LANDING KINEMATICS AFTER ACL RECONSTRUCTION; DO THE BIOMECHANIST AND PHYSIOTHERAPIST SEE DIFFERENT THINGS?

Ina Janssen[1], Marieke van Hunen[2], Marsha Tijssen[2]
Sports Science and Innovation, Sportcentrum Papendal, Arnhem, Netherlands[1]
Sports Medical Centrum Papendal, Arnhem, Netherlands[2]

Rehabilitation following ACL reconstruction is a long process where the chance of a recurrent injury remains high. Compensatory and asymmetric landing strategies, which may lead to these re-injuries, often remain present during the rehabilitation process although not often visually identified. Therefore, the purpose of this study was to compare the visually identified asymmetries with objective inertial sensor data during the Single and Triple Hop test. The kinematic data was able to identify asymmetric kinematics that led to altered strategies that were not identified subjectively by the physiotherapist in both the Single and Triple Hop, in particular in the hip joint. It is speculated that being able to able to identify these asymmetric strategies will improve ACLR rehabilitation and reduce the chance of a re-injury.

KEY WORDS: INERTIAL SENSORS, REHABILITATION, ELITE SPORT

INTRODUCTION: In several sports including basketball, football and team handball, an anterior cruciate ligament (ACL) injury occurs during pivoting or landing after a jump shot (Koga et al., 2010; Olsen et al., 2004). It has been estimated that yearly 15% of elite athletes suffer an injury to their ACL. Following this injury, an ACL reconstruction (ACLR) is often performed which includes 9-12 months of rehabilitation before Return to Play (RTP) is recommended. However, approximately 35% of those who undergo an ACLR do not return to their pre-injury sport level, with 50% identifying their injury as the main reason for this (Arden et al., 2011). A re-injury or injury on the opposite leg within 5 years has also been shown to occur in 22-25% of ACLR patients (Wiggins et al., 2016).

For these reasons, optimising ACLR rehabilitation for elite athletes is essential to ensure an effective RTP. Physiotherapists commonly use the Gustavsson hop tests, a cluster of several one-legged hops, as a tool to identify whether an athlete is suitable to RTP. These hop tests compare the horizontal distance attained with the operative and non-operative legs while the physiotherapist visually inspects the movement. However, recent research has identified that ACLR patients can attain a symmetrical horizontal distance using sagittal plane compensatory strategies in their operative leg (Kotsifaki et al. 2022). It is possible that physiotherapists are unable to visually identify these compensatory strategies during the hop tests, and the benefit of quantifying the landing kinematics is clear.

The development of portable inertial sensor systems, such as Xsens, provide the opportunity to collect accurate kinematic data during the hop tests in the elite rehabilitation setting. Previous research showed good concurrent validity of kinematics from the Xsens system against a high-speed camera method (Janssen et al., 2019). Xsens can objectify the hop landing biomechanics in three-dimensions, and with this data limb asymmetries and compensatory movement strategies may be identified. These data may then guide optimal rehabilitation for the athlete. However, in order to determine whether using an inertial sensor system would aid in ACLR rehabilitation, it is firstly important to investigate how the subjective physiotherapist evaluation compares to the objective kinematic data, as was the aim of the current study. In addition, as these tests were conducted in an elite sport environment, several challenges and questions relevant to conducting research in such environment will be discussed.

METHODS: 15 athletes from various sports provided consent to participate in this study (Table 1). All athletes were eligible if they had an ACLR at least 4 and maximal 18 months before the test date, were able to jump on the operative leg, and their therapist provided consent for the athlete to perform the hop tests. Each athlete wore the Xsens system (Awinda, 100Hz; Xsens technologies, Enschede, The Netherlands) composed of 8 inertial measurement units (IMUs) positioned bilaterally on top of the feet, shanks, mid-thighs, one on the pelvis and one on the sternum. Each sensor integrated a tri-axial accelerometer (±160 m/s2), gyroscope (±2000 deg/s) and magnetometer (±1.9 Gauss). Participant anthropometrics including body height, foot length, ankle height, knee height, hip height and hip width were collected for input into the Xsens MVN model. A static N-pose and dynamic walking trial were used to calibrate the position of the sensors and segment orientations. Xsens data was collected at single level and was high-definition reprocessed using the MVN Analyze software (v.2022.0.2).

Table 1. Athlete characteristics that participated in the study.

