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# RetroBRACE: clinical, socioeconomic and functional–biomechanical outcomes 2 years after ACL repair and InternalBrace augmentation in comparison to ACL reconstruction and healthy controls—experimental protocol of a non-randomised single-centre comparative study

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## ABSTRACT

**Introduction** Despite good clinical outcomes reported in the literature, to date, scientific evidence for the functional and biomechanical benefit of primary anterior cruciate ligament (ACL) repair with augmentation is scarce. We present an experimental protocol for a detailed multimodal (clinical, socioeconomic, functional and biomechanical) comparative study in patients after primary ACL repair and InternalBrace augmentation, patients after ACL reconstruction and healthy controls.

**Methods and analysis** In this non-randomised single-centre comparative study with prospective data collection with three arms (patients 2 years after ACL repair and InternalBrace augmentation; patients 2 years after ACL reconstruction using hamstring autografts; and healthy controls), 30 participants per study arm will be included. The study is designed as non-inferiority study with three arms. Required sample size was estimated based on data reported in the literature on muscle strength, proprioception and balance parameters, resulting in at least 28 participants per group. Outcome parameters include patient-reported outcome measures (EQ-5D-5L, Tegner Activity Scale, Knee Injury and Osteoarthritis Outcome Score (KOOS), International Knee Documentation Committee and ACL-Return to Sports Injury Scale), socio-economic parameters, anterior tibial translation, range of motion and functional-biomechanical data of the lower extremities. Functional–biomechanical parameters include proprioception, isokinetic muscle strength, single-leg balance, walking, running and single-leg hops with additional lower extremity 3D joint kinematics and kinetics and muscle activity. These parameters will be compared between limbs in patients, between groups and to the current literature.

**Ethics and dissemination** The results of this study will be disseminated through peer-reviewed publications and presentations at national and international conferences. Ethical approval was obtained by the regional ethics board (Ethics Committee Northwest Switzerland EKNZ 2020–00551), and the study is registered at clinicaltrials.gov. Trial registration number NCT04429165.

## Strengths and limitations of this study

- Comprehensive analysis of clinical, socioeconomic, functional and biomechanical outcomes and the relationship among these outcomes.
- Non-randomised retrospective comparative study with prospective data collection with three arms as basis for designing future randomised clinical trials.
- Age-matched and sex-matched groups in each arm.
- Standardised instructions for rehabilitation and retrospective documentation of rehabilitation programme.
- No prospective functional–biomechanical data or postoperative MRI imaging.

## INTRODUCTION

Rupture of the anterior cruciate ligament (ACL) is one of the most common injuries of the knee and may cause pain, instability, significant limitations in activities of daily living as well as early onset of osteoarthritis.[1] Recent studies suggested that active patients may benefit from surgical treatment, leading to significantly greater objective tibiofemoral stability, lower likelihood of meniscal tears and osteoarthritis and earlier return to work and sport activities.[2 3]

While arthroscopic ACL reconstruction (ACL-R) using autologous grafts is still considered the gold-standard surgical treatment,[4] the rapid evolution of arthroscopic techniques and devices in recent years has resurrected the interest in primary repair of proximal ACL ruptures, where the ligament is preserved by suturing with or without reinforcement.[5 6] For instance, Mackay *et al* introduced a synthetic brace meant as secondary stabiliser of the primary ACL repair, thus stimulating and ensuring the healing of the ligament.[7] Advantages of primary ACL repair compared with traditional gold-standard ACL-R using autografts include shorter surgery time, a minimally invasive approach with smaller bone tunnels, no donor site morbidity (ie, abdication of graft harvesting) and (if necessary) less complicated revision surgery.[8] Furthermore, preservation of the native ligament presumably preserves nerve endings, blood supply and proprioception.[9]

According to Yosmaoglu *et al*,[10] not only mechanical but also neuromuscular stability—which depends on an intact proprioception—determine the successful outcome of ACL surgery. However, proprioception and joint position sense are not fully restored after ACL-R and this particular deficit might increase the risk of further injuries to the knee joint[11] and potentially the premature development of tibiofemoral osteoarthritis.[12] Although it has been reported that progressive rehabilitation alone after ACL injury may lead to good clinical and functional outcomes,[13 14] preserving the native ACL with its nerve endings and vessels may also preserve proprioception.[15] This may be beneficial regarding the postoperative rehabilitation, postoperative strength, return to work and sports as well as long-term joint degeneration. However, to date, supporting evidence for these presumed advantages are scarce.

