Extended Reality & Virtual Reality for Return-to-Sports Screening

Glenn Van Wallendael*, Julie Artois*, Hannes Mareen*, Robbe Capelleman†, Joke Schuermans†, Evi Wezenbeek†, Peter Lambert*
*Ghent University – imec, IDLab, Faculty of Engineering and Architecture, Department of Electronics and Information Systems, Technologiepark-Zwijnaarde 122, 9052 Gent, Belgium
†Ghent University, Faculty of Medicine and Health Sciences, Department of Rehabilitation Sciences, De Pintelaan 185, 9000 Gent, Belgium
firstname.lastname@ugent.be, https://media.idlab.ugent.be

***Abstract*—Anterior cruciate ligament (ACL) injuries are common in sports such as soccer, often requiring extensive rehabilitation post-surgery. Return-to-sport (RTS) rehabilitation protocols typically involve clinical and kinematic evaluations to ensure safety. This study investigates the added value of non-immersive (Extended Reality XR) and immersive (Virtual Reality VR) on movement quality during RTS assessment of male soccer players post ACL reconstruction, compared to healthy control players. Our XR tests were performed using a projection on a big screen on 11 male soccer players with a soccer-related ACL tear. Additionally, our VR tests were performed using a Head Mounted Display (HMD) on 31 male soccer players, including 14 with ACL reconstruction and 17 healthy control players. We performed clinical tests and kinematic analyses with statistical comparisons between testing conditions. The utilization of XR seems to elicit the mechanism associated with ACL rupture more significantly, suggesting its potential value in incorporating XR into RTS screening and rehabilitation protocols. Analysis of the VR-results revealed greater knee flexion and valgus range compared to non-VR, demonstrating VR's potential for enhanced kinematic sensitivity. As such, VR-based kinematic analysis may improve sensitivity in detecting movement deviations during RTS evaluations post-ACLR. Further research is needed across diverse athletic populations. In conclusion, this study highlights the potential for both XR and VR applications in identifying ACLR-related deficits, and motivates their integration with conventional clinical RTS screening batteries.**

***Index Terms*—Extended reality, virtual reality, return to sport screening, clinical study**

I. Introduction

The anterior cruciate ligament (ACL) is a knee ligament crucial for stability. It often suffers non-contact injuries during pivoting, cutting, or landing, especially in sports like soccer and basketball. ACL injuries lead to prolonged absence from sports, substantial healthcare costs, and potential knee osteoarthritis.

Currently, ACL reconstruction (ACