# Postural stability and regulation before and after anterior cruciate ligament reconstruction – A two years longitudinal study

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# Postural stability and regulation before and after anterior cruciate ligament reconstruction – A two years longitudinal study

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ABSTRACT

*Objectives:* To evaluate postural regulation and stability among patients who underwent anterior cruciate ligament reconstruction (ACLR) and rehabilitation over a two-year follow-up period.
*Design:* Longitudinal;
*Setting:* Biomechanics laboratory;
*Participants:* 30 ACLR patients (32.0 ± 12.2 years, 14 males) with isolated ACL rupture.
*Main outcome measures:* Postural regulation was tested before ACLR, as well as at six-weeks, twelve-weeks, six-months, one-year and two-years post-ACLR and standardized rehabilitation. Postural regulation was measured for stability indicator (ST), weight distribution index (WDI), synchronization (foot coordination) and sway intensities (postural subsystems).
*Results:* Significant time effects (pre-vs. two-years postoperative) were found for WDI ($\eta_p^2 = 0.466$), synchronization ($\eta_p^2 = 0.368$), mediolateral weight distribution ($\eta_p^2 = 0.349$), ST ($\eta_p^2 = 0.205$), visual/nigrostriatal systems ($\eta_p^2 = 0.179$) and peripheral-vestibular system ($\eta_p^2 = 0.102$). The largest difference (preoperative: $\eta_p^2 = 0.180$) to the matched sample was calculated for WDI. The most significant differences to the matched sample were observed for ST (preoperative: $\eta_p^2 = 0.126$; six-weeks postoperative: $\eta_p^2 = 0.103$) and WDI (preoperative: $\eta_p^2 = 0.180$; six-weeks postoperative: $\eta_p^2 = 0.174$).
*Conclusion:* ACLR and rehabilitation influence postural subsystems, postural stability, weight distribution and foot synchronization. Normalization of mediolateral weight distribution requires one year following ACLR. The ACLR leads to a suppression of the somatosensory and cerebellar system which was compensated by a higher activity of the visual and nigrostriatal systems.


## 1. Introduction

Anterior cruciate ligament reconstruction (ACLR) continues to be the standard of care for ACL-deficient athletes who aim to return to high-level sporting activities (Marx, Jones, Angel, Wickiewicz, & Warren, 2003). However, post-surgical outcomes have varied (Dunn, Spindler, & MOON Consortium, 2010; Hartigan, Axe, & Snider-Mackler, 2010) and may be poorer than previously reported (Ardern, Webster, Taylor, & Feller, 2011). Less than half of the athletes who undergo reconstruction are able to return to sport within the first year after surgery (Ardern et al., 2011). For those athletes who do successfully return to activity, it is estimated that approximately 1 in 3–4 will sustain a second knee injury (Heath et al., 2018; Hui et al., 2011; Leys, Salmon, Waller, Linklater, & Pinczewski, 2012).

Deficits in neuromuscular control during dynamic and complex movements may be partially responsible for secondary ACL injury (Hewett, Di Stasi, & Myer, 2013; Paterno et al., 2010). Numerous evidence (Diermann et al., 2009; Fulton et al., 2014; Lehmann, Paschen, & Baumeister, 2017; Ordahan, Kücüksen, Tuncay, Salli, & Ugurlu, 2015) suggests that ACL tears can negatively influence postural regulation, as well as mechanical stability and somatosensory function. This reduction in postural stability, weight distribution and foot coordination (Bartels et al., 2018) can then lead to a higher risk for subsequent ACL injury resulting in a pathological

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cycle (Fulton et al., 2014; Paterno et al., 2010; Wright et al., 2007).

Bartels et al. (2018) found that ACLR patients presented with significant longitudinal improvements in the somatosensory system, especially between preoperative and six-weeks postoperative. However, despite the recognized importance of postural stability and the acute improvement in this area post-surgery, there is still no research describing if postural stability is retained for extended periods of time following surgery. The current study is a follow-up to this previous work with the purpose of extending the postoperative testing periods: six-weeks, twelve-weeks, six-months, one-year, and two-years postoperative. The following specific hypotheses were tested: (1) mediolateral and anteroposterior weight distribution and foot coordination will be unbalanced due to ACL rupture and surgery, (2) postural stability will be reduced pre- and postoperative, (3) the somatosensory and cerebellar subsystem will show the greatest suppression after ACLR, and postural performance will be reduced (below percentile 50) compared to healthy matched individuals.

## 2. Material and methods

### 2.1. Design

In accordance with Lee, Lee, Ahn, and Park (2015) this longitudinal study included all patients scheduled for ACLR with a primary isolated ACL tear confirmed by MRI and physical examination (positive anterior drawer, Lachman, and/or pivot shift tests (more than grade II)). Patients with concomitant meniscus tear, bilateral ACL injuries or associated injuries to any other ligament, previous injury/surgery to either knee, or any associated extra-articular lesions were excluded. Patients were diagnosed with an ACL rupture verified by MRI and physical examination performed by an experienced (500 ACL surgeries per year) orthopedic surgeon. Furthermore, patients were also excluded if they were unable to perform the posturography due to pain or limited motion of the knee (Bartels et al., 2018).

Postural regulation and stability were measured with the Interactive Balance System (IBS) during six testing sessions: preoperative, six-weeks postoperative, 12-weeks postoperative, six-months postoperative, one-year postoperative, and two-years postoperative (Fig. 1). This system provides a comprehensive and sufficient reference database stratified by age and gender and has already been published (Schwesig, Fischer, & Kluttig, 2013). Therefore, we were able to compare the postural regulation of our ACLR subjects to this reference data of healthy subjects. We used a matched-pairs technique in order to ensure a valid comparison. Each patient was matched in terms of age ($p = 0.985$), gender ($p = 1.000$), body height ($p = 0.851$) and body weight ($p = 0.720$). For this reason, recruitment of an asymptomatic control group was not necessary.

### 2.2. Subjects

Thirty (39%) of an initial 77 (Bartels et al., 2018) patients (14 males; age: $32.0 \pm 12.2$ years, range: 13–61 years; body height: $1.75 \pm 0.09$ m; body mass: $76.0 \pm 13.8$ kg; BMI: $24.7 \pm 3.23$ kg$\cdot$m$^{-2}$) completed all six examinations. Therefore, only the data from these 30 participants were used for the further analysis. Twenty-eight of these subjects were classified as having acute ACL tears (surgery less than 3 months after injury), while two were classified as chronic tears (surgery 3 months or more following injury). This classification was made only for the sample description within the baseline demographic characteristics (Table 1). Seventeen patients (57%) had a right-sided ACL injury. Most of these tears occurred during participation during a team sport (46%) or skiing (36%). The average period from time of injury to surgery was 48 days.