One of the recent developments in repair for proximal ACL ruptures and augmentation is the InternalBrace (Arthrex, Naples, Florida). Besides the above-stated major advantages of primary ACL repair, the additional augmentation with the InternalBrace has the potential to reduce the failure rate as recently shown by Jonkergouw *et al*.[16] At our centre, we started treating patients with proximal ruptures of the ACL with direct repair and InternalBrace augmentation in May 2016. To date, many studies have been published on biomechanics after ACL-R as summarised in several systematic reviews,[17–23] yet only few studies have reported on gait analysis (with a simple marker model) and functional hop testing in patients after ACL repair and dynamic intraligamentary stabilisation (DIS) (Ligamys).[24 25] While Leister *et al*[26] reported comparable single leg hop performance after primary ACL repair with InternalBrace augmentation and after ACL-R and the few available reviews and case–control studies on small numbers of patients have shown promising results regarding clinical outcomes,[27–32] to date, comprehensive clinical, socioeconomic and functional–biomechanical analyses after this procedure are scarce.

We designed an experimental protocol for a detailed clinical, socioeconomic and functional-biomechanical evaluation of patients treated with InternalBrace compared with the gold-standard ACL-R (using autologous hamstring tendons) and to a healthy (uninjured) age-matched and sex-matched control group. The comprehensive approach of our study will provide new important insights into the functional state of the knee after ACL repair and InternalBrace augmentation as well as after ACL-R. Hence, the results will contribute to understanding potential functional and physiological benefits of primary ACL repair and making recommendations for an optimal and cost-effective treatment strategy for future patients (including optimised patient selection) as well as for optimising the rehabilitation of patients after ACL repair or ACL-R.

## METHODS AND ANALYSIS

### Objectives and hypothesis

The primary objective of this study is to investigate bilateral functional–biomechanical outcomes (proprioception, muscle strength, single leg balance, walking, running and single leg hop performance including 3D joint kinematics, kinetics, muscle activity and plantar pressure), which have been reported to have an important impact on postoperative outcomes after ACL-R as well as after ACL repair and DIS.[24 33 34] According to Janssen *et al*,[35] the remodelling of hamstring grafts used for ACL-R is completed at the earliest 2 years after surgery. Hence, only then function in daily life and sport activities should be assessed to obtain meaningful data regarding long-term function. Consequently, these parameters will be assessed bilaterally in patients 2 years after ACL repair and InternalBrace augmentation, in patients 2 years after ACL-R and healthy controls and compared within patients (side-to-side differences: operated vs contralateral side) and between the two patient groups and healthy control subjects. ‘Comparable’ was defined as not being statistically significantly different and a difference from comparator <10%.

Hypothesis 1: functional–biomechanical outcomes (in particular: knee range of motion, static anterior tibia translation, knee proprioception, isokinetic muscle strength, single leg balance, single leg hop performance, joint kinematics and kinetics during walking, running and single leg hops; SLH) in the operated knee 2 years after primary ACL repair and InternalBrace augmentations are

1.1: comparable to the contralateral (healthy) knee.

1.2: comparable or superior to those in knees after ACL-R.

1.3: comparable to those in knees of healthy controls.

Hypothesis 2: side-to-side differences (operated vs contralateral side) in functional–biomechanical outcomes (see above) in patients 2 years after ACL repair and InternalBrace augmentations are

2.1: comparable to or smaller than those in patients 2 years after ACL-R.

2.2: comparable to those in healthy subjects.

The secondary objective is to compare patient-reported outcome measures (PROMs) assessed as EQ 5D-5L, Numeric Pain Rating Scale at rest/at daily activities/during sport, Tegner Activity Score, KOOS, International Knee Documentation Committee (IKDC), ACL-Return to Sports Injury Scale (ACL-RSI) as well as socioeconomic parameters (duration of total and/or partial disability to work, duration and number of physio and training therapy sessions) between all groups.[36–40] Furthermore, we aim to investigate the relationship between PROMs and functional–biomechanical outcomes (see above).

Hypothesis 3: PROMs and socioeconomic outcome in patients 2 years after primary ACL repair and InternalBrace augmentation are comparable to or better than in patients 2 years after primary ACL-R.

Hypothesis 4: patients treated with ACL repair and InternalBrace augmentation have fewer risk factors for early onset of osteoarthritis (eg, postoperative quadriceps weakness or persisting instability) compared with patients after ACL-R.

Hypothesis 5: patients 2 years after surgery (independent of surgical approach) with better clinical outcome (PROMS) show better functional–biomechanical outcomes.

