstring group patients' preoperative ipsilateral hindfoot PP (25.97 ± 4.93 N/cm^2) was found to have increased (30.51 ± 5.16 N/cm^2) in the postoperative measurements (P = 0.01). Contralateral foot pressure changes were not significant according to preoperative values. When comparing the postoperative ipsilateral and contralateral foot pressures, we could not find any significant difference. Analysis indicated that hamstring allograft group patients' ipsilateral foot follow-up PP values were not significantly different than the control group subjects, as shown in Table 3.

4. Discussion

Gait analysis studies have demonstrated that lower extremity biomechanics of ACL-deficient patients differ from those of healthy subjects. Their knee joint moments are altered during level walking, jogging, and stair activities when compared to healthy subjects (4). The present study demonstrates the effects of ACL deficiency on plantar pressure distribution. Patients have altered plantar pressure distributions and reduced hindfoot but increased midfoot loading in the stance phase of the gait as compared to healthy subjects.

To our best knowledge, the present study is the first study demonstrating plantar pressure distribution differences of ACL-deficient patients compared to healthy subjects. However, Milltmeier et al. evaluated plantar pressure distributions following ACL reconstructions

Table 2. Plantar pressure distribution data [mean (standard deviation)] of the ACL-deficient (ACLD) patient group's ipsilateral feet and the control group.

	Control group	ACLD group	P-value
Whole foot peak pressure (PP) (N/cm^2)	47.05 (15.81)	45.33 (10.74)	0.573
Forefoot PP	25.18 (4.26)	25.42 (3.75)	0.786
Midfoot PP	9.45 (5.47)	12.48 (6.73)	0.030
Hindfoot PP	30.86 (6.49)	27.05 (5.84)	0.007
Medial column PP	24.11 (11.22)	23.12 (8.55)	0.659
Middle column PP	35.58 (12.29)	36.11 (9.38)	0.831
Lateral column PP	23.02 (11.08)	24.83 (11.44)	0.475

Table 3. Plantar pressure distribution data [mean (standard deviation)] of the hamstring (HS) group's ipsilateral feet and the control group.

	Control group	HS group	P-value
Whole foot peak pressure (PP) (N/cm^2)	47.05 (15.81)	45.36 (11.60)	0.725
Forefoot PP	25.18 (4.26)	26.98 (4.15)	0.190
Midfoot PP	9.45 (5.47)	10.73 (2.79)	0.424
Hindfoot PP	30.86 (6.49)	30.50 (5.16)	0.859
Medial column PP	24.11 (11.22)	22.67 (6.65)	0.665
Middle column PP	35.58 (12.29)	36.10 (7.11)	0.886
Lateral column PP	23.02 (11.08)	26.52 (11.46)	0.331

(using bone-patellar tendon-bone autografts) to monitor functional rehabilitation. They reported significantly reduced heel loading compared to the contralateral foot in the first 6 weeks after ACL reconstructions, but this pressure asymmetry could not be observed after 12 weeks (5).

Decreased heel loading is probably the result of altered gait characteristics in ACL-deficient patients. In the literature, the most commonly emphasized gait abnormality for ACL-deficient patients is quadriceps avoidance gait, defined as decreased external flexion moment of the knee (reduced quadriceps contraction) at the midstance phase of gait to prevent excessive anterior tibial translation (4,10,11). Two possible mechanisms were reported for walking with a quadriceps avoidance gait; one of them is the reduced knee flexion angle in the midstance phase of gait (in 72% of patients), and the other one is leaning forward during midstance (increased hip external flexion moment) (12). Both of the mechanisms are likely to carry the center of gravity to the anterior side of the body, probably reducing the load at hindfoot in the midstance phase of the gait.

Although gait abnormalities observed in quadriceps avoidance gait were reported to be symmetric for both extremities, this is not consistent with our results. In this study we observed pressure distribution changes limited to the ipsilateral foot; contralateral foot pressure distributions were similar to those of control group subjects. Although quadriceps avoidance is specific to the midstance phase of the gait, our results demonstrate the plantar pressure distribution in the whole stance phase. Thus, pressure changes, particularly in the heel strike phase of the gait, are also important to interpret our results. It also seems to be related to quadriceps muscle function; decreased quadriceps strength in ACL-deficient patients affects the heel strike. It has been shown that paralysis of the quadriceps muscle results in a large increase in the heel strike transient (vertical component of ground reaction force at heel strike) (13). Heel strike transients were also higher in patients with reconstructed ACL than controls (14). According to these studies we would expect to see increased heel pressures in the heel strike phase of the gait, which is not supporting our results.

Although we did not evaluate quadriceps muscle strength, it is more likely to be related to our results. It is known that ACL-deficient patients have decreased quadriceps strength (15) and patients with greater quadriceps strength show more normal dynamic knee functions (2). Quadriceps muscle strength is necessary to return to normal joint kinematics and muscle activities following ACL reconstruction; inadequate strength contributes to altered gait patterns (16). It was reported that patients have decreased toe and heel plantar pressures after malignant bone tumor resection and endoprosthetic replacement of the distal femur. There is a positive correlation between the load under the foot and knee extension strength (7).

Pain is another factor affecting heel loading and has to be taken into consideration. Decreased heel loading has been reported in patients with knee and hip osteoarthritis and interpreted as an attempt to compensate the pain in arthritic joints during walking (17,18). Concomitant pathologies such as minor meniscal tears or chondral injuries may affect the walking performance during pedobarographic evaluation. In the current study, patients did not have significant knee pain during pedobarographic evaluations preoperatively or at follow-up.

We observed that ACL reconstructions improved the altered plantar pressure distributions to normal when compared to control group subjects. Preoperative asymmetry between the ipsilateral foot and contralateral foot returned to normal in the postoperative evaluation. These results were consistent with studies reporting that ACL reconstruction improves gait characteristics (19,20).

The ACL reconstruction procedure is necessary to gain a normal gait and plantar pressure distribution pattern.

A limitation of the current study is the lack of isokinetic measurement of quadriceps muscle strength in combination with pedobarography. That would probably give more information to understand the mechanism behind plantar pressure distribution changes and to interpret the results. We also do not have information about the natural course of plantar pressure changes in untreated patients. This could be clarified if the observed changes are due to surgery and following physical therapy or attributed to a compensation mechanism. Comparing the reconstruction methods according to their effects on plantar pressure distributions and examining whether one of them is better in restoration of plantar pressure changes can be planned as a future study.

In conclusion, this study shows that ACL-deficient patients have altered plantar pressure distributions compared to healthy individuals and that ACL reconstruction improves the changed distribution to normal. Thus, we recommend ACL reconstruction to gain a normal gait and plantar pressure distribution pattern besides the treatment of functional instability. These results may guide us to evaluate the utility of pedobarography, a practical tool, for dynamic functional assessment of patients following ACL reconstructions, as with similar successful applications for lower extremity reconstructive procedures.

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