An obstacle clearance test for evaluating sensorimotor control after anterior cruciate ligament injury: A kinematic analysis

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Abstract
Sensorimotor deficits, particularly proprioceptive, are often reported following rupture of the anterior cruciate ligament (ACL). High secondary injury rates and long-term negative consequences suggest that these deficits are not properly identified using current assessment methods. We explored a novel obstacle clearance test to evaluate sensorimotor control in individuals following ACL reconstruction (ACLR) and rehabilitation. Thirty-seven post-ACLR individuals, 23 nonathletic asymptomatic controls (CTRL), and 18 elite athletes stepped over a hurdle-shaped obstacle, downward vision occluded, aiming for minimal clearance. Kinematic outcomes (3D motion capture) for the leading and trailing legs, for two unpredictably presented obstacle heights, were categorized into Accuracy: vertical foot clearance and minimal distance from the obstacle; Variability: end-point and hip/knee trajectory; and Symmetry: trunk/hip/knee crossing angles, hip–knee–ankle movement, and velocity curves. Accuracy was worse for CTRL compared with both other groups. ACLR had less leading and trailing vertical foot clearance with their injured compared with their noninjured leg. ACLR and athletes had less crossing knee flexion in their injured/nondominant legs compared with their contralateral leg, both leading and trailing. ACLR showed greater trunk flexion when crossing with their injured leg, both leading and trailing. For the leading leg, ACLR showed greater asymmetry for the hip–knee–ankle velocity curve compared with elite athletes. Trailing leg trajectory variability was lower for ACLR compared with CTRL and athletes for higher obstacles. Clinical significance: Sensorimotor deficits in individuals post-ACLR were reflected by greater asymmetry and less variable (more stereotypical) trajectories rather than limb positioning ability. This consideration should be addressed in clinical evaluations.

KEYWORDS
ACL, proprioception, sensorimotor deficits, symmetry, variability
1 | BACKGROUND

Anterior cruciate ligament (ACL) tear is a prevalent sport-related injury and often results in long-term consequences, such as reduced knee function, weakened knee muscle strength, and deficient postural control. Furthermore, ACL-reconstructed individuals have been reported to have a high rate of graft rupture as well as contralateral ACL injury. Postinjury sensorimotor deficits may underlie this tendency, originating in damage to proprioceptors within the ligament, and assumed to persist despite extensive rehabilitation.

Human motor activity involves the integration of multiple sensory afferents within an elaborate neural network for the planning and optimal execution of voluntary motor commands. Such integration occurs mostly within the central nervous system (CNS) and is generally referred to as sensorimotor control. Due to the abundance of neural components and the complex nature of the body–environment interaction in constantly changing conditions, the study of sensorimotor control is a complex endeavor. Clinically, defining the sensorimotor control of an individual as deficient often refers to symptoms of insufficiency, attributed to one or more of the different sensory or neuromuscular components. Proprioception, defined broadly as the ability to sense the position and movement of one’s own body, is considered a key element in sensorimotor control. Two meta-analyses demonstrated proprioceptive deficits following an ACL injury, compared with either the contralateral side or to noninjured individuals. In contrast, an additional systematic review, which included studies with an average time after surgery of 20 months, concluded that there was no evidence of proprioceptive deficits after ACL reconstruction, suggesting that either assessment methods are not sensitive enough or that proprioception, in fact, improves over time. Regardless, initially altered sensory input from the knee, along with injury-associated inflammation, joint instability, and movement compensations are suggested to lead to postinjury sensorimotor compensations that may not be sufficient for adequate motor control.

Proprioception cannot be directly assessed, though various methods have been implemented to target different components encompassed within the term “proprioceptive ability.” This is mainly done through movement detection and angle/force reproduction tasks. These tasks often require custom-built devices and/or expensive equipment and are thus impractical in the clinics where such assessment tools are virtually lacking. Furthermore, the use of functional assessments is more frequent in clinical settings. Generally, performances in different functional tests (e.g., squat, vertical hop, and hop for distance) are deemed central to the decision of whether or not an individual is eligible to return to preinjury activity level/sports. However, the high rate of secondary injury suggests that such tests may not be sufficient to identify those with sensorimotor deficiencies, possibly due to coarse outcome variables that should otherwise be broken down into detailed movement characteristics rather than summed to overall functional scores.

