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# An in-depth Analysis of the Side Hop Test in Patients 9 Months Following Anterior Cruciate Ligament Reconstruction

*Eine ausführliche Analyse des Side Hop Tests bei Patienten 9 Monate nach Rekonstruktion des vorderen Kreuzbandes*

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## Summary

› **Purpose:** The current criterion to evaluate 30-second side hop (SH) test performance following anterior cruciate ligament reconstruction (ACLR) is limited to the absolute number of jumps, neglecting the quality of execution. This study aims to assess the relevance of spatiotemporal and force plate derived parameters during the SH test.

› **Methods:** Seventeen patients nine months post-surgery and 27 healthy controls were instructed to realize a maximal number of jumps during 30 seconds over a 40 cm-distance. Spatiotemporal and force plate derived variables were recorded from two force plates: number of jumps, flight time, contact time, jump distance, vertical impact force, average and instantaneous vertical loading rate. Group (patients and controls) by leg (non-operated/first tested and operated/second tested) interactions were tested using a mixed model analysis of variance.

› **Results:** Patients performed a similar number of jumps compared to controls. No differences were found for spatiotemporal and force plate derived parameters, neither for lateral nor medial jumps. High interindividual spread of impact peak forces existed in both groups.

› **Discussion:** Patients 9 months following ACLR and successful rehabilitation can safely perform strenuous lateral hops similar to controls. Although the force plate derived parameters during the SH test were normalized compared to controls, impact peak forces outlined particularly high loading parameters in some participants. Applying biomechanical analysis in association to the commonly used clinical parameters helps to point out individual and potentially harmful loading strategies during the SH test.

## Zusammenfassung

› **Einleitung und Zielstellung**: Das aktuelle Kriterium zur Bewertung des einbeinigen 30-sekündigen Side Hop (SH) Tests nach Rekonstruktion des vorderen Kreuzbandes (VKB) ist auf die absolute Anzahl gültiger Sprünge beschränkt, wobei die Qualität der Ausführung nicht berücksichtigt wird. Das Ziel dieser Studie war, die Relevanz der raumzeitlichen und von Kraftmessplatten abgeleiteten Parametern während des SH Tests zu bewerten.

› **Material und Methode**: Siebzehn Patienten neun Monate nach VKB-Rekonstruktion und 27 gesunde Kontrollprobanden wurden angewiesen, eine maximale Anzahl von SH-Sprüngen während 30 Sekunden über 40 cm zu absolvieren. Die Sprünge wurden auf zwei Kraftmessplatten durchgeführt. Raumzeitliche Parameter und von Kraftmessplatten abgeleiteten Belastungsparameter wurden erfasst: Anzahl der Sprünge, Flugzeit, Bodenkontaktzeit, Sprungdistanz, am Körpergewicht normierte vertikale Bodenreaktionskraft, durchschnittliche und momentane vertikale Belastungsrate.

› **Interaktionen** von Gruppen (Patienten und Kontrollprobanden) und Bein (nicht-operiertes/erst-getestetes und operiertes/zweit-getestetes) wurden mit einer gemischten Varianzanalyse getestet. Das Signifikanzniveau wurde auf $p<0.05$ festgelegt.

› **Ergebnisse:** Patienten absolvierten eine gleiche Anzahl von Sprüngen wie die Kontrollprobanden. Keine Unterschiede wurden für die raumzeitlichen und Belastungsparameter gefunden, weder für laterale noch für mediale Sprünge. Beide Gruppen wiesen eine hohe interindividuelle Streuung bezüglich der Bodenreaktionskräfte auf.

› **Diskussion:** Patienten absolvierten 9 Monate nach VKB-Rekonstruktion und erfolgreicher Rehabilitation anspruchsvolle seitliche einbeinige Sprünge, die in der Ausführung mit denen von Kontrollprobanden vergleichbar sind. Eine biomechanische Analyse kann dabei helfen, individuelle, potenziell ungünstige Belastungsstrategien während des SH Tests aufzudecken.