All participants provided written consent to participate after being informed of all procedures and risks. A parental or guardian consent for all young patients (age under eighteen years; at examination one: $n = 7$) involved in this investigation was obtained. The study was approved by the local ethics committee (reference number: 2016-144).

### 2.3. Measurements

Each participant underwent clinical examination and postural regulation measurements using the Interactive Balance System (IBS) (neurodata, Vienna, Austria). Patients were assessed during six testing sessions (Fig. 1) in order to evaluate the entire rehabilitation process and the long term effects of ACLR and standardized rehabilitation and subsequent individual treatment (Table 2). All measurements were performed at the same time of day and in a quiet room to minimize any disruptions during testing.

The IBS consists of four independent force plates supporting the heels and forefeet in order to measure postural regulation (sampling rate: 32 Hz). Patients were tested during a single trial (32 s)

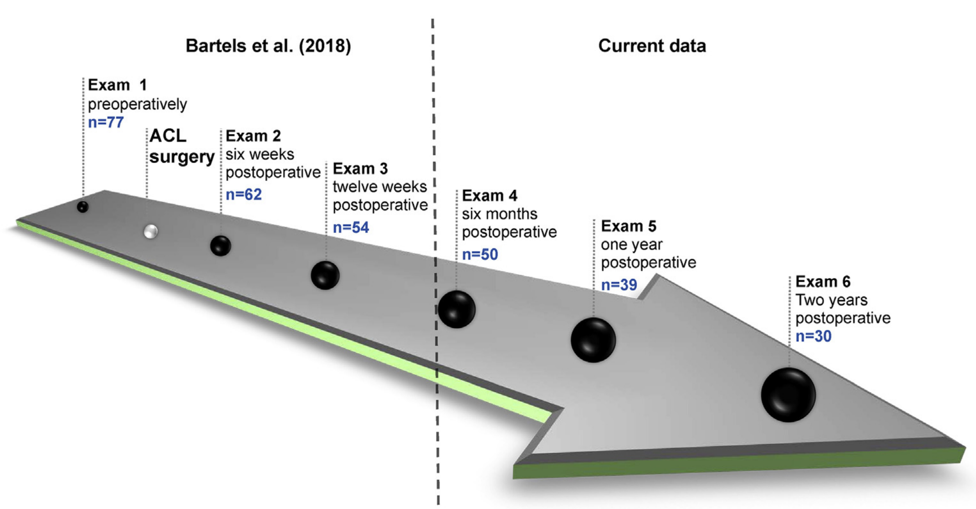


**Fig. 1.** Flow chart of the longitudinal study design. ACL, anterior cruciate ligament.

**Table 1**
Demographic and anthropometric characteristics of subjects with acute and chronic anterior cruciate ligament (ACL) tears.

| | Acute ACL group (n = 28) | Chronic ACL group (n = 2) |
|---|---|---|
| Sex, male:female | 13:15 | 1:1 |
| Laterality, left:right | 12:16 | 1:1 |
| Age (yr) | 31.9 ± 12.6 (12.6–60.7) | 32.6 ± 7.21 (27.5–37.7) |
| Height (m) | 1.75 ± 0.09 (1.54–1.99) | 1.74 ± 0.13 (1.64–1.83) |
| Weight (kg) | 75.6 ± 14.1 (54.2–106.4) | 81.4 ± 10.1 (74.2–88.5) |
| Body mass index (kg/m$^2$) | 24.6 ± 3.28 (17.9–32.0) | 27.0 ± 0.82 (26.4–27.6) |
| Time interval trauma vs. surgery (day) | 43.5 ± 74.0 (7–395) | 111 ± 77.1 (56–165) |

Results reported as mean ± standard deviation (range).

**Table 2**
Posturographic testing: test positions (NO–HF) (Bartels et al., 2018) and parameters (Reinhardt et al., 2019).

| Test positions (NO–HF) | | | |
|---|---|---|---|
| **Abbreviation** | **Standing position** | **Head position** | **Eyes** |
| NO | Without foam pads | straight | open |
| NC | Without foam pads | straight | closed |
| PO | On foam pads | straight | open |
| PC | On foam pads | straight | closed |
| HR | Without foam pads | rotated 45° to the right | closed |
| HL | Without foam pads | rotated 45° to the left | closed |
| HB | Without foam pads | up (dorso-flexed) | closed |
| HF | Without foam pads | down (ventro-flexed) | closed |

| Parameters | | | |
|---|---|---|---|
| **Abbreviation** | **Designation** | **Description** | |
| *Process parameters* | | | |
| F1 | Frequency band 1 [0.01–0.03 Hz] | Visual and nigrostriatal system | The raw signal (force-time signal) is subtracted from the mean value and then subjected to a FFT with a rectangular window. On the ordinate, the amplitude of the frequency components is exposed and consequently, the ordinate is dimensionless in that the results of the FFT are proportional to the output signal. |
| F2-4 | Frequency band 2–4 [0.03–0.5 Hz] | Peripheral –vestibular system | |
| F5-6 | Frequency band 5–6 [0.5–1.0 Hz] | Somatosensory system | |
| F7-8 | Frequency band 7–8 [>1.0 Hz] | Cerebellar system | |
| *Parameters of motor output* | | | |
| ST | Stability indicator | ST describes the level of postural stability (the greater ST, the greater instability). ST indicates the amount of force fluctuations among the four plates and is calculated with the following equation: $ST = \frac{100}{n} \cdot \sum_{i=1}^{n} \sqrt{(A_{i+1}-A_i)^2 + (B_{i+1}-B_i)^2 (C_{i+1}-C_i)^2 (D_{i+1}-D_i)^2}$ ST is highly correlated with the COP path length (Reinhardt et al., 2019). | |
| WDI | Weight distribution index | WDI describes the asymmetry of weight distributions from an expected mean of 25% per plate (Reinhardt et al., 2019). $WDI = \sqrt{\frac{(\overline{A}-25\%)^2 + (\overline{B}-25\%)^2 + (\overline{C}-25\%)^2 + (\overline{D}-25\%)^2}{4}}$ | |
| Synch | Synchronization | Six values describing the relationship of vibration patterns between plates calculated as scalar product; 1000 – complete coactivity; −1000 – complete compensation, 0 – no coactivity or compensation | |
| Heel | Forefoot–hindfoot ratio | Percentage of weight distribution forefoot vs. hindfoot with description of heel loading. | |
| Left | Left side | Percentage of weight distribution left vs. right with description of left side loading | |

under eight standardized test conditions (Bartels et al., 2018) (Table 3). Postural regulation was measured as: stability indicator (general postural stability), weight distribution index and synchronization (foot coordination measured as relationship of vibration patterns between plates). Sway intensities at different frequency ranges (0.01–0.03 Hz; 0.03–0.5 Hz; 0.5–1.0 Hz; >1.0 Hz) were determined by Fast Fourier Transformation (FFT) of the postural sway waves.