		N (%)
Sex		
	Male	6 (40%)
	Female	9 (60%)
Age		21.8 ± 5.2 years (range 18-35 years)
Surgery on dominant leg*		5 (33.3%)
Weeks since operation		47 ± 16 (26-78) weeks
Type of surgery		
	Hamstring	10 (66.6%)
	Quadriceps tendon	2 (13.3%)
	Bone patella bone	3 (20%)
Isokinetic strength <10% difference		9 (60%)

**dominant leg defined by 'Which leg do you kick a ball with?'*

A physiotherapist conducted the standardized tests of ACL rehabilitation including the Gustavsson tests (Single Leg Hop for Distance, Triple Hop for Distance, Side Hop), and the isokinetic strength tests. A good isokinetic test indicated that there was less than 10% left/right difference. For the current study, only the Xsens data from the Single and Triple Hop were compared. Horizontal hop distance was quantified with a measuring tape and the furthest hop was used to calculate the Limb Symmetry Index (LSI), a common tool used for RTP criteria following ACLR. All successful hops (where the athlete had a stable landing for at least 3 seconds and hands stayed on their back) were visually assessed by one of two physiotherapists, both who have over 10 years clinical experience, for altered or asymmetric movement strategies for these categories: trunk, hip, knee, ankle/foot, and general observations including the sound of the landing.

In the Xsens data, initial contact (IC) was defined as the moment when the toe segment decelerated abruptly in the Z-axis, as visually inspected. Ankle, knee, hip and trunk flexion angles at IC, max and range of motion of the landing leg were analyzed. Limb asymmetries were defined when there was, on average from the 3 successful trials, more than 20% difference in kinematic values between the left and right limb. For each athlete, asymmetrical and compensatory hop strategies were logged per body part for the visual and kinematic data in the Single and Triple Hop. Although the focus of the current study was sagittal plane kinematics as has been compared in the literature (Kotsifaki et al., 2022), frontal plane kinematics were also collected and will be analyzed in the future. Yet, compensatory trunk movement was also noted when there was lateral flexion or rotation over the stance leg as this has been identified as a compensatory strategy (King et al. 2021).

RESULTS: The subjective and objective data were compared to identify how much agreement was present (Table 2) and categorized as neither methods finding a difference (0), both finding a difference (2), the visual (1 blue) or kinematic data (1 orange) finding a difference. For example, during the Single Hop for Athlete 6, asymmetrical strategies were identified by both methods in the ankle and foot region, in addition to the physiotherapist noting the knee and the kinematic data noting the hip as displaying altered landing strategies. This overview suggests the physiotherapist observed more athletes with knee asymmetries than the kinematic data, which identified more hip and ankle/foot asymmetries. Additionally, during the

Triple Hop movement, more asymmetries were found in some athletes (ie. Athlete 5) compared to the Single Hop. A sub-cohort (N=7) that had a LSI score of more than 100% and good isokinetic result are italicized. Kinematic and visually asymmetry was observed in all of these athletes.

Table 2. Agreement between the subjective and objective analyses of altered strategies during the Single Hop (SH) and Triple Hop (TH).

	Trunk		Hip		Knee		Ankle/Foot		General	
Athlete	**SH**	**TH**	**SH**	**TH**	**SH**	**TH**	**SH**	**TH**	**SH**	**TH**
1	***0***	***1***	***0***	***0***	***0***	***0***	***0***	***1***	***0***	***0***
2	***0***	***0***	***0***	***0***	***1***	***1***	***0***	***0***	***1***	***1***
3	0	0	1	1	0	2	0	0	0	0
4	0	1	1	0	2	1	0	0	0	0
5	0	2	1	1	2	0	2	1	0	0
6	0	2	1	0	1	0	2	1	0	0
7	***0***	***2***	***0***	***0***	***0***	***0***	***0***	***0***	***2***	***0***
8	1	1	0	0	1	0	1	1	0	0
9	***1***	***1***	***1***	***0***	***1***	***0***	***1***	***0***	***1***	***0***
10	0	0	1	0	1	1	2	0	0	1
11	2	0	0	0	2	0	1	2	0	0
12	***1***	***0***	***0***	***0***	***1***	***1***	***0***	***0***	***0***	***1***
13	0	0	0	1	1	0	1	2	0	0
14	***0***	***1***	***1***	***1***	***1***	***2***	***1***	***0***	***0***	***0***
15	***0***	***1***	***0***	***1***	***0***	***0***	***1***	***0***	***1***	***1***

Altered strategies identified by: 0 = neither method; 2 (green) = both methods; 1 (blue) = visually; 1 (orange) = kinematically. Athletes who had a LSI of more than 100% are in italicized (1,2,7,9,12,14,15).