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## Introduction

The current decision-making process for a safe return to sports (RTS) following anterior cruciate ligament reconstruction (ACLR) is commonly based on clinical and functional evaluations, including a strength and hop test battery (2, 3, 7, 21). The 30-second side hop (SH) test is popular because it challenges knee stability in the frontal plane while inducing muscle fatigue (7). Clinicians use the limb symmetry index (LSI) to determine within-subject side-to-side differences (27). A LSI of 97% during the SH test has been reported nine months post-surgery, when patients are evaluated for RTS (29). However, as deficits after surgery are also common in the contralateral leg, this symmetry index risks to overestimate the hop performance (5, 6, 30).

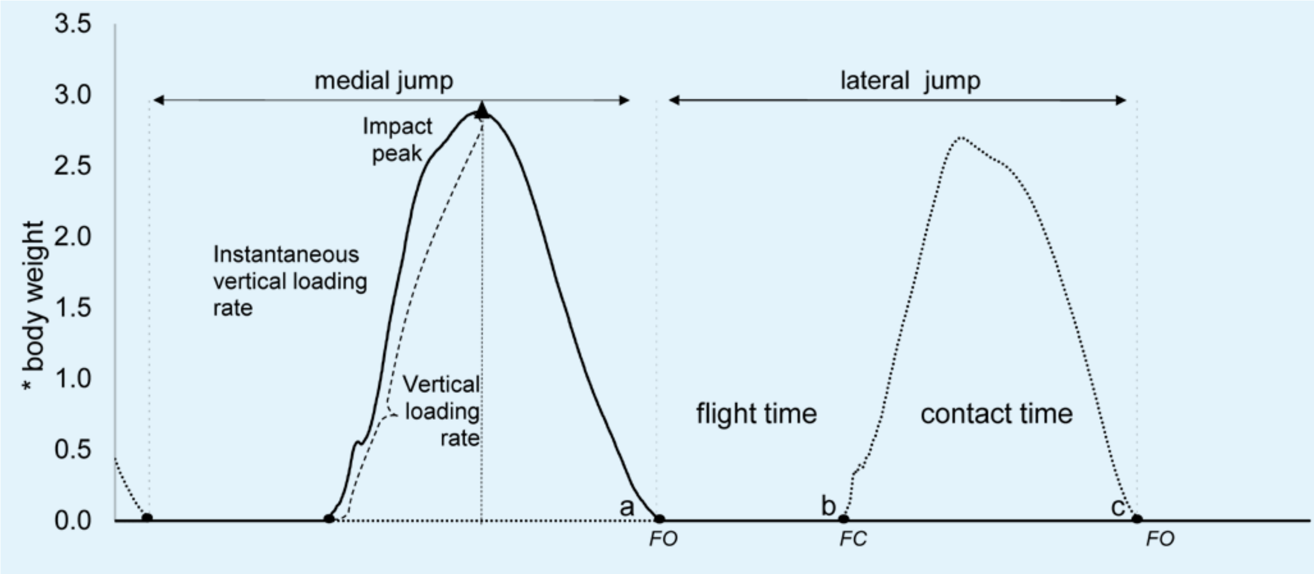


**Figure 1**

Schematic representation of one side hop on the ACLR leg visualizing the normalized vertical ground reaction force curve of both force plates (FP1, FP2) during a medial and lateral side hop. The full line represents the FP1 signal, the plotted line the FP2 signal. The black dots illustrate the Take-Off (TO) and Initial Contact (IC) events. a-c: one complete lateral side hop, a-b: flight time, b-c: contact time, the triangle illustrates the impact peak (Fmax), the dashed line marks the time to the impact peak (the vertical loading rate is the peak vGRF by the time to peak impact peak), the square marks the peak of the first derivative of the force-time curve and illustrates the instantaneous vertical loading rate.

Other qualitative information are overlooked by limiting the SH test evaluation to the number of valid jumps.(4, 13) For example, the same number of jumps can be achieved by adapting spatiotemporal parameters, i.e. contact time, flight time and/or jump distance. Moreover, given that the SH test consists of jumping alternatively medially and laterally, contact forces are likely to differ between medial and lateral side hops. Special attention may be given to the lateral jumps, which are similar to the side cutting movement described to be close to the ACL injury mechanism (12, 14, 15, 23, 28). We therefore need a in-depth analysis and better definition of SH test criteria. A separate analysis of medial and lateral side hops may reveal relevant information on knee function recovery.