Postural subsystems were associated with different functional frequency bands (visual and nigrostriatal; peripheral-vestibular; somatosensory; cerebellar) and have been previously validated by several interdisciplinary studies (Friedrich et al., 2008; Oppenheim, Kohen-Raz, Alex, Kohen-Raz, & Azarya, 1999; Schwesig et al., 2009; Schwesig et al., 2011; Schwesig, Fischer, Becker, & Lauenroth, 2014b). Schwesig et al. (2011), have used IBS for assessing the visual system among handicapped subjects, the nigrostriatal system among Parkinson's patients (Schwesig et al., 2009), the cerebellar system among patients with cerebellar disease (Schwesig et al., 2009), the peripheral-vestibular system among patients with cochlear implants (Schwesig, 2006) and patients with vestibular neuritis (Schwesig et al., 2014b), and the somatosensory system using plantar cold application (Schwesig, 2006). The patients used in these previous studies were all diagnosed by experienced physicians (e.g., neurologist, ophthalmologist, otorhinolaryngologist) and verified using standardized clinical and discipline-specific investigations (e.g., Hoehn and Yahr) and advanced diagnostic tests (e.g., EEG, fMRI, optometric evaluation which included visual acuity test using the Landholt C visual acuity test, pure tone audiometry, speech audiometry, videonystagomography after caloric irrigation, video head-impulse test).

For example, the frequency band 0.01–0.03 Hz (F1) was validated using samples of healthy controls (n = 52), Parkinson's

**Table 3**
Phases of rehabilitation.

| Phase | Week | Goals and content |
|---|---|---|
| 1 | 1–2 | • Goal: pain relief, no effusion, pain free Range of Motion (ROM)<br>• Constant support with an orthesis for full leg extension<br>• Partial weight bearing with crutches (30 kg)<br>• Lymph drainage 2–3 times per week<br>• Isometric exercises with special regard to knee extension ROM<br>• Electrotherapy of the thigh muscles for improvement of neuromuscular sensitivity |
| 2 | 3–6 | • Goal: pain free full ROM, full weight bearing, safe muscular stabilization of knee joint<br>• Support with orthesis<br>• Lymph drainage<br>• Physiotherapy (sensorimotor training, axial leg training, patella mobilization, myofascial techniques, stretching) |
| 3 | 7–12 | • Goal: recovery of full general function<br>• Intense rehabilitation in clinic or institution<br>• Physiotherapy and sports therapy (strength and endurance) |
| 4 | 13–20 | • Goal: recovery of sports-specific function<br>• Running exercises (treadmill)<br>• Successive sports-specific training |
| 5 | 21st week and later | • Goal: Restoration of full working or sports ability<br>• Patient receives instructions/recommendations for further independent training (without therapist) related to their specific sport or occupation<br>• Patient should return to competitive sport after 7–8 month |

disease ($n = 52$) and cerebellar disease ($n = 52$) patients. Variance analysis of the Parkinson's group and control group revealed the largest differences in frequency range F1 (Schwesig, 2006; Schwesig et al., 2009). In other studies (Friedrich et al., 2008; Schwesig, 2006), visually handicapped subjects ($n = 52$) were compared with subjects with normal vision ($n = 52$) using the IBS. The visually impaired and the normal groups differed significantly in the frequency range F1 ($p = 0.002$). Consequently, the IBS is able to predict (not measure) these postural subsystems by a FFT of sway in an indirect manner. The IBS supplements, but does not replace the differential diagnosis in balance related medical disciplines (e.g., neurology, orthopaedics, ophthalmology, otorhinolaryngology, ophthalmology) in a feasible manner.

Instructions for the subjects' positions, frequency bands and parameters of motor output (including interpretation) used in the IBS have been previously described (Bartels et al., 2018; Schwesig, Becker, & Fischer, 2014a; Schwesig et al., 2013, 2014b; Schwesig et al., 2017). The IBS has previously shown good intraobserver reliability. Intraclass correlation coefficients for every parameter and all test positions ranged from 0.71 to 0.95 (Schwesig et al., 2014a, 2014b, 2017). Furthermore, this assessment has an extensive ($n = 1724$) reference database for asymptomatic subjects (Schwesig et al., 2013). Reinhardt et al. (2019) recently showed that the time series of the four IBS plates can also be used to calculate trajectories equivalent to the COP displacement (Table 3). In accordance with these reliability studies, we also used the mean values obtained in the eight test positions (Table 3) for all parameters.

All surgical procedures were performed by two experienced knee surgeons. A quadruple bundled hamstring-transplant (tendon of the semitendinosus muscle) with hybrid fixation and femoral bone-wedge technique was used for all participants to provide high pull-out strength (Weiler, Richter, Schmidmaier, Kandziora, & Südkamp, 2001). All participants completed the same twenty-one week rehabilitation protocol, which was divided into five phases (Table 2).

### 2.4. Statistical analysis

An a priori power analysis (nQuery 4.0, Statistical solutions Ltd, Cork, Ireland) was performed to determine the sample size using a two-sided hypothesis test at an alpha level of 0.05 and a power of 0.8. The results of this analysis indicated that 54 knees would be required to detect a significant mean difference of three (main parameter: stability indicator). Considering a dropout rate of 30%, we initially recruited 77 patients with ACL rupture (Bartels et al., 2018).

Descriptive statistics (mean, standard deviation, 95% confidence interval) were reported for all parameters. Mean differences between test sessions (1–6) and groups (ACLR-patients vs. matched subjects) were tested using a one-factorial (time or group) univariate general linear model. The variance analysis was divided into three parts:

1 ***Longitudinal analysis within the ACLR patients (*****Table 4*****).*** Comparison of preoperative examination vs. two-year postoperative examination in order to evaluate the total time effect for each parameter. We also calculated the effects between adjacent examinations (e.g., preoperative vs. six-week postoperative) to assess the effectiveness of each rehabilitation phase. For the unilateral parameters heel and left limb (Table 3), it was necessary to create two new variables (anteroposterior and mediolateral), which are independent from the side of injury. We calculated the difference in weight distribution from an ideally assumed value of 50%, in order to avoid a division and reduction of the sample (patients with left-sided injury ($n = 13$) vs. patients with right-sided injury ($n = 17$)) and a loss of power.
2 ***Cross-sectional comparison of ACLR patients with matched subjects (*****Table 4*****, grey highlighted).*** We conducted this analysis for each time point. Additionally, we performed a percentile analysis (percentile 25, 50, 75, interquartile range) (Figs. 2a–4b).
3. We performed a variance analysis separately for the patients with a left-sided ACL injury ($n = 13$) and right-sided ACL injury ($n = 17$) (Fig. 4a and b).