Another approach for addressing sensorimotor control involves context-conditioned variability in the execution of voluntary movements. The sensorimotor system is rarely constrained to a single solution of a motor task but rather utilizes a variety of context-specific movement patterns. In other words, multijoint task-specific coordination solutions are part of a healthy repertoire available to move an end-point of a limb to the same location despite environmental or sensory constraints, various body configurations, and different task requirements. Such repertoire, referred to as motor abundance, is considered necessary for optimal control of movements performed in various contexts and under changing environmental demands. In addition, less movement variability (i.e., more stereotypical movements) has been previously reported in ACL-injured individuals during postural control tasks, in particular in those who suffered more than one injury.

The obstacle clearance (OC) paradigm has been previously implemented as a means of investigating the involvement of vision and proprioception within a common locomotion task. It features a participant stepping over an obstacle while maintaining only a minimal margin during crossing. This task requires both identifications of the obstacle’s position in space and well-coordinated limb movements to step over the obstacle without hitting it with either leg. This article presents a novel attempt to implement an OC paradigm among individuals who had suffered an ACL-injury, targeting their reliance on proprioception by means of standard OC outcomes (i.e., distance from the obstacle), while evaluating the sensorimotor control throughout the task by also addressing movement variability and between leg symmetry. We compared the performance of individuals following ACL-injury, who had undergone reconstruction (ACLR) and rehabilitation, to that of asymptomatic controls (CTRL) and elite athletes (ATH), the latter assumed to have superior sensorimotor control and body awareness than the less-active CTRL group. The use of elite athletes also provided a certain proxy to the preinjury state of ACLR as most of them were highly sports active before their injury. We hypothesized that ACLR would perform the OC test with larger margins (i.e., longer distances from the obstacle) and show greater leg asymmetry. Variability of performance was expected to be greater for ACLR in terms of endpoint consistency, yet more stereotypical movement patterns were also hypothesized, reflected as less trajectory variability.

2 | METHODS

2.1 | Participants

In the current case–control study (level of evidence: III), we included 37 individuals following ACLR and two reference groups: 23 age- and sex-matched asymptomatic controls and 18 elite athletes (Table 1). The project was approved by the Regional Ethical Review Board and all participants provided written informed consent. ACLR participants were recruited from an orthopedic clinic at Norrlands University Hospital, Umeå, Sweden and from a private clinic (Sports Medicine Umeå, Sweden). Inclusion criteria for ACLR were 17–34 years of age, with unilateral ACL injury (time from injury <10 years) treated with surgical reconstruction using a hamstring autograft (standard practice nationally). Participants had to have completed...
TABLE 1  Participant characteristics, mean (SD) unless otherwise stated

|                           | ACLR (N = 37) | CTRL (N = 23) | ATH (N = 18) | p value |
|---------------------------|--------------|---------------|-------------|---------|
| Male/female (N)           | 9/28         | 3/20          | 2/16        | NS      |
| Age (years)               | 23.7 (4.4)   | 23.5 (3.4)    | 20.8 (2.9)  | 0.03    |
| Body height (cm)          | 170.8 (6.6)  | 169.6 (7.0)   | 170.6 (7.5) | NS      |
| Body mass (kg)            | 69.3 (9.8)   | 64.4 (7.1)    | 63.3 (7.7)  | NS      |
| BMI (kg/m²)               | 23.7 (2.5)   | 22.4 (2.2)    | 21.7 (1.3)  | 0.01*   |
| Months after surgery [median (range)] | 12.8 (7 – 129) | – | – | – |
| Tegner¹, preinjury [median (range)] | 8 (3 – 10) | – | – | – |
| Tegner, current           | 7 (3 – 9)*   | 4 (1–6)**    | 8 (8 – 9)   | <0.01** |

Abbreviations: ACLR, anterior cruciate ligament reconstructed; ATH, elite athletes; BMI, body mass index; CTRL, asymptomatic non-athletic controls. 
*Statistically significant: ACLR–ATH. 
**Statistically significant: CTRL compared with all groups.

2.2  Apparatus and data processing

Kinematic data were collected using an eight-camera 3D motion capture system (Oqus, Qualisys AB; 240 Hz). Reflective passive spherical markers (n = 44) were attached bilaterally with double-sided adhesive tape at anatomical landmarks (for details, see Supporting Information Material 1). Marker positions were tracked in Qualisys track manager (QTM, version 2.11, Qualisys AB). Data were then exported to Visual 3D (C-Motion Inc.) and filtered using a zero-lag fourth-order low-pass Butterworth digital filter with a cutoff frequency of 6 Hz. A body model consisting of eight rigid segments (trunk, pelvis, thighs, shanks, and feet) was constructed.