The main objective of this study was to analyse the 30-second SH test performance at the presumed time for RTS in patients following primary ACLR. Our exploratory hypotheses were that during the SH test ACLR patients would present a (1) lower number of valid jumps, (2) decreased flight time, jump distance and greater contact time, and (3) different outcomes in force plate-derived parameters compared to healthy controls.

**Table 1**

Demographics of study participants. Variables are presented as means (±SD). ST semitendinosus graft, BPTB bone-patellar tendon-bone graft. [1]Associated meniscal lesions: lateral meniscus (n = 4), medial meniscus (n = 1) or both (n = 6). [2]Sport activity level pre-injury: level I corresponds to sports with jumping, pivoting, cutting mechanism (e.g. football, handball, hockey), level II corresponds to moderate jumping, pivoting and lateral movements (e.g. tennis, volleyball, fencing, gymnastics), and level III refers to sports with no pivoting actions (running, cycling, riding).

| DEMOGRAPHICS OF PARTICIPANTS | PATIENTS (N =17) | CONTROLS (N = 27) |
|---|---|---|
| Age (years) | 24.2 (±6.8) | 25.5 (±4.1) |
| BMI (kg.m$^{-2}$) | 23.1 (±2.5) | 22.4 (±1.9) |
| Gender | 5F/12M | 13F/14M |
| Time post-surgery (months) | 8.9 (±1.3) | - |
| Injury mechanism | 4 contact/ 13 non-contact | - |
| Graft type | 11 ST/6 BPTB | - |
| Associated lesions[1] | yes (n = 11)/ no (n = 6) | - |
| | lateral meniscal lesion (n = 4), medial meniscal lesion (n = 1); both (n = 6) | |
| Sport activity level[2] | I (n = 13); II (n = 2); III (n = 2) | I (n = 11); II (n = 7); III (n = 9) |

## Methods

Patients who underwent primary ACLR were recruited from a single institution. Inclusion criteria were: age between 15 - 35 years, minimum 9 months post-unilateral ACLR, complete knee extension and a minimum of 140° knee flexion, medical clearance to perform a jump test battery, absence of any other musculoskeletal or neurological disorders including other lower limb joint surgery and preinjury sports participation of at least two hours per week.

Twenty-seven active healthy volunteers were recruited as a control group during the same period. The inclusion criteria for the healthy controls were: age between 15 - 35 years, absence of any musculoskeletal or neurological disorders including lower limb joint surgery and participation at least two hours per week in sports activities.

All participants obtained a verbal description of the study protocol and provided written informed consent before participation. All study procedures were approved by the National Ethics Committee for Research (201101/05).