The critical level of significance was adjusted using the Bonferroni correction. After applying a Bonferroni correction, significance level (p) of 0.05 divided by the number of tests (9). Differences between means were considered as statistically significant if p values were <0.006 or partial eta squared (partial-$\eta^2$ ($\eta_p^2$)) values were greater than 0.10 (Richardson, 2011).

All statistical analyses were performed using SPSS version 25.0 for Windows (SPSS Inc., Chicago, IL, USA).

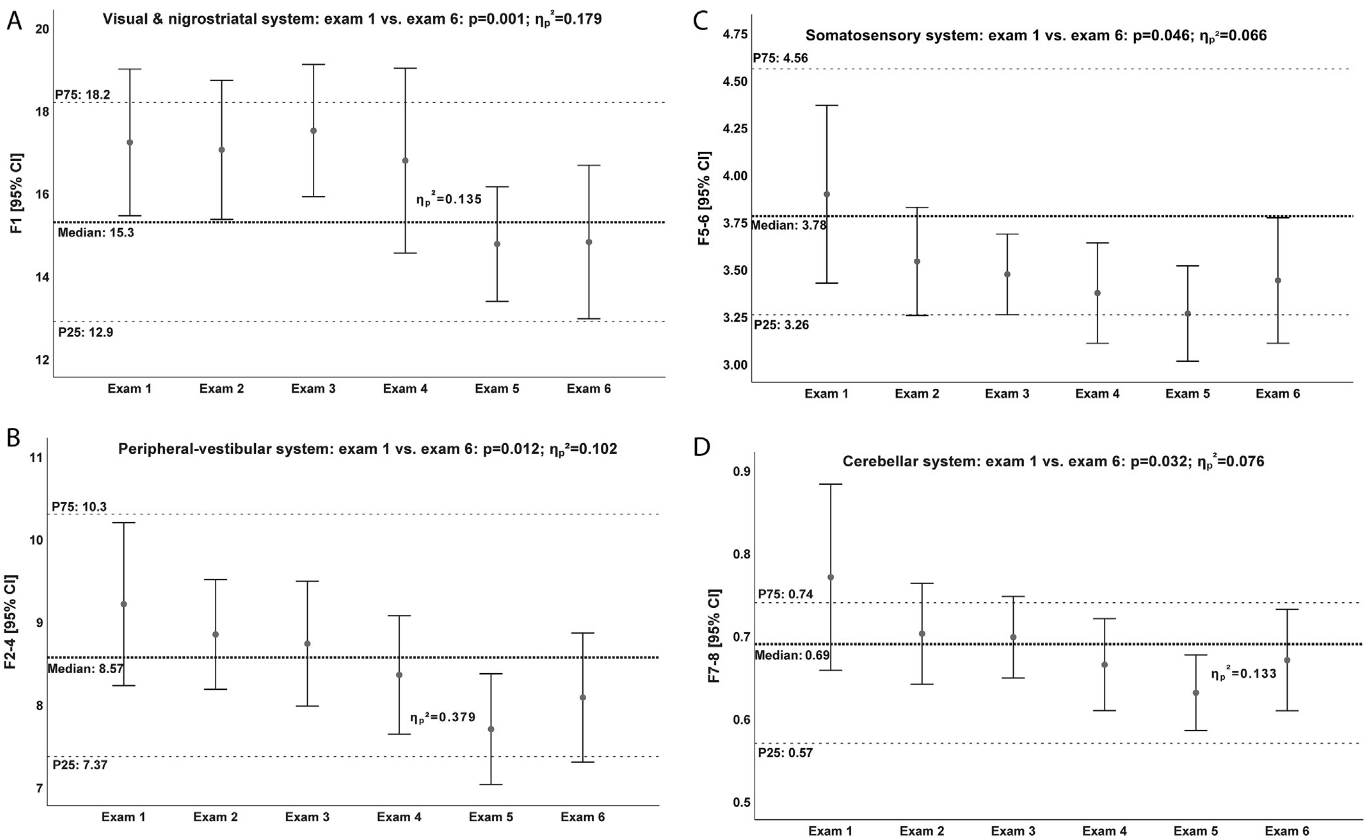


**Fig. 2. a-d.** Postural subsystems over the two-year investigation period and in comparison to the matched reference sample based on median and percentile (P25, P75; interquartile range) analysis. Total and partial effects (threshold: $\eta_p^2 \geq 0.10$) of variance analysis are reported.

## 3. Results

### 3.1. Longitudinal analysis

We found significant longitudinal improvements (preoperative vs. two-year postoperative) in visual & nigrostriatal, peripheral-vestibular, stability indicator (ST), weight distribution index (WDI), synchronization, and mediolateral weight distribution (Table 4; Fig. 2a and b**, 3a-c, 4b**). The WDI was the parameter with the largest improvement ($\eta_p^2 = 0.466$) over the total time of investigation (two-years). Improvements between adjacent examinations for this parameter were detected between examination at six-weeks and twelve-weeks postoperative ($\eta_p^2 = 0.166$), between twelve-weeks and six-months ($\eta_p^2 = 0.107$) and between six-months and one-year postoperative ($\eta_p^2 = 0.256$). The parameters synchronization (exam 1 vs. 6: $\eta_p^2 = 0.368$; Fig. 3c) and mediolateral weight distribution (exam 1 vs. 6: $\eta_p^2 = 0.349$) showed similar high time effects (Fig. 4b). In contrast to the mediolateral weight distribution, the anteroposterior weight distribution was almost unaffected across the time ($\eta_p^2 = 0.046$; Table 4). The ACL injury led to a short-term increase of the forefoot load (exam 1: 54.3 vs. exam 2: 57.4%, $\eta_p^2 = 0.122$; Table 5, Fig. 4a). The highest time effect ($\eta_p^2 = 0.379$) between adjacent examinations was observed for the peripheral-vestibular system between six-months postoperative and one-year postoperative (Fig. 2b). Except for synchronization at two-years postoperative, we observed the performance maximum for all parameters at one-year postoperative; Table 4).