## Study design

This is a non-randomised single-centre retrospective comparative study with prospective data collection with three arms.

## Participants

Patients treated at our centre with either ACL repair and InternalBrace augmentation or with ACL-R using an autologous hamstring tendon will be contacted 2 years (±2 months) postoperatively via phone, mail or e-mail. Knee-healthy, sex-matched and age-matched (maximum ±2 years) subjects will be recruited as controls from the local community (via online platforms and flyers). This is a non-randomised study: all patients presenting initially with ACL ruptures in our outpatient clinic are continuously screened. Patients with proximal ACL ruptures (fulfilling the inclusion criteria (below) and without other indication for surgery (eg, concomitant meniscal lesion)) are free to choose between ACL repair and InternalBrace augmentation, ACL-R or non-operative treatment. Likewise, patients with all other locations of ACL injuries have the choice between ACL-R and non-operative treatment. The aim is to include at least 30 participants per group (ACL repair and InternalBrace, ACL-R, controls; see sample size estimation below). Detailed inclusion and exclusion criteria are presented in table 1. This study was started in May 2019 with an anticipated last-patient-in date in April 2022.

**Table 1** Inclusion and exclusion criteria

| | Patients | Controls |
|---|---|---|
| **Inclusion criteria** | 2 years since<br>► *ACL repair and InternalBrace* for proximal ACL ruptures or<br>► *ACL reconstruction* with autologous hamstring tendon | ► No previous injury of lower extremity, menisci or ligament apparatus of the knee |
| **Exclusion criteria** | ► Concomitant injury to index ACL injury of more than one of the collateral ligaments or the posterior cruciate ligament<br>► Previous injury or surgical treatment of the injured leg within the past 6 months<br>► Previous surgical treatment of the contralateral leg<br>► Age <18 and>60 years<br>► Body mass index >35 kg/m$^2$<br>► High-level recreational or professional athletes<br>► Neuromuscular diseases or pathologies that affect lower limb/knee movement or mobility<br>► Inability to give or no informed consent | |

ACL, anterior cruciate ligament.

## Surgical procedures

### ACL repair and InternalBrace augmentation

Surgical repair and InternalBrace augmentation are performed within 3 weeks after sustaining a proximal ACL tear (Sherman classification I and II).[41] In a first step, the torn ACL is proximally grasped with two sutures (eg, FiberLink, Arthrex, Naples, Florida, USA). By using conventional tibial and femoral ACL targeting devices, 4.5 mm drill holes are then placed into the tibial and femoral footprints. The two fibres suturing the ACL are passed through the femoral tunnel, so that the torn ligament attaches at its femoral footprint. Via a transtibial shuttle suture, a FiberTape (ie, the InternalBrace) is applied to the native ACL for reinforcement (figure 1). Femoral fixation is performed using a flip button (eg, Rigidloop, DePuy Synthes, Mitek Sports Medicine, Raynham, Massachusetts, USA), and the two ACL repair sutures are firmly tied to the button. Distally, the FiberTape is fixed to the tibia by screw or button fixation (eg, EndoTack (Karl Storz SE and Co. KG, Tuttlingen, Germany)). Since the native ACL can be preserved in this procedure and no autologous tendons have to be harvested, hamstring and quadriceps muscle function are not affected.

### ACL reconstruction

Reconstruction surgery is performed by using an autologous hamstring tendon (semitendinosus and/or gracilis)

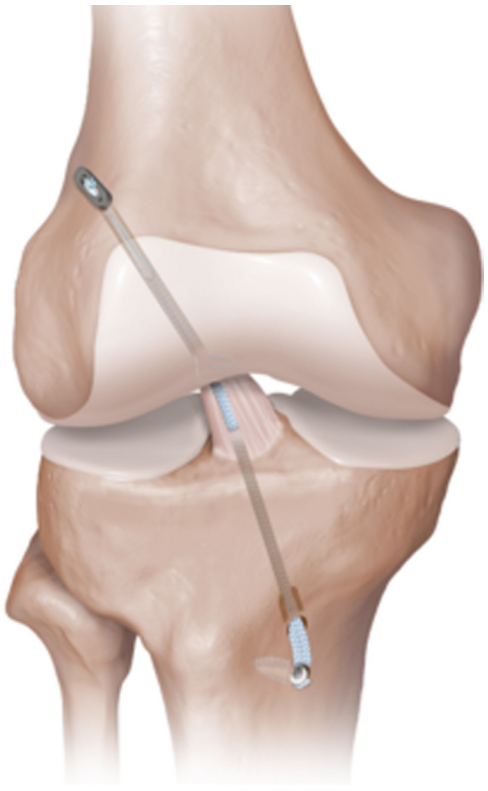

**Figure 1** Schematic representation of ACL repair and InternalBrace augmentation (with kind permission from Arthrex). ACL, anterior cruciate ligament.