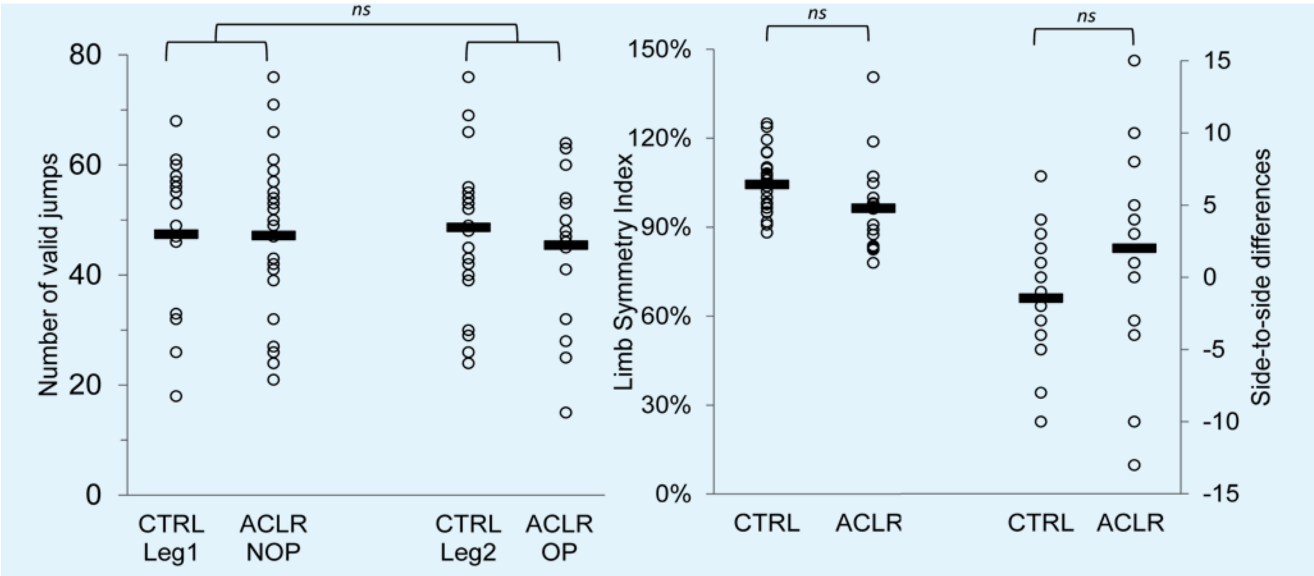


**Figure 2**

Total number of valid jumps during the 30-second side hop test, displaying individual results of the number of jumps of the non-operated (NOP) leg and operated (OP) of ACLR patients and first tested leg ($Leg_1$) and second tested leg ($Leg_2$) in controls (CTRL). Right: Individual results of the commonly used parameters of the 30-second side hop performance evaluation, the Limb Symmetry Index (LSI) calculated on the total number of side hops performed and side-to-side differences between the OP and NOP leg of ACLR patients and second $Leg_2$ and $Leg_1$ in CTRL, the black lines represent mean values.

## Test Protocol

The study participants performed a 10-minute warm-up run at a self-selected pace on a treadmill, followed by the 30 seconds single leg SH test. Participants were provided with a standardized sport shoe prototype during testing, to avoid influencing landing biomechanics by shoe wear (17, 24).

The participants were asked to perform a maximal number of jumps on two separate and parallel placed force platforms (Arsalis 3D-8050; Arsalis Sprl; Louvain-la-Neuve, Belgium). They were asked to jump from one force plate to the other during 30 seconds and land on the outside of two parallel tape strips placed 40 cm apart (7). They received instructions to start from a unipodal standing position, with hands on the hips during the whole test. Patients always started the test on their non-operated leg, while the first-tested leg of the healthy controls was randomly chosen. A preliminary analysis of the control group supported earlier findings that leg dominance does not influence the results in jump tests (5, 19, 26). Participants performed the task on each leg, with a 3 minutes rest period in between. The test was repeated if more than 25% of all jumps were invalid, i.e. landing onto or within the tape stripes, in accordance with the clinical execution guidelines (7). Three-dimensional ground reaction forces (GRF) from each force plate were recorded at 1000 Hz.

## Data Processing

All data processing was completed using Visual 3D software (v6; C-Motion Inc., Germantown, MD, USA). The initial contact (IC) and take-off (TO) events were defined based on a 10N threshold of the raw vertical GRF and were used to compute the spatiotemporal parameters.

The jumps were differentiated in lateral and medial side hops, depending on the landing direction (10). Using IC and TO events, the number of jumps, contact time, flight time and jump distance (Figure 1) were computed. A complete jump was defined from the TO event of one force plate to the TO of the other force plate. The time from TO to IC defined the flight time, while the time from IC to the subsequent TO defined the contact time. If any adjustment jumps were performed due to lack of stability on the same platform before leaving towards the other, the contact time was extended to reflect the full period of time spent on the same platform. Jump distance was calculated as the two-dimensional Euclidean distance between the centres of force application from TO to subsequent IC. The LSI was defined as the ratio of the number of jumps from the operated (OP) over the non-operated (NOP) leg for patients and from the second-tested (Leg2) over first-tested (Leg1) leg in controls. Moreover, the side-to-side difference was calculated as the difference of the number of jumps between the non-operated versus the operated leg and first-tested versus the second-tested leg.