### 3.2. Cross-sectional analysis - ACLR patients versus matched individuals

The largest difference (preoperative: $\eta_p^2 = 0.180$) to the matched sample was calculated for the weight distribution index (WDI). The most significant differences to the matched sample were observed for ST (preoperative: $\eta_p^2 = 0.126$; six-weeks postoperative: $\eta_p^2 = 0.103$) and WDI (preoperative: $\eta_p^2 = 0.180$; six-weeks postoperative: $\eta_p^2 = 0.174$; Table 4).

At one-year postoperative, the postural regulation had reached the "healthy" level for visual & nigrostriatal system, ST, WDI, and Heel load distribution (Figs. 2–4). The somatosensory and cerebellar system of ACLR patients (Fig. 2c and d) almost reached the "healthy" reference level at six-weeks postoperative. The peripheral-vestibular system (Fig. 2b) and the synchronization (foot coordination, Fig. 3b) reached a similar level at (twelve-weeks postoperative.

### 3.3. Mediolateral analysis - patients with a left-sided vs. right sided ACL injury

A significant increase in mediolateral weight distribution was placed on the injured side throughout the postoperative test sessions (Table 5). This effect was slightly more pronounced in the patients with left-sided ACL injury (exam 1 vs. 6: $\eta_p^2 = 0.489$ vs. 0.386). At the same time, this was the largest change for all parameters. The left-side weight distribution in the ACLR patients with left-sided injury was the only parameter with significant

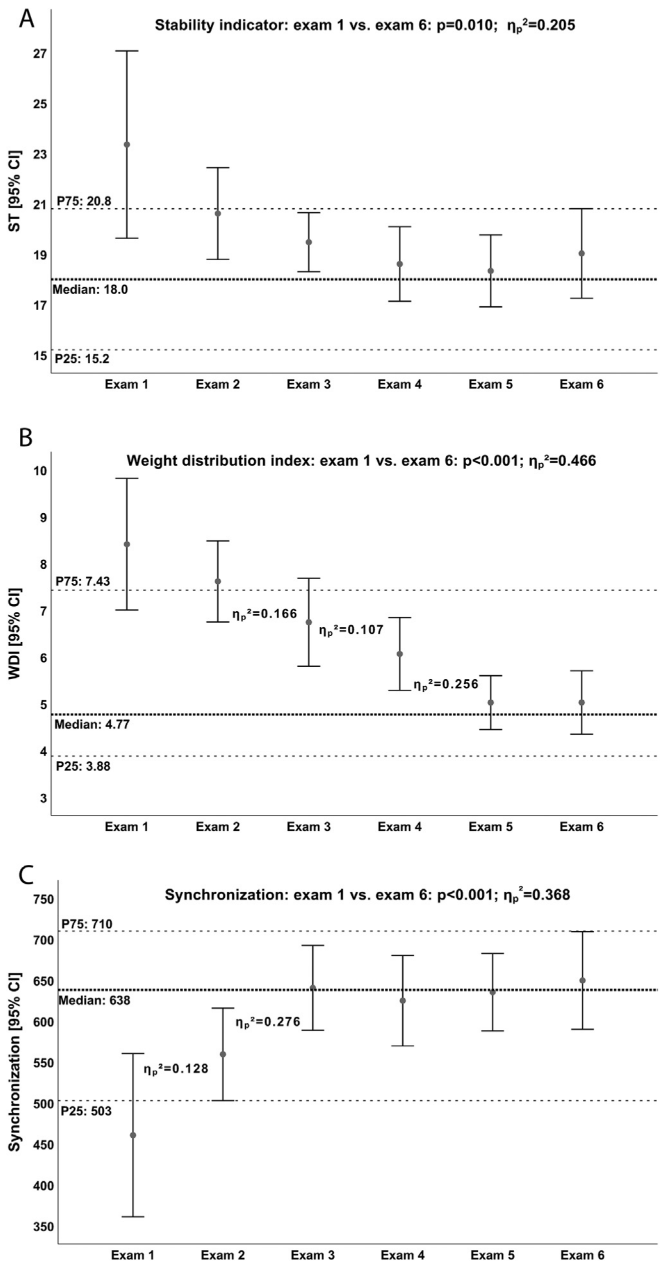


**Fig. 3. a-c.** Bilateral (ST, WDI, Synch) posturographic parameters over the two-year investigation period and in comparison to the matched reference sample based on median and percentile (P25, P75; interquartile range) analysis. Total and partial effects (threshold: $\eta_p^2 \geq 0.10$) of variance analysis are reported.

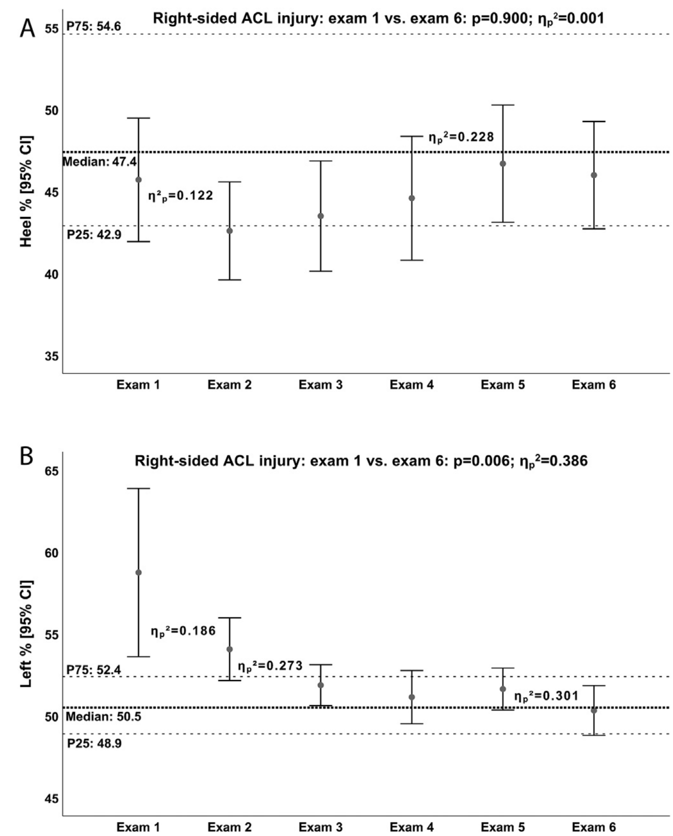


**Fig. 4. a-b.** Unilateral (heel, left) posturographic parameters over the two-year investigation. period and in comparison to the matched reference sample based on median and percentile (P25, P75; interquartile range) analysis for the patients with right-sided ACL injury (n = 17). Total and partial effects (threshold: $\eta_p^2 \geq 0.10$) of variance analysis are reported.

changes in all four postoperative observation periods (Table 5). In contrast, the improvements in the anteroposterior weight distribution were much lower, in particular for the patients with right-sided ACL injury (exam 1 vs. 6: $\eta_p^2 = 0.139$ vs. 0.001). At the end of the observation period, there was still an increased forefoot load (55% and 54%; Table 5).