Trunk, hip, and knee angles were calculated for both the leading and trailing legs, based on the orientation of the distal segment coordinate system in relation to the proximal segment coordinate system, using a Cardan rotation sequence of X (mediolateral axis), Y (anteroposterior axis), and Z (longitudinal axis). To measure the continuous distance to the obstacle, an approximated model of the sole of the foot and shin was constructed. The model consisted of 10 line segments, based on markers of the foot and the shank, as well as on proportion estimations previously made based on the feet of 20 asymptomatic persons (detailed description in Supporting Information Material 1).

2.3  Test protocol

Participants stood in front of a resizable hurdle-shaped obstacle, placed at a standardized distance anterior to the tip of the big toe, equal to 7% of participant height (Figure 1A). This constituted an optimal distance, ensuring OC with comfortable hip and knee range of motion (ROM). Two standardized heights were used: 13% and 18% of participant height. All ratios were chosen based on pilot testing, targeting knee joint angles of 40° and 65°, respectively, corresponding to target angles frequently used in joint position sense assessments and were compatible with the ROM required to step over the obstacle. Participants were not provided any information regarding obstacle heights or how many there were. Custom-made goggles occluded downward vision, and participants were instructed to look straight forward at a red dot displayed on a TV screen at approximately eye level. Participants stood barefoot with their leading foot on a 2 cm-high platform, while the trailing foot was placed parallel on the floor. This level discrepancy was used to increase reliance on limb position sensation by creating an initial mismatch between legs and thus further challenging the trailing leg. First, the participants were asked to place and hold their foot on top of the obstacle for approximately 3 s and memorize its height. After returning to the starting position, they were asked to immediately step over the obstacle with as little clearance as possible. Arms were free to aid balance when needed. The obstacle was removed by the examiner (unbeknownst to the participant) immediately after the participant had returned to the starting position. This was done to avoid contact with the obstacle, which could have resulted in possible overcompensation during subsequent trials. All participants performed four trials for both heights for each leg (a total of 16 trials). A balanced unpredictable order was generated for each participant before testing. Intratest reliability was assessed for vertical clearance (the most commonly used outcome of such paradigms) and was good to excellent for all four test conditions (intraclass
correlation coefficient [ICC] (3,4) ≥ 0.85, 95% confidence interval [CI]: 0.78–0.90). Test–retest reliability (16.9 ± 8.6 days between tests) was also evaluated on 10 asymptomatic participants with resulting ICCs (3,2) in the range of 0.27–0.80, (95% CI: 0.00–0.95), with higher values for the low obstacle height.

2.4 | Outcome measures

For between-group comparisons, the injured legs of ACLR were compared with the nondominant legs of CTRL and ATH. Our rationale for this was that our paradigm involved open kinetic chain movements, meaning that for noninjured individuals the more adept leg was assumed to be the dominant leg (i.e., the leg used to kick a ball). Therefore, comparing the reconstructed leg of ACLR with the nondominant leg of CTRL and ATH was deemed a more stringent comparison, in line with previous research.1,2,31,31,32

1) Accuracy: I) Vertical foot clearance—the minimal vertical distance from the obstacle at the point of crossing (either heel, mid-foot, or toe crossing); II) Minimal leg distance up to crossing—the distance of the closest foot-shank segments from heel-up to the mid-foot crossing. These variables were considered to reflect proprioceptive acuity, as they reflected the error associated with reproduction of lower limb configurations, much like joint position sense paradigms.33