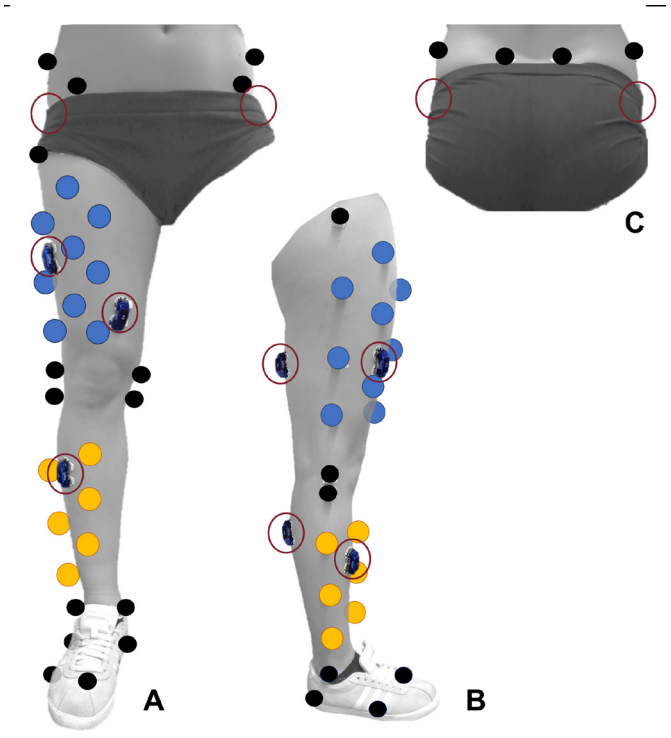


**Figure 2** Electromyographic electrodes (red circles; electrodes on gluteus medius under the shorts) and marker placement for 3D motion analysis (black: anatomical marker; blue: thigh cluster marker; yellow: shank cluster marker) in ventral (A), sagittal (B) and dorsal (C) view.

graft. Drill holes with diameters corresponding to the size of a four-stranded graft are placed into the femoral and tibial footprints. Femoral fixation is realised by using a flip button (eg, Rigidloop, DePuy Synthes, Mitek Sports Medicine, Raynham, Massachusetts, USA), and tibial fixation is performed with an interference screw (eg, MILAGRO DePuy Synthes, Mitek Sports Medicine, Raynham, Massachusetts, USA).

### Postoperative rehabilitation

For both surgical procedures (ACL repair and ACL-R), the same initial rehabilitation protocol is applied. Patients are limited to partial weight-bearing (touch-toe, 10–15 kg) and flexion to 90° using a knee brace for 6 weeks. Full weight bearing and beginning of strength and proprioceptive training are advised in weeks 7–12 followed by a guided 3-month strength training (medical training therapy). Subsequently, rehabilitation is continued according to patient need. At the time of assessment, patients will be asked about the total duration and number of sessions of physiotherapy and training therapy.

## EXPERIMENTAL PROTOCOL

The complete assessment (duration of approximately 3 hours) will be performed at the Functional Biomechanics Laboratory at the University Hospital Basel (Switzerland). Written informed consent will be obtained before participants complete questionnaires regarding their health, activity level and knee function including pain, symptoms and confidence. For the functional–biomechanical assessment, surface electrodes will be placed on the participants' lower extremities (figure 2), followed by knee proprioception and muscle strength measurements. Reflective markers will be placed (figure 2) for subsequent examination of balance, gait and jumping tasks, for which participants will wear their own footwear. The detailed experimental protocol is illustrated in figure 3.

### Acquisition of outcome parameters

#### Clinical assessment

##### *Patient-reported outcome measures*

To assess overall health and knee-related symptoms, pain, functionality as well as everyday ability and activity level, patients will be asked to complete the following questionnaires: EQ-5D-5L,[39] Tegner Activity Scale,[40] KOOS,[38] IKDC[37] and ACL-RSI.[36] These clinical scores will be calculated using their corresponding analysis tools.

##### *Socioeconomic outcomes*

Duration of temporary partial or total disability to work, number of physiotherapy and training therapy sessions and length of hospital stay will be recorded for each patient.