## 4. Discussion

### 4.1. Study aim and main results

The aim of this study was to investigate the influence of ACL injury and subsequent surgical reconstruction and rehabilitation on postural regulation, stability, weight distribution and foot coordination using a longitudinal design (two-years) compared to healthy matched individuals. Based on the initially formulated hypotheses, our results indicate that the ACL rupture leads to a massive weight relief of the injured side (assumption for hypothesis one). Normalization of the mediolateral weight distribution requires one year postoperative. After the injury and ACL surgery, weight distribution, postural stability and foot coordination are strongly reduced (assumption for hypothesis two). Postural stability continued to increase up to one-year postoperative. The greatest changes across the two-year investigation period were found for weight distribution ($\eta_p^2 = 0.466$), especially for the mediolateral weight distribution ($\eta_p^2 = 0.349$) and the synchronization ($\eta_p^2 = 0.368$). With the exception of the synchronization at two-years postoperative, all maximum performances were achieved at one-year postoperative. The largest change (9%, preoperative vs. six-weeks postoperative) and lowest activity (suppression) after ACL surgery could be observed in the somatosensory system (assumption of hypothesis three). The cerebellar postural subsystem displayed the same reduction of activity (9%) as a result of the ACL surgery. In contrast, the visual and nigrostriatal systems showed the smallest change (0.5%, preoperative vs. six-weeks postoperative) and highest activity (compensation) after the ACL surgery.

### 4.2. Weight distribution and postural stability

In line with our longitudinal study design (n = 30; method: posturography; age, sex, body height and body weight matched

**Table 4**
Descriptive comparison of six examinations (performance maxima marked in bold) and analysis of variance (significant differences marked in bold), calculation of effect size ($\eta_p^2$) for bilateral posturographic parameters and body mass among patients (n = 30) with ACL injury. Grey highlighted the descriptive data (mean ± standard deviation in column 1) and comparisons at each time point with the reference matched sample (p/$\eta_p^2$).

| Parameter | Examinations (exam) | | | | | | Variance analysis | | |
|---|---|---|---|---|---|---|---|---|---|
| | Exam 1 | Exam 2 | Exam 3 | Exam 4 | Exam 5 | Exam 6 | Comparison of exam 1 vs. exam 6 | | Comparison of adjacent exams |
| Matched sample | preoperative | 6 weeks postoperative | 12 weeks postoperative | 6 month postoperative | one year postoperative | two years postoperative | **p** | **$\eta_p^2$** | **$\eta_p^2$** |
| Visual & Nigrostriatal | 17.2 ± 4.75 | 17.1 ± 4.50 | 17.5 ± 4.29 | 16.8 ± 5.98 | **14.8 ± 3.71** | 14.8 ± 4.96 | **0.001** | **0.179** | 4 vs. 5 (0.135) |
| 16.1 ± 4.31 | 0.335/0.016 | 0.403/0.012 | 0.205/0.028 | 0.607/0.005 | 0.209/0.027 | 0.294/0.019 | reference matched sample | | |
| Peripheral-vestibular | 9.21 ± 2.64 | 8.85 ± 1.78 | 8.74 ± 2.02 | 8.36 ± 1.92 | **7.70 ± 1.79** | 8.09 ± 2.09 | **0.012** | **0.102** | 4 vs. 5 (0.379) |
| 8.83 ± 1.87 | 0.515/0.007 | 0.965/0.000 | 0.857/0.001 | 0.342/0.016 | 0.021/0.089 | 0.152/0.035 | reference matched sample | | |
| Somatosensory | 3.90 ± 1.26 | 3.54 ± 0.77 | 3.47 ± 0.57 | 3.37 ± 0.71 | **3.27 ± 0.67** | 3.44 ± 0.89 | 0.046 | 0.066 | – |
| 3.85 ± 0.89 | 0.872/0.000 | 0.152/0.035 | 0.054/0.063 | 0.025/0.084 | **0.006/0.125** | 0.078/0.053 | reference matched sample | | |
| Cerebellar | 0.77 ± 0.30 | 0.70 ± 0.16 | 0.70 ± 0.13 | 0.67 ± 0.15 | **0.63 ± 0.12** | 0.67 ± 0.16 | 0.032 | 0.076 | 5 vs. 6 (0.133) |
| 0.68 ± 0.13 | 0.138/0.037 | 0.571/0.006 | 0.607/0.005 | 0.654/0.003 | 0.125/0.040 | 0.783/0.001 | reference matched sample | | |
| Stability indicator | 23.4 ± 9.96 | 20.6 ± 4.88 | 19.5 ± 3.13 | 18.6 ± 3.96 | **18.3 ± 3.83** | 19.0 ± 4.76 | **0.010** | **0.205** | – |
| 17.8 ± 3.49 | **0.005/0.126** | **0.012/0.103** | 0.053/0.063 | 0.394/0.013 | 0.561/0.006 | 0.252/0.023 | reference matched sample | | |
| Weight distribution index | 8.41 ± 3.77 | 7.62 ± 2.32 | 6.74 ± 2.51 | 6.07 ± 2.09 | **5.03 ± 1.54** | 5.03 ± 1.81 | < **0.001** | **0.466** | 2 vs. 3 (0.166)<br>3 vs. 4 (0.107)<br>4 vs. 5 (0.256) |
| 5.56 ± 2.24 | **0.001/0.180** | **0.001/0.174** | 0.059/0.060 | 0.370/0.014 | 0.286/0.020 | 0.315/0.017 | reference matched sample | | |
| Synchronization | 461 ± 267 | 560 ± 151 | 641 ± 139 | 625 ± 148 | 635 ± 127 | **650 ± 160** | < **0.001** | **0.368** | 1 vs. 2 (0.128)<br>2 vs. 3 (0.276) |
| 605 ± 139 | **0.011/0.106** | 0.230/0.025 | 0.326/0.017 | 0.593/0.005 | 0.382/0.013 | 0.254/0.022 | reference matched sample | | |
| anteriorposterior | 7.64 ± 5.36 | 9.18 ± 5.79 | 9.09 ± 5.72 | 8.30 ± 4.94 | **6.23 ± 3.83** | 6.21 ± 4.73 | 0.249 | 0.046 | 4 vs. 5 (0.181) |
| 7.38 ± 5.35 | 0.850/0.001 | 0.214/0.026 | 0.235 0.024 | 0.489/0.008 | 0.343/0.016 | 0.374/0.014 | reference matched sample | | |
| mediolateral | 8.45 ± 8.95 | 4.72 ± 4.11 | 3.22 ± 2.84 | 2.87 ± 2.38 | **2.32 ± 1.68** | 2.39 ± 1.77 | < **0.001** | **0.349** | 1 vs. 2 (0.161)<br>2 vs. 3 (0.190) |
| 2.63 ± 2.39 | **0.001/0.167** | 0.021/0.090 | 0.386/0.013 | 0.693/0.003 | 0.568/0.006 | 0.661/0.003 | reference matched sample | | |