The force plate derived parameters for each jump such as impact peak of the vertical GRF (vGRF), vertical loading rate (vLR) and instantaneous vertical loading rate (vLRi) were derived from the vGRF trace (Fig. 1) which was filtered using a 15 Hz low-pass, 4th order Butterworth filter. The vertical loading rate was calculated by dividing the peak vGRF by the time to peak whereas instantaneous vertical loading rate was defined as the peak of the first derivative of the force-time curve. All loading parameters were normalized to body weight.

## Statistical Analysis

An a-priori power calculation of 10 patients revealed that the inclusion of at least 16 participants in each group would allow us to detect an effect size of 1.0 for the side-to-side difference in peak knee power at a power of 0.80 and a significance level of 0.05. Based on the IC and TO events, spatiotemporal parameters were calculated as means over 30 seconds. Leg and group differences were tested by comparing the NOP and OP leg of the patients and the randomized first Leg1 and Leg2 leg of the controls. All variables were analysed for statistical differences using a mixed model analysis of variance (group (2) × leg (2)). Concerning the total number of jumps, the side-to-side differences were compared between groups using the student's t-test. All data are expressed as means ± standard deviation (SD). Statistical significance was set at $p<0.05$. The statistical analyses were performed using SPSS version 24 (IBM; Houston, TX, USA//Armonk, NY).

Table 2

Number of jumps and spatiotemporal variables of lateral and medial side hops for the non-operated (NOP) and operated (OP) leg for the ACLR patients and the first (Leg1) and second tested leg (Leg2) for the healthy controls. Data are reported as means (±SD).

| VARIABLES | ACLR PATIENTS (N=7) | | CONTROLS (N=27) | | P-VALUES | | |
|---|---|---|---|---|---|---|---|
| Definitions | NOP | OP | Leg1 | Leg2 | Leg effect | Group effect | Group*Leg |
| Total number of valid jumps | 47 (±14) | 45 (±14) | 47 (±14) | 49 (±13) | 0,75 | 0,72 | 0,75 |
| Lateral contact time (ms) | 490 (±320) | 520 (±330) | 480 (±220) | 460 (±210) | 0,66 | 0,64 | 0,66 |
| Medial contact time (ms) | 480 (±280) | 520 (±350) | 500 (±290) | 450 (±200) | 0,91 | 0,71 | 0,91 |
| Lateral flight time (ms) | 190 (±20) | 190 (±10) | 180 (±20) | 190 (±20) | 0,73 | 0,5 | 0,73 |
| Medial flight time (ms) | 200 (±20) | 190 (±20) | 190 (±20) | 190 (±20) | 0,48 | 0,26 | 0,48 |
| Lateral jump distance (cm) | 57.9 (±3.8) | 57.6 (±2.8) | 58.8 (±4.4) | 59.7 (±4.7) | 0,59 | 0,2 | 0,59 |
| Medial jump distance (cm) | 59.1 (±3.5) | 58.1 (±3.1) | 58.7 (±4.6) | 59.7 (±3.5) | 0,92 | 0,62 | 0,92 |

## Results

The participants' characteristics are presented in Table 1. Seventeen ACLR patients were evaluated at 8.9 ± 1.3 months post-surgery. Eleven patients were operated with a semitendinosus graft and six with a bone-patellar tendon-bone graft. Intraoperative concomitant meniscal tears were reported in eleven (65%) patients, seven of them were treated with meniscal repair surgery (all unimeniscal repairs), three with a partial menisectomy (one bimeniscal meniscectomy) and one bimeniscal tear was left in situ. Preinjury level I sports activity was reported in 76%, 12% in level II and 12% in level III sports.(9) In the control group, 41% participated in level I, 26% in level II and 33% in level III sports.

To perform a valid SH test with less than 25% of the jump errors according to the clinical guidelines (7), a second trial had to be recorded for two (12%) patients, one on the operated and one on the non-operated leg respectively. In the control group, four (15%) participants were asked to perform a second trial.