##### *Clinical examination*

Patients' age, sex, date of trauma, injured side and dominant limb as well as knee pain at rest, during activities of

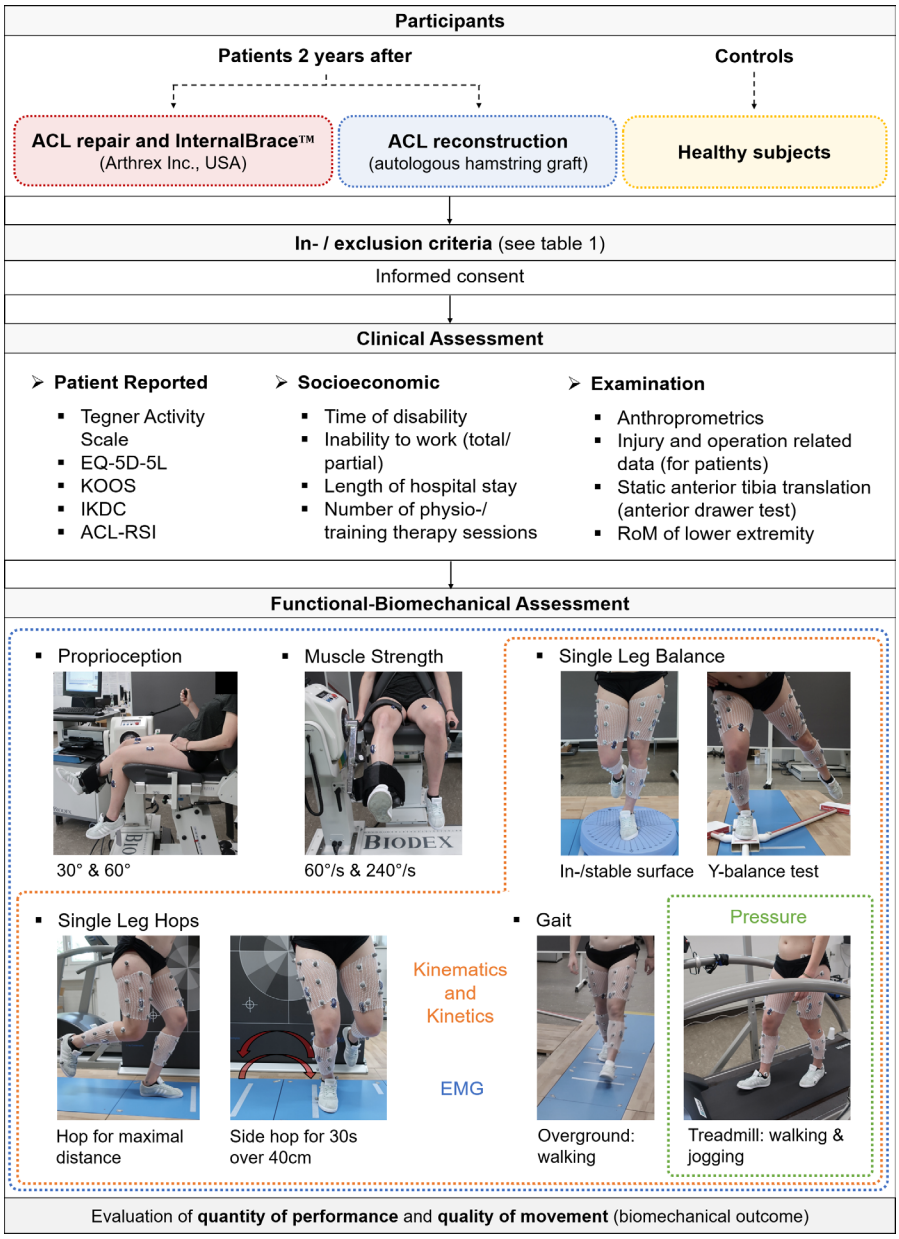


**Figure 3** Study protocol and clinical and functional-biomechanical assessments. All assessments will be made in a single session for each participant. ACL, anterior cruciate ligament; ACL-RSI, ACL-Return to Sports Injury Scale; EMG, electromyography; EQ-5D-5L, EuroQol Questionnaire; KOOS, Knee Injury and Osteoarthritis Outcome Score; IKDC, International Knee Documentation Committee; RoM, range of motion.

daily living and sports, will be recorded. Surgical details or concomitant injuries will be extracted from patient records. Static knee laxity in anterior–posterior translation (drawer test, knee flexion of 20–30°) will be assessed using the Rolimeter[42] (Aircast Europe GmbH, Neubeuern, Germany), and range of motion of lower extremities will be assessed using a goniometer.