Values are presented as mean ± standard deviation.
Significance was set at p < 0.006 or $\eta_p^2 \geq 0.10$.

**Table 5**
Descriptive comparison of six examinations (performance maxima marked in bold) and analysis of variance (significant differences between exam 1 and 6 marked in bold), calculation of effect size ($\eta_p^2$) for unilateral posturographic parameters (left and heel) and for patients with left-sided (n = 13) and right-sided (n = 17) ACL injury separately. Regarding the comparison of adjacent examinations only significant differences are reported.

| Parameter (%) | Examinations (exam) | | | | | | Variance analysis | | |
|---|---|---|---|---|---|---|---|---|---|
| | Exam 1 | Exam 2 | Exam 3 | Exam 4 | Exam 5 | Exam 6 | Comparison of exam 1 vs. exam 6 | | Comparison of adjacent exams |
| | preoperative | 6 weeks postoperative | 12 weeks postoperative | 6 month postoperative | one year postoperative | two years postoperative | p | $\eta_p^2$ | $\eta_p^2$ |
| **Patients with left-sided ACL injury** (n = 13) | | | | | | | | | |
| Heel | 41.7 ± 6.52 | 38.9 ± 5.90 | 39.7 ± 7.38 | 40.9 ± 5.30 | 45.0 ± 5.00 | **45.2 ± 6.98** | 0.190 | 0.139 | 1 vs. 2 (0.173)<br>4 vs. 5 (0.424) |
| Left | 42.6 ± 8.47 | 45.1 ± 5.29 | 46.2 ± 4.08 | 48.3 ± 3.99 | **50.0 ± 2.86** | 49.5 ± 3.13 | 0.005 | 0.489 | 1 vs. 2 (0.128)<br>2 vs. 3 (0.107)<br>3 vs. 4 (0.300)<br>4 vs. 5 (0.163) |
| **Patients with right-sided ACL injury** (n = 17) | | | | | | | | | |
| Heel | 45.7 ± 7.32 | 42.6 ± 5.81 | 43.5 ± 6.54 | 44.6 ± 7.35 | **46.7 ± 6.97** | 46.0 ± 6.37 | 0.900 | 0.001 | 1 vs. 2 (0.122)<br>4 vs. 5 (0.228) |
| Left | 58.7 ± 9.98 | 54.1 ± 3.72 | 51.9 ± 2.43 | 51.2 ± 3.16 | 51.6 ± 2.49 | **50.3 ± 2.95** | **0.006** | **0.386** | 1 vs. 2 (0.186)<br>2 vs. 3 (0.273)<br>5 vs. 6 (0.301) |

Values are presented as mean ± standard deviation.
Heel: Percentage of weight distribution forefoot vs. heel with description of heel loading; Left: Percentage of weight distribution left vs. right with description of left side loading.
*Significance was set at p < 0.006 or $\eta_p^2 \geq 0.10$.

with healthy control sample), Dauty, Collon, and Dubois (2010) compared postures of an ACLR population (n = 35) with an age and sex-matched healthy control population. This previous research used a stabilometric platform and showed that ACL patients relied more heavily on the contralateral leg. The overloading of the injured side feet also reduced significantly during the one year period after surgery.

Consistent with our results, Mohammadi et al. (2012) also showed that eight months after ACLR, competitive athletes (n = 30) still demonstrated postural asymmetries compared to matched controls. ACLR subjects have been shown to have greater displacement, velocity, area and total distance in the involved limb in comparison with the contralateral limb and matched limb of controls (Ben Moussa, Zouita, Dziri, & Ben Salah, 2009; Dauty et al., 2010; Mohammadi et al., 2012). The authors discussed the existence of direct connections between neurologic structures of the ACL and the spinal cord, as well as supraspinal areas (Henriksson, Ledin, & Good, 2001). Thus, it is possible that damage of the ligament may diminish afferent information (Mohammadi et al., 2012).

Brattinger, Stegmüller, Riesner, Friemert, and Palm (2013) reported a 25% reduction in postural stability following an ACL-tear. Lehmann et al. (2017) used a systematic review and meta-analysis to report that individuals with ACL injury have decreased postural stability. We found a 30% reduction in postural stability (parameter: stability indicator; preoperative: median reference: 18.0 vs. 23.4). Six-weeks after ACL surgery instability is largely reduced (14%; 18.0 vs. 20.6) and at six-months postoperative the ACLR patients were similar to the healthy matched control population (3%; median reference: 18.0 vs. 18.6). This postural instability may be due to damage of the ACL mechanoreceptors, which are sensitive to mechanical deformation of the tissue, and signal joint position and motion. The resulting proprioceptive deficit of the knee causes reduced sensorimotor control of surrounding joint musculature (Konishi, 2011). According to the model of Kapreli and Athanasopoulus (2006) mechanoreceptor damage due to the ACLR may lead to a disorder of sensory transmission, contributing to alterations of afferent feedback and stabilizing reflexes that may implicate increased instability (Lehmann et al., 2017).

As expected, patients in our study showed an increased weight distribution of the injured side throughout the rehabilitation process. Significant changes across the entire investigation period were only observed for the mediolateral ($\eta_p^2 = 0.349$) weight distribution. Especially between preoperative and six-weeks postoperative ($\eta_p^2 = 0.161$), as well as six-weeks and twelve-weeks postoperative ($\eta_p^2 = 0.190$) (Table 4). The improvement in the mediolateral direction was much larger than in the anteroposterior direction ($\eta_p^2 = 0.349$ vs. 0.046). While the ACLR patients almost reached the reference level in the mediolateral direction (left-sided load, exam 4: 51.2% vs. median reference: 50.5%), we still observed a decreasing overload in the forefoot (exam 4: 55.4%, exam 5: 53.3% vs. median reference: 52.6%). This may be explained by Shimokochi, Ambegaonkar, Meyer, Lee, and Shultz (2013) who reported that patients with ACL injuries may present with an increased forward lean to assist with decreasing the anterior shear force on the ACL and subsequent activation of the quadriceps. At this point it becomes clear how important the comparison with matched reference data is in order to avoid misinterpretations. Otherwise, the increased forefoot load could be misinterpreted as a result of ACL injury and subsequent reconstruction or rehabilitation.