With respect to the total number of valid jumps (Table 2), no significant group-by-leg interaction, group effect or leg effect was found. A high spread in the number of valid jumps (Figure 2) was observed in both groups and for both legs. No significant group difference was detected for the side-to-side differences of the total number of valid jumps (P=.08), nor of the LSI (P=.07) (Figure 2). The LSI revealed symmetric SH performance in patients and controls; both groups showed a 4%-difference between both legs.

Concerning the spatiotemporal parameters, no significant group-by-leg interaction, group effect or leg effect was found for contact time, flight time and jump distance in lateral and in medial jumps (Table 2). A high spread was observed in boths groups for all three spatiotemporal parameters in lateral and in medial jumps. The mean jump distance over 30 seconds was 58.2 cm (±3.3 cm) in patients and 59.2 cm (±4.3 cm) in controls. Of all analyzed side hops, one out of 1510 jumps (0.1%) in patients and seven out of of 2644 (0.3%) in healthy controls did not reach the required jump distance of 40 cm based on force application point.

The results for the force plate-derived parameters are depicted in Table 3. No significant group and leg effect was detected for peak vGRF, vLR and vLRi in lateral and in medial jumps. The medial vGRF displayed a significant group-by-leg interaction (P=.02), without leg (P=.32) or group (P=.62) effect.

## Discussion

The main finding of this study was that the quality of the SH test performance was not negatively affected in patients at 9 months after ACLR compared to controls. No significant differences in number of jumps, spatiotemporal and force plate-related parameters during the SH test were observed between both groups, neither for lateral nor for medial jumps. A significant group-by-leg interaction was found for medial vGRF, illustrating higher interlimb differences in patients.

The high SH performance of the patients may be explained by our strict inclusion criteria. Patients were selected from an in-house cohort and included only if at 9 months post-surgery and if medically cleared to perform hop tests. Likewise, patients' high sports activity level and their sport-specific rehabilitation program, including plyometrics, may have positively influenced jump performance. The controls may not have been as specifically prepared for unilateral hops, which could negatively affect SH performance (11). With an average of 45 jumps on the operated leg, patients achieved a high level of SH performance nine months post-surgery. This was superior to the study by Thomée et al. where patients achieved the same number of SH 24 months post-surgery (25), but inferior to the study of Welling et al.,(29) where elite athletes performed 10 jumps more 9 months post-surgery. The side-to-side difference and LSI average scores indicated symmetric hop performance in both groups. This symmetry index confirms the study of Welling et al., who found a 97% LSI in elite athletes (29). Although not significant, we observed a trend for higher LSI and lower side-to-side differences in controls, as they performed more hops on their second-tested than on their first-tested leg, contrary to the patients. This finding seems hower not clinically important, considering that differences in LSI scores might be attributed to measurement error and were below estimated meaningful difference of 10-15% (11).

The innovative approach of this study was the assessment of spatiotemporal parameters during the SH test using force plates. Analysing contact time, flight time and jump distance did not reveal any deficits in patients. However measuring jump distance precisely based on force plate data helped to objectify the number of invalid jumps, originally defined as "jumps with touching the tape"(7). To date, the amount of invalid jumps has been neglected in the SH test evaluation. As they provide relevant information about SH test performance, our analysis included jumps below 40 cm. Patients performed a similar number of invalid jumps compared to controls. In

Table 3
Force plate derived variables of lateral and medial side hops for the non-operated leg (NOP) and operated (OP) for the ACLR patients and the first (Leg1) and second tested leg (Leg2) for healthy controls. Data are reported as means (±SD). *Significant differences ($p<0.05$). (Bw) Bodyweight.