### Functional–biomechanical assessment

Patients will first warm-up on a treadmill while walking at a self-selected speed for 5 min. After randomisation to determine the leg to be tested first in each assessment, the following functional–biomechanical assessments will be performed.

#### *Knee proprioception*

Proprioception will be measured bilaterally with a dynamometer (Biodex Medical Systems, Shirley, New York, USA) using an active–active joint position sense test protocol.[43] The participants will sit on the dynamometer with knee and hip flexed at 90° and 70°, respectively (figure 3). Starting from this position, participants will be asked to extend their leg until they are stopped by the dynamometer at the determined target knee angle, to remember this position within the following 5 s and to return their leg to the starting position. Participants will then be asked to reproduce the previously memorised leg position and confirm it by pushing a button held in their

hand.[3 4] This procedure will be repeated three times for the target knee flexion angles of 60° and 30°. The deviation between the target and the reproduced knee flexion angle will be used for further analysis (table 2).

### Isokinetic muscle strength

Isokinetic muscle strength will be measured using the same dynamometer. Congruency of the axes of rotation of the dynamometer and the knee joint (femoral transeicondylar line) will be checked, hip flexion will be set to 85° and the distal pad of the dynamometer arm will be placed proximal to the malleoli with a constant length of the dynamometer arm for both legs. To restrict movements to the knee only, the upper body and the thigh of the tested leg will be fixed with straps (figure 3). Participants will be instructed to perform maximum knee flexion and maximum knee extension actively and as quickly and powerfully as possible. Two trials with an angular velocity of 60°/s (four repetitions) will be followed by one trial with a velocity of 240°/s (15 repetitions)[44] with 30 s rest between trials. For familiarisation, three to four full knee flexion and extension movements with submaximal intensity will be performed prior to testing. Maximum torques will be recorded for each direction of movement and leg, normalised to body weight and also used for calculating the hamstrings-to-quadriceps ratio (table 2).

### Single leg balance

Postural stability will be determined by a 30 s single leg stance on a stable respective unstable surface and by the Y-balance test on a force plate with hands placed at the hips.

Single leg stance tests will be performed for each leg, and participants will be instructed to flex and lift their contralateral leg and to hold this position. Variability of movement in the horizontal plane and the length, velocity and area of the centre of pressure line will be calculated for further analysis (table 2).[45 46]

For the Y-balance test, participants will perform four trials (one trial includes all directions in the order: anterior, posteromedial, posterolateral). They will be instructed to stand with the test leg on the middle box of the test device (toes on the red line, start position), to push the boxes on the rods as far away as possible with the other leg and hold the maximum position for at least 1 s before returning to the start position and proceeding with the next direction (figure 3).[47] A maximum of two additional trials in each direction will be allowed if no valid trial can be achieved (eg, because of weight bearing on the movable boxes or the ground or lifting hands from the hip or the test foot from the middle box). The maximum distances in each direction will be normalised to the participant's leg length (table 2).

### Gait: walking and jogging

Study participants will be asked to walk at a self-selected walking speed back and forth on the walkway and for 2 min on the treadmill. Additionally, participants will be

**Table 2** Outcome parameters

| Parameter | Unit |
|---|---|
| ***Clinical*** | |
| *PROMs* | |
| Pain | |
| At rest | 0–10 points |
| During activities of daily living | 0–10 points |
| During sports | 0–10 points |
| Health state | 0–1 point |
| Activity level | |
| Prior to injury | 0–10 points |
| 2 years postoperative | 0–10 points |
| Knee function | |
| Symptoms | 0–100 points |
| Pain | 0–100 points |
| During activities of daily living | 0–100 points |
| During sports | 0–100 points |
| Related to quality of life | 0–100 points |
| Overall knee function | 0–100 points |
| Knee confidence | 0%–100% |
| *Socioeconomic* | |
| Work | |
| Duration of total disability | weeks |
| Duration of partial disability | weeks |
| Physio- and training therapy duration | weeks |
| Number of sessions | N |
| *Clinical examination* | |
| Anterior tibial translation | mm |
| ROM of lower extremity (ankle, knee, hip) | ° |
| **Functional biomechanical** | |
| *Knee proprioception* | |
| Knee angular deviation | |
| At 30° knee flexion | ° |
| At 60° knee flexion | ° |
| *Isokinetic muscle strength* | |
| Maximum torque | |
| Knee extensors 60°/s | Nm/kg |
| Knee flexors 60°/s | Nm/kg |
| Knee extensors 240°/s | Nm/kg |
| Knee flexors 240°/s | Nm/kg |
| LSI | % |
| Hamstrings-to-quadriceps ratio<br>EMG | %<br>% |
| *Single leg balance* | |
| Stance on stable/instable surface | |
| Centre of pressure | |