FIGURE 1 Experimental paradigm and outcome measures for the obstacle clearance test. (A) Participants wore goggles occluding downward vision and were instructed to cross a hurdle-shaped obstacle, with as little foot clearance as possible. 1) Leading leg was placed on a 2 cm wooden platform. 2) Participants probed with the leading foot, placing it on the obstacle for approximately 3 s. 3) Leading leg returned to the start position. 4) Participant crossed the obstacle (leading leg) while the examiner removed the obstacle (unbeknownst to the participant). 5) Trailing leg crossed the obstacle. (B) Main outcome measures, calculated for both the leading and trailing legs. Each diagram features angles at mid-foot crossing and accuracy outcomes, that is, proximity to the obstacle both at the point of minimal distance (inside the frames) and minimal vertical clearance at crossing. (C) Schematics are featured as a representation of joint angles over the entire movement, used to estimate trajectory variability. End-point variability is featured as dot clusters (enlarged within left frames), representative of ankle-center positions at the point of mid-foot crossing (across 16 trials) [Color figure can be viewed at wileyonlinelibrary.com]
2) **Variability:** (I) End-point variability—the locations of each ankle center relative to the obstacle were averaged, at the point of mid-foot crossing, within each condition. Standard deviations were then calculated, with lower deviations reflecting a more consistent performance; (II) Trajectory variability—time series of hip and knee joint sagittal angles and angular velocities from heel-up to mid-foot crossing were constructed and time-normalized for each trial (%). Standard deviations were then calculated for each data point (n = 100) and averaged into four values (one for each condition). This variable quantified context-conditioned variability, whereby lower values implied a more rigid/stereotypical performance while higher values reflected greater movement flexibility and adaptability. Outcome measures are illustrated in Figure 1B.C.

3) **Symmetry:** (I) Between-leg symmetry—based on vertical foot clearance, minimal leg distance, and joint angles at the point of mid-foot crossing (hip, knee, and trunk); (II) Multijoint coordination symmetry—dissimilarity indices (DI) were calculated based on bilateral hip–knee–ankle movement and velocity profiles assessed by generalized procrustes analysis (GPA). (detailed description in Supporting Information Material 3).

### 2.5 Statistical analysis

Due to the exploratory nature of the proposed paradigm, determining an adequate sample size a priori was difficult. Based on other studies implementing an OC test, sample sizes ranged from 6 to 24 participants in healthy populations. No previous study has implemented such a paradigm among ACLR individuals. We, therefore, to achieve sufficient power, aimed for >30 ACLR individuals.

The Statistical Package for the Social Sciences software (version 25, IBM SPSS Statistics) was used for analyses. Descriptive statistics were computed for all variables in each block of trials, based on median values (due to a small number of trials per condition and to reduce the influence of extreme values) for each subject in each condition (i.e., low/high obstacle heights and injured/nondominant, noninjured/dominant leading legs). The Shapiro–Wilks test was used to assess data distribution for each outcome measure. Variables of interest were analyzed using a two-way analysis of variance (ANOVA) design. Each statistical model consisted of two within-group factors: leading leg and obstacle height (two levels each: injured/nondominant—noninjured/dominant, low–high, respectively), as well as a grouping factor (three levels: ACLR, CTRL, and ATH). Bonferroni corrections were applied for multiple comparisons. Similar models were used without a grouping factor for detecting between-leg differences for each group separately. Assumptions on the absence of outliers were met for all variables. Both variability and GPA variables failed to meet normality assumptions and were therefore log-transformed, subsequently conforming to normality and were then analyzed using the same ANOVA model. Effect-size estimates were assessed using $\eta_p^2$. Significance level was set to $p < 0.05$.

### 3 RESULTS

All groups performed the task successfully in most trials (i.e., clearing the obstacle), with a success rate of $\geq 90.8\%$ (±20.9) for the leading leg and $\geq 84.7\%$ (±18.5) for the trailing leg (full success rate results are detailed in Supporting Information Material 3).

#### 3.1 Accuracy

Significant group effects were found for the crossing margins of the trailing leg, as CTRL had greater vertical foot clearance and minimal leg distance compared with the other groups ($F (75,2) = 3.88$, $p = 0.025$, $\eta_p^2 = 0.09$; $F(75,2) = 3.34$, $p = 0.041$, $\eta_p^2 = 0.08$, respectively; Table 2), with an average of 3.3 cm difference for $\Delta_{\text{CTRL–ACLR}}$ ($p = 0.032$) in vertical foot clearance and an average of 2.4 cm difference for $\Delta_{\text{CTRL–ATH}}$ ($p = 0.047$) in minimal leg distance.