| VARIABLES | ACLR PATIENTS (N = 17) | | CONTROLS (N = 27) | | P-VALUES | | |
|---|---|---|---|---|---|---|---|
| Definitions | NOP | OP | Leg1 | Leg2 | Leg effect | Group effect | Group*Leg |
| Lat vGRF (Bw) | 2.46 (±0.31) | 2.42 (±0.21) | 2.36 (±0.22) | 2.41 (±0.26) | 0,86 | 0,44 | 0,11 |
| Med vGRF (Bw) | 2.63 (±0.38) | 2.51 (±0.28) | 2.49 (±0.38) | 2.54 (±0.35) | 0,32 | 0,62 | 0,02 |
| Lat time to peak (s) | 0.09 (±0.02) | 0.09 (±0.02) | 0.09 (±0.02) | 0.09 (±0.02) | 0,36 | 0,27 | 0,64 |
| Med time to peak (s) | 0.11 (±0.02) | 0.10 (±0.02) | 0.10 (±0.03) | 0.10 (±0.02) | 0,72 | 0,77 | 0,46 |
| Lat average loading rate (Bw/s) | 27.39 (±4.26) | 28.14 (±5.98) | 28.25 (±4.51) | 30.50 (±6.08) | 0,08 | 0,26 | 0,37 |
| Med average loading rate (Bw/s) | 25.92 (±4.28) | 25.55 (±4.21) | 26.22 (±4.86) | 26.38 (±4.77) | 0,88 | 0,65 | 0,71 |
| Lat instantaneous loading rate (Bw/s) | 41.78 (±7.46) | 41.76 (±8.61) | 41.89 (±8.00) | 44.70 (±8.42) | 0,33 | 0,47 | 0,33 |
| Med instantaneous loading rate (BW/s) | 41.59 (±6.56) | 39.87 (±7.01) | 41.27 (±7.88) | 41.48 (±6.45) | 0,53 | 0,73 | 0,42 |

fact, both groups failed to reach the 40 cm distance in less than 0.2% of the jumps only, illustrating that the 40 cm guideline standardizes adequately the jump distance.

Performing adjustment jumps, defined as multiple hops on the same force plate, reflects poor performance when stabilising landings. Adjustment jumps were included in the analysis by summing up the total time spent on the force plates. While patients and controls had similar contact times, the interindividual differences were high. The patients with the highest contact times should consider improving their stabilisation strategy immediately after landings before safely returning to sport (18).

The importance of biomechanical testing after ACLR was highlighted in a recent review (13), illustrating symmetric single-legged hop performance in ACLR patients while the biomechanical analysis revealed deficits of the operated leg. We therefore expected our biomechanical analysis to detect deficits likely overseen with the simplistic approach of counting the number of side hops. Surprisingly, our overall findings showed no deficits in loading conditions when comparing patients to controls. A significant group-by-leg interaction was however found for medial vGRF, as patients displayed higher interlimb differences than controls, with lower loading on the operated than on the non-operated leg. The clinical relevance concerning the difference in the vGRF magnitude requires further investigation. Furthermore, the high interindividual spread of impact peak forces in both groups indicates particularly high loading parameters in only certain participants. These participants, especially those following ACLR, might be specifically prone to develop early-onset knee osteoarthritis which could be related to high loading parameters (1, 8). High loading strategies were not exclusively observed in patients performing the lowest number of hops. Therefore, applying biomechanical analysis of the SH test in addition to commonly used clinical parameters could be useful to point out individual, potential harmful loading strategies. Establishing individual thesholds of impact peak scores which might call for treatment intervention might also be helpful for injury prevention.(16) Further research might also need to explore whether participants with poorer jump performance are at greater risk of sustaining a (re-)injury.

During the laboratory tests, the present study cohort was also analysed during a bilateral drop vertical jump (20). The findings demonstrated that patients unloaded their operated leg compared to their non-operated leg, an observation which could not be repeated by our results of the unilateral SH task. This discrepancy is concordant to the study of Baumgart et al., who found unloading compensations in ACLR patients only during a two-legged vertical jumps (1). The authors concluded that single-legged jumps are rather suited to reveal inter-joint compensation strategies than loading asymmetries (22).

## Conclusions

An in-depth analysis of the SH test performance demonstrated that 9 months following ACLR and after successful rehabilitation patients can safely perform strenuous lateral hops. Patients achieved on both legs a similar number of hops than healthy active controls. An additional analysis of force plates derived parameters revealed that patients achieved this performance without altered spatiotemporal or overall lower limb loading parameters. Although patients' force plate-derived parameters were normalized, important interinvididual differences existed in both groups. This observation highlights the interest of using force plates in association to the clinical used parameters to objectify individual hop strategies during the SH test following ACLR.

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**Conflict of Interest**
*The authors have no conflict of interest.*

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