Continued

**Table 2** Continued

| Parameter | Unit |
|---|---|
| Path length | mm |
| Velocity | m/s |
| Area | $cm^2$ |
| LSI | % |
| Kinematics and kinetics | °; N/kg; Nm/kg* |
| EMG | % |
| Y-Balance | |
| Maximum distance | |
| Anterior | m |
| Posteromedial | m |
| Posterolateral | m |
| Leg length-related distance | |
| Anterior | % leg length |
| Posteromedial | % leg length |
| Posterolateral | % leg length |
| All directions | % leg length |
| LSI | % |
| Kinematics and kinetics | °; N/kg; Nm/kg* |
| EMG | % |
| *Gait* | |
| Walking | |
| Kinematics and kinetics | |
| At self-selected speed | °; N/kg; Nm/kg* |
| At 4.3 km/h | °; N/kg; Nm/kg* |
| EMG | |
| At self-selected speed | % |
| At 4.3 km/h | % |
| Running | |
| Kinematics | N/kg* |
| At self-selected speed | ° |
| At 8.0 km/h | ° |
| EMG | |
| At self-selected speed | % |
| At 8.0 km/h | % |
| Plantar pressure | |
| At self-selected speed | $N/mm^2$ |
| At 8.0 km/h | $N/mm^2$ |
| *Single leg hops* | |
| For maximal distance | |
| Maximum distance | m |
| Normalised distance | % body height |
| LSI | % |
| Kinematics and kinetics | °; N/kg; Nm/kg* |
| EMG | % |
| Side to side (in 30 s over 40 cm) | |
| Maximum number | N |
| LSI | % |
| Kinematics and kinetics | °; N/kg; Nm/kg* |
| EMG | % |

*Angles in °; moments in Nm/kg; ground reaction force in N/kg.
EMG, electromyography; LSI, limb symmetry index; MVC, maximum voluntary contraction; ROM, range of motion.

asked to walk at a speed of 1.2 m/s and to run at a self-selected running speed and a running speed of 2.2 m/s on the treadmill (figure 3).

### *Single leg hops*

Hop performance of each leg will be determined by SLH of maximum distance onto a force plate and side hops (SH) onto two force plates (figure 3). To reduce injury risk, a submaximal pretest must be passed before: forward (for SLH) and side-to-side (medial and lateral direction for SH) single leg hop over 40 cm with hands placed on the hip and controlled single leg landing with sufficient knee stability according to Keller *et al*.[48] For SLH, participants will be instructed to jump with one leg as far as possible (using arms freely), so that a stable single leg landing position (for at least 2 s) on the same leg will be accomplished (valid trial). If less than three valid trials are achieved within four repetitions or if the patient feels that maximum distance is not reached, a maximum of two additional trials per leg will be granted. For the SH test, participants will be asked to jump as many times as possible sideways back and forth over a distance of 40 cm within 30 s on the same leg with arms placed at the hips. The tests on the first leg will be followed by a recovery break of 3 min. Only jumps with a distance of at least 40 cm and balanced single leg landing will be considered as valid. The maximum distance (for SLH) and the number of valid hops (for SH) will be used for further analysis (table 2).

### *Biomechanical measurements*

Instrumented 3D movement analysis will be conducted by simultaneously collecting synchronised joint kinematic and kinetic, ground reaction force and electromyographic (EMG) data during single leg balance, walking, running and single leg hop tests and additionally plantar pressure during walking and jogging on the treadmill. Moreover, EMG will also be recorded during proprioception and isokinetic muscle strength tests (figure 3).

Kinematics and kinetics of the lower extremities will be collected using a 10-camera Vicon system (Oxford, UK; sampling rate 240 Hz), a walkway with two embedded force plates (Kistler AG, Winterthur, Switzerland; sampling frequency 2400 Hz) and reflective markers attached to defined anatomical locations bilaterally on the pelvis and legs (anterior superior iliac spine (ASIS) and posterior

superior iliac spine (PSIS), iliac crest, trochanter major, and medial and lateral malleoli, femoral and tibial epicondyles) and as a cluster on the thigh (nine markers) and shank (six markers) (figure 2). 3D joint kinematics (rotation and translation) and kinetics will be calculated from the marker data using the point cluster technique.[49–53]

Muscle activity will be assessed using a 12-channel wireless surface EMG system (myon AG, Schwarzenberg, Switzerland; sampling frequency 2400 Hz) with bipolar surface electrodes, which will be attached bilaterally to the glutaeus medius, vastus medialis and lateralis, semitendinosus, tibialis anterior and gastrocnemius medialis muscles according to the SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) recommendations.[54] The intensity of the filtered and full wave-rectified EMG signals will be normalised to those from the maximum voluntary contraction of isokinetic muscle strength test and from normal walking, and an analysis of muscles synergies is planned.