#### 3.2 Variability

There was no between-group difference in end-point variability. However, the ACLR group showed on average less trajectory variability in their trailing leg for the high obstacle compared with the asymptomatic groups (Figure 2). Significant group effects were seen for hip and knee trajectory variability ($F (75,2) = 4.42$, $p = 0.015$, $\eta_p^2 = 0.11$; $F (75,2) = 5.65$, $p = 0.005$, $\eta_p^2 = 0.13$, respectively). Post hoc comparisons showed less variability for ACLR compared with CTRL ($p = 0.025$) in hip flexion and for ACLR compared with both CTRL and ATH ($p = 0.012$, $p = 0.039$, respectively) in knee flexion. A group effect was also seen for knee angular velocity, with ACLR showing less variability ($F (75,2) = 3.48$, $p = 0.017$, $\eta_p^2 = 0.09$). Post hoc comparisons were however nonsignificant. For the lower obstacle height, both ACLR and CTRL had less variable knee flexion in their trailing noninjured/dominant leg ($p = 0.026$, $p = 0.048$, respectively) compared with their injured/nondominant leg.

#### 3.3 Symmetry

ACLR showed significantly less vertical foot clearance in their injured leg compared with the noninjured leg, both when it was leading ($F (36,1) = 9.45$, $p = 0.004$, $\eta_p^2 = 0.21$) and when it was trailing ($F (36,1) = 5.29$, $p = 0.027$, $\eta_p^2 = 0.19$). No significant between-leg differences in obstacle distances were found for the other groups (Table 2).

ACLR and ATH showed significantly less knee flexion than CTRL in the injured/nondominant leg both when it was leading ($F (36,1) = 10.56$, $p = 0.003$, $\eta_p^2 = 0.23$; $F (17,1) = 14.71$, $p = 0.001$, $\eta_p^2 = 0.46$, for ACLR and ATH, respectively) and when it was trailing ($F (34,1) = 6.66$, $p = 0.014$, $\eta_p^2 = 0.16$; $F (17,1) = 12.91$, $p = 0.002$, $\eta_p^2 = 0.43$, for ACLR and ATH, respectively). ACLR also had more hip flexion in the injured leg when it was trailing ($F (36,1) = 4.44$,
TABLE 2  Accuracy outcomes (cm), mean (SD)

|                        | Leading foot vertical clearance | Trailing foot vertical clearance | Leading leg minimal distance | Trailing leg minimal distance |
|------------------------|---------------------------------|----------------------------------|-----------------------------|-------------------------------|
|                        | Low    | High   | Low    | High   | p value (between legs) | p value (between groups) |
| Injured/nondominant leg|        |        |        |        |                     |                         |
| ACLR                   | 6.26 (2.92) | 4.94 (2.62) | 7.64 (3.78) | 5.43 (3.06) | 0.004                | NS                      |
| CTRL                   | 7.34 (3.66) | 6.52 (3.88) | 7.22 (3.27) | 5.96 (3.61) | NS                   |                         |
| ATH                    | 8.47 (4.33) | 6.54 (3.83) | 9.51 (4.78) | 7.16 (4.36) | NS                   |                         |
| Noninjured/dominant leg|        |        |        |        |                     |                         |
| ACLR                   | 10.63 (5.13) | 8.53 (5.08) | 9.67 (4.97) | 6.83 (4.85) | 0.027                | NS                      |
| CTRL                   | 14.78 (6.51) | 10.82 (5.26) | 13.42 (6.20) | 9.72 (5.07) | NS                   | 0.03 a                 |
| ATH                    | 11.63 (5.83) | 7.78 (4.29) | 9.81 (6.19) | 6.70 (4.62) | NS                   |                         |

Abbreviations: ACLR, anterior cruciate ligament reconstructed; ATH, elite athletes; CTRL, asymptomatic nonathletic controls; NS, not significant.

*p < 0.05 ACLR versus CTRL.