### *4.3. Postural regulation and subsystems*

The performance of all postural subsystems was reduced in different form because of ACL rupture and surgery. In contrast to the literature, which has shown multiple postulated decreases in proprioceptive capacity (Brattinger et al., 2013; Palm, Schlumberger, Riesner, Friemert, & Lang, 2015), we found the lowest preoperative difference to the matched individuals (3%; median reference: 3.78 vs. 3.90) in the somatosensory system. But in line with the literature, the largest reductions (9%) after the ACL surgery were calculated for the somatosensory and the cerebellar system. Six weeks after ACL surgery the patients in our study moved between percentile 50 and 25 for the somatosensory system. Similarly, the cerebellar subsystem was suppressed at six-weeks postoperative (median reference: 0.69 vs. 0.70; Fig. 2d; Table 4). In contrast, the amount of change was the smallest for the visual and nigrostriatal subsystems. The ACLR patients did not reach the level of the healthy matched control population until one-year postoperative (3%; median reference: 15.3 vs. 14.8; Fig. 2a; Table 4). The holistic view of postural subsystems is a good example for the neuroplasticity of biological systems and the model of selective compensatory optimization. The alteration of afferent sensory (proprioceptive) information, potentially caused by mechanoreceptor damage (ACL surgery), may subsequently contribute to disturbances of postural regulation (Lehman et al., 2017). In our investigation we showed reduced activity in the somatosensory system after ACL surgery and the subsequent examinations (consistently below the healthy median reference; Fig. 2c). A similar reduction at six-weeks postoperative was observed for the cerebellar system (Fig. 2d). This may explain the connection between the somatosensory system and the spinocerebellum, which is responsible for processing the afferent (somatosensory) information. Conversely, the suppression effects are compensated by an increased activity of the visual and nigrostriatal systems. These are the only systems which were unaffected by the ACL surgery. At six-months postoperative, we were able to measure an increased activity between percentile 50 and 75 (Fig. 2a). Interestingly, we found the exact opposite effect in a study of postural control in subjects with visual impairment (11 with congenital blindness and 39 with acquired visual impairment) compared to 50 healthy controls (Schwesig et al., 2011). Fourier analysis revealed that the visually impaired subjects showed decreased intensity values within the lowest frequency range of 0.1 Hz and below. Simultaneously, somatosensory and vestibular systems may serve as compensatory mechanisms. Especially, in the visually impaired subjects who showed a moderate increment of intensity at the somatosensory related range (0.5–1.0 Hz) (Schwesig et al., 2011). Baumeister, Reinecke, and Weiss (2008) also found increased cortical processing in the brain related to ACL injury, also demonstrating significantly higher frontal brain activity in both the injured and non-injured leg. Based on this rationale, some investigations have also shown altered postural regulation after ACL injury (Angoulos et al., 2011; Lee et al., 2015).

### *4.4. Limitations*

Although our subjects all completed a standardized rehabilitation program, a limiting factor in this examination was that the participants' rehabilitations were not performed under the care of the investigators, so we cannot verify that each protocol was followed precisely as prescribed. Furthermore, after 21 weeks postoperative, there was no uniform standardized treatment as patients were released from clinical supervision. The longitudinal comparison is limited, because of the variations in observation periods (e.g., six weeks, twelve weeks, six months). Consequently, the longest time interval from exam 4 to 5 (six months) may have had the greatest potential for changes. A further limitation could be the missing evaluation of sidedness (dominant vs. non-dominant leg) which can be a considerable factor for postural dysfunction. Although some research has shown bilateral differences in gait Alonso, Brech, Bourquin, and Greve (2011) showed that leg-dominance does not affect single leg balance. Muehlbauer, Mettler, Roth, and Granacher (2019) compared bilateral static balance and muscle activity during one-leg standing under various sensory conditions and also concluded no bilateral differences.

### *4.5. Clinical implications*

From a clinical treatment perspective the results of this study demonstrate that ACLR patients need a treatment program with professional support in order to avoid the postural performance reduction from one-year postoperative and later. The program should be more accentuated towards feedforward mechanisms to stimulate improvements in the somatosensory and cerebellar systems. For example, Bartels et al. (2016) described and investigated a rehabilitation concept using disturbances causing reaction time under 200 ms five month following ACL surgery. These authors concluded that reaction training appears to be more appropriate for the later stages of ACLR rehabilitation compared to other sensorimotor rehabilitation programs. From a more diagnostic point of view, Brattinger et al. (2013) reported that established clinical scores and questionnaires are unsuitable for estimation of postural stability deficits after an ACL injury. The results of our study offer the possibility to implement a valid, reliable and practicable posturographic assessment (IBS) in clinical practice. According to Lehmann et al. (2017), the measure of center of pressure, with the IBS, is the gold standard and allows a functional distinction of postural stability between subjects with and without ACL injury. The IBS may assist physicians and physiotherapists to identify patients at greater risk for suffering a subsequent ACL injury and consequently allow for treatment modifications and return to play strategies.

## 5. Conclusion

The results of this study indicate that following ACL injury, surgical reconstruction and rehabilitation results in postural regulation, with improvements in postural subsystems, postural stability, weight distribution and foot coordination. Also, overloading of the injured side foot decreases significantly over the two-year period after surgery. At two-years postoperative, the patients' postural regulation had reached the level of a reference group in all parameters with except the stability indicator and the anteroposterior weight distribution. The normalization of the mediolateral weight distribution needs one year. The comparison with a healthy matched reference group shows, that ACLR leads to a suppression of the somatosensory and cerebellar system which was compensated by a higher activity of the visual and nigrostriatal systems. This investigation provides further insights into underlying mechanisms of postural regulation and in the understanding of the interaction of postural subsystems. As such, we suggest that the widespread isolated orthopedic view (flexibility, strength, pain) should be replaced by a more holistic approach.

## Ethical approval

The study protocol was approved by the Ethics Committee of the Martin-Luther-University Halle-Wittenberg (reference number: 2016-144). All patients signed the free and informed consent statement.

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## Conflicts of interest

None declared.

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