Plantar pressure data will be collected on a treadmill with integrated pressure plate (h/p/cosmos, Zebris FDM-T, Isny, Germany; sampling frequency 120 Hz; 7168 sensors; area: 1.5 * 0.5 m; range: 1–120 N/cm$^2$; precision: 1–120 N/cm$^2$±5%), and mean and maximum pressure and vertical ground reaction force will be calculated.

### Statistics and determination of sample size

This study is designed as a non-inferiority study with three arms. The sample size estimation was based on a study by Clark *et al*[55] providing information on within-subject differences (p values and effect sizes, although separated by sex) for eight balance parameters. The sex differences reported by Clark *et al*[55] provide an estimate of the relevant effect sizes in order to show a comparability between the affected and healthy leg. Another key measurement parameter in our study is proprioception (joint position sense) at 60° and 30° and the corresponding side differences. Kalimuthu *et al*[56] have shown results for this parameter at 60°. From the published results (p values and Z-scores), an average of 1.7 and a SD of 5.9 for individual differences in joint position sense can be concluded. Therefore, an SE of 1.08 in our study with 30 patients can be expected, what is relatively high when determining comparability. However, this study assessed patients after ACL rupture and, hence, a much higher homogeneity 2 years after surgical treatment is likely why an SE of 0.3 is expected. The clinical relevance of differences in the IKDC Score is assumed to be 10% and the clinical relevance of side differences in joint angles as 5° and 10% in torques, respectively.

These assumptions and our preliminary results and data reported in the literature[19 57 58] resulted in a calculated sample size of 28 subjects to detect a statistically significant difference with a power of 80% and a significance level of 5%. With an estimated dropout rate of 25%, we should be able to achieve the necessary sample size with the patients recorded in our system (60 patients * 25% dropout rate=45 subjects). In the event that both methods are equally efficient, the difference between the methods would be positive with 50% probability and negative with 50% probability, regardless of the sample size. As lowest limit of the CI for determining non-inferiority, we select parameters that correspond to a clinical relevance.

### Planned analysis

The primary endpoints are the biomechanical–functional outcomes measured as joint position sense, isokinetic muscle strength and balance tests, walking, running, SLH tests and biomechanical movement analysis including kinematics and kinetics, muscle activity and plantar pressure. For balance, gait and hop tests, the quantity of performance and the quality of movement (kinematics and kinetics between tibia and femur, muscle activity) will be analysed.

Secondary endpoints are the outcomes of clinical assessment 2 years after ACL repair and InternalBrace augmentation or after ACL-R, including socioeconomic parameters and return to work and activity. According to Keller *et al*,[48] functional single leg balance and hop tests will be used to determine the ability 'return to activity'.

The population distribution of the various parameters (table 2) will be visualised, described and averages with 95% CIs will be listed. For bilaterally measured parameters, the differences between the operated and the healthy contralateral leg of patients and between the operated legs of patients and the healthy legs of controls will be analysed and the limb symmetry index patients: operated/contralateral*100; controls: lower/higher*100) will be calculated in each group. These side-to-side differences in all groups will be compared. Observed distributions of all other parameters will be compared between groups. For all differences, mean values will be presented with 95% CIs.

We will describe correlations between all outcome parameters (table 2) in scatterplots and with correlation coefficients. All analyses will also be carried out stratified after the occurrence of a revision surgery. The significance level for all statistical tests will be set a priori to 0.05.

### Patient and public involvement

There was no patient or public involvement in the development of research questions and/or the study design.

## ETHICS AND DISSEMINATION

The testing protocol has been approved by the regional ethics board (Ethics Committee Northwest Switzerland EKNZ 2020–00551) and is registered at clinicaltrials.gov. Written informed consent will be obtained by all participants prior to participation. Each patient can decide at any time point to withdraw from the study. The results of this study will be disseminated and presented at national and international conferences and published in peer-reviewed journals.

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