**p < 0.05 ATH versus CTRL.

4.1  Accuracy outcomes and proprioception

ACLR was similar to ATH in terms of both vertical clearance and minimal distance from the obstacle. Clearing the obstacle with minimal margins represented better joint positioning ability, as visual input was obscured during the task. Alternatively, participants might have placed their limbs closer than intended due to miscalculating the height of the obstacle. The first argument is however more likely as it is supported by the fact that our elite athletes, assumed to have a better limb positioning ability, were closer to the obstacle. Therefore, it seems likely that ACLR did not have noticeable functional proprioceptive deficits at this point of their clinical stage (i.e., when already returned to preinjury activity level). This is further corroborated by ACLR having even less vertical foot clearance with their injured leg as compared with the noninjured. Possibly, more robust deficits would have been observed in recently injured/operated ACLR individuals due to recent trauma and subsequent loss of ACL proprioception.7,8 We, however, did aspire to study persons at a later stage postinjury since it is predominantly for those that assessment is currently lacking.19 Reliance on hip/ankle proprioception may also have compensated for deficient knee sensory function, yet this distinction could not be made within our functional paradigm. Another possible mechanism for sensorimotor control during obstacle crossing is an overreliance on attentional strategies, such as movement timing calculation. This explanation rests on evidence from neuroimaging studies such as Baumeister et al.35 in which ACLR was reported to exhibit increased electrocortical activity in areas
related to focused attention during a joint positioning paradigm. With this, as well as ample other evidence of post-ACLR neuroplasticity,\textsuperscript{9} it is possible that proprioception was still deficient though successfully compensated for in our paradigm. Finally, all groups had lesser vertical foot clearance and shorter minimal leg distances in high-obstacle trials, both for the leading and trailing legs. This might be because hip and knee joints were closer to the limits of their ROM, thus reducing potential margins of error. In these ranges, both spindle activity\textsuperscript{36} and joint mechanoreceptor firings\textsuperscript{37} are increased, making it more likely for proprioception to play a dominant role in controlling the limb, possibly contributing to the lesser clearance distances. Conversely, with low obstacles, greater distances might be due to participants allowing for a larger margin of error to guarantee a successful crossing while receiving less proprioceptive feedback.

4.2 Variability of performance

Less trajectory variability was observed for ACLR in both hip and knee joint sagittal movements of the trailing leg compared with the other groups. This finding supports the notion of a more rigid system, characterized by more stereotypical movements and thus limited in its ability to adapt to both different task constraints, as well as unexpected perturbations.\textsuperscript{22,23,38} Furthermore, a similar finding was
previously reported by Paterno and colleagues, as a characteristic of individuals following ACLR, which later suffered a secondary injury. Conversely, since excessive variability might also reflect a failure to successfully implement an underlying motor program, in this context, decreased variability is expected when motor learning has occurred and the performance has stabilized. Indeed, previous studies have observed increased trajectory variability in ACL-injured individuals, which was interpreted as an indication of a less stable system. However, even supporters of the latter view acknowledge that the same goals are achievable by using a variety of kinematic patterns, known as motor equivalence. Finally, the concept of "optimal variability" was introduced by Stergiou and colleagues in an attempt to balance the two approaches. On the one end, invariability would result in a rigid system, while excessive variability could be considered as unwanted noise. Both could negatively affect the ability of the motor system to resist unexpected perturbations. Bringing an end-point to a target involves moving a kinematically redundant limb, prompting trajectory variability as a necessity for synergies to emerge. The term "stability" does not necessarily apply to individual links in the kinematic chain but rather to the end-point trajectory and final outcome. In this context, trajectory variability is required to stabilize the foot in line with the task constraints (i.e., not hitting the obstacle). In this study, there were no between-group differences in end-point variability, yet trajectory variability was different between groups for high obstacles, suggesting that low obstacle trials were not challenging enough to reflect variability.

**FIGURE 3** Kinematics of the lower limb and trunk at obstacle crossing. Sagittal plane angles, taken at the time of obstacle vertical crossing, are presented for the leading (A–C) and trailing (D–F) legs; for two obstacle heights (low, high) and for when the leading leg is either the injured (I) or noninjured (NI) for the ACLR group, and either the dominant (D) or nondominant (ND) for the control (CTRL) and athlete (ATH) groups. Significant group differences and leg asymmetries (asy) are shown (*). ACLR, anterior cruciate ligament reconstructed [Color figure can be viewed at wileyonlinelibrary.com]
differences. Interestingly, ACLR showed greater knee flexion variability in their injured leg compared with the noninjured leg when crossing lower obstacles. This may be a result of preceding rehabilitation, with more emphasis given to the injured leg, thus potentially resulting in an increased repertoire of movement patterns for that leg, to some extent. As a result, acquired between-leg differences were perpetuated when the task constraints were minimized (i.e., lower obstacles may result in generating different kinematic solutions as there is a larger potential ROM available for successful crossing).