DISCUSSION: In an elite sports setting, reducing the amount of recurring traumatic knee injuries, such as an ACL, is crucial. The results of this study indicate that an inertial sensor system can provide useful information on the hop kinematics in order to guide and optimize the rehabilitation of an ACLR. In particular, the objective data was able to identify asymmetric strategies that were not visually identified by physiotherapists. It is speculated that being able to modify these altered strategies will improve ACLR rehabilitation and reduce the chance of a re-injury.

During the Single and Triple Hop test, the kinematic data identified more athletes with asymmetric strategies than were visually identified. This difference was also present in the sub-cohort which is pertinent as they passed the two main criteria for RTP – a LSI score more than 100% and a good isokinetic result. However, despite being able to pass this criterion, hop kinematics identified asymmetric kinematics which are considered not optimal for RTP. These results are in line with the literature where a compensatory movement strategy was present even when patients were cleared to RTP, in particular at the hip, pelvis and trunk (Kotsifaki et al., 2022). An inertial sensor system is able to detect these strategies better than visual inspection and plays an important role in quantifying the hop test quality to guide optimal rehabilitation for the athlete.

Most of the visually inspected asymmetries were present in the knee joint, although this was not the case in the kinematic data. Furthermore, it is noticeable that the largest discrepancy between the visual and kinematic data was in the hip region where the hip joint was not identified visually in any of the athletes for either the Single or Triple Hop. Together, it is speculated that the physiotherapist may focus more on the knee joint than other joints, although this needs to be confirmed in future studies. One potential explanation for this is clothing restrictions around the pelvic region. Using an inertial sensor system, the pelvis segment is more visible making hip flexion (and lateral pelvic tilt in the frontal plane) easier to identify that visually.

As these hop tests are performed multiple times during the ACLR process, implementation of Xsens can provide objective data to guide and monitor the rehabilitation process. In addition, the physiotherapist assessed only the successful hops and the unsuccessful hops were disregarded. With the sensors it is possible to also analyze the trials in which the athlete did not stick the landing to see why this was the case. For example, one of the athletes demonstrated lateral pelvic tilt during the unsuccessful trials, suggesting weak gluteus medius activation, and did not stick the landing. These data could provide more insight into movement and neuromuscular control of the rehabilitating athlete.

Besides providing objective 3D data, using an inertial sensor system in the elite rehabilitation environment has additional benefits. For example, post testing the hop movements are made visual for the athlete by showing them the avatar of their technique, potentially even comparing it to a previous test. Practically, as it is a portable system, testing can be conducted in the field or in the physiotherapy clinic during a treatment session, albeit allowing for an additional 5-10 min for strap placement and calibration.

Despite these advantages, some challenges and questions regarding the use of hop tests and kinematic data for ACLR rehabilitation were raised. Firstly, the feasibility of using hop tests for all ACLR athletes as a RTP criteria, even those who do not perform jumps or hops in their sport (such as judo), and thus are unfamiliar with the movement. In addition, should athletes who jump regularly off one leg in their sport aim for a LSI greater than 100% as they likely have greater demands from that leg? And what is the importance of the dominant leg being injured, as was the case in 33% of these athletes? In contrast to a hospital setting, various surgeons, surgery techniques, and time of the rehabilitation were involved in this study, making strong conclusions about these influences difficult. However, in the elite environment, this is often the case. Finally, utilizing a criteria of 20% kinematic asymmetry may not be the most suitable criteria for compensatory hop strategies. Pre-injury kinematic data during these hops would provide more insights, however, collecting these kinematics of every athlete that trains at a large training centre is not feasible. Although the current focus was sagittal plane kinematics, frontal plane kinematics will be analyzed in the future.

CONCLUSION: Using an inertial sensor system such as Xsens can provide hop kinematics in an elite sport rehabilitation setting following ACLR. These data can identify hop compensatory and asymmetrical strategies that are missed when visually assessing technique, highlighting that objective kinematic data during RTP is critical. This would assist in guiding ACLR rehabilitation in order to reduce the chance of a re-injury.

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