4.3 | Movement symmetry

Both biomechanical and functional asymmetries were previously reported in ACLR persons. Our results likewise revealed between-leg differences in both foot clearance, and knee and trunk kinematics. As for knee flexion, ATH also showed between-leg differences, which may be expected due to uneven limb function during their years of training. ACLR also showed an increased trunk flexion when crossing with their injured compared with their non-injured leg (both leading and trailing). This is comparable to the results of Markström and colleagues, who reported that ACLR persons exhibit both decreased knee flexion and increased trunk flexion during the take-off phase of a vertical hop task with their injured leg, even long after the injury. Trunk flexion was also increased in the landing phase when landing on the injured leg. These findings were explained within the context of a knee unloading strategy within weight-bearing tasks. However, for an open kinetic chain task such as OC, reducing reaction forces is less of a priority. Forward bending results in shifting the center of mass more anteriorly, which facilitates counterbalancing with the trailing leg. This strategy to clear an obstacle might be a manifestation of altered neural pathways, which highlights central compensations and sensory integration reorganization following initial disruption to afferent input following an ACL injury.

GPA discriminated between groups, as ACLR was significantly less symmetrical in terms of coordinating inter-joint angular velocities, as compared with ATH. This demonstrates the added value of addressing angular velocities and inter-joint coordination, as
traditional outcomes showed some kinematic similarity between ACLR and ATH. Furthermore, GPA revealed that the multijoint asymmetry of ACLR persons was similar to that of untrained controls despite having completed extensive rehabilitation and resumed physical activity.

4.4 Study limitations

The OC test paradigm is not yet an established and validated test for sensorimotor control after an ACL injury. We recognize this limitation and advise to treat our results accordingly. Further development of similar functional paradigms is warranted, possibly building on our proposed analysis methods. Our protocol in the context of other data collection was also designed with a minimal number of repetitions, which potentially limited the validity of our variability analysis.

Future test designs would benefit from more repetitions if a similar analysis is to be considered. Another limitation was the large variation of postreconstruction time in our cohort. We included participants who were over 5 years after surgery, and it is possible that further sensorimotor adaptations continue to occur in time while engaging in diverse activities. Finally, the ACLR group had a larger proportion of males compared with both other groups, though this did not seem to affect any of the statistical comparisons.

4.5 Clinical implications

Deciding whether or not a person is eligible to return to preinjury activity following ACLR rehabilitation is challenging. Despite adequate functional performance,49 tested skills might not be transferred from a controlled environment (i.e., lab/clinic) to real-life situations. Evaluations within real-life environments should be encouraged as more ecologically valid alternatives to traditional functional tests performed in a clinical or laboratory setting. However, this should be complemented by addressing sensorimotor control when interpreting such tests. The OC paradigm, although performed in a controlled environment, holds merits as it addresses salient aspects of sensorimotor control, undetected by traditional assessment methods. We recommend that more attention be given to rehabilitation to movement symmetry and its potential importance. Motor abundance should also be encouraged by increasing variability in practice and incorporating exercise in more challenging scenarios, thus increasing the flexibility and adaptability of the sensorimotor system when performing functional tasks.

Finally, we acknowledge that while the use of an advanced 3D measuring system was required for our analysis, such equipment is rarely available for clinicians to use. However, outcomes from more simplistic equipment (i.e., a basic video camera and a physician scale) have been shown to correlate with 3D analysis of kinematic and kinetic measurements.50 Furthermore, similar tools are also in use for calculations of symmetry indices, therefore establishing the validity of such assessments when looking at between-leg differences.49,51

5 CONCLUSION

Sensorimotor deficits were identified in postrehabilitated ACLR, as greater lower limb movement asymmetry and reduced trajectory variability. These elements should thus not be overlooked during functional clinical screening procedures. In contrast, joint positioning ability did not seem a prominent deficiency in postrehabilitation ACLR persons. Assessments of sensorimotor control, such as the proposed OC paradigm, should be further developed with the goal of future implementation in clinical settings for better patient discrimination.

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AUTHOR CONTRIBUTIONS

Adam Grinberg contributed to data collection, carried out data and statistical analyses, interpreted the results, and drafted the manuscript. Andrew Strong contributed to test design, data collection, and writing of the manuscript. Sebastian Buck contributed to pilot work, initial analysis, and writing of the manuscript. Jonas Selling contributed to test design, programming, biomechanical modeling, and provided ongoing technical support and feedback. Charlotte K. Häger led the conceptualization and design of the project, obtained funding, and contributed to the analysis and the writing of the manuscript. All authors read and approved the final manuscript.

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SUPPORTING INFORMATION
Additional Supporting Information may be found online in the supporting information tab for this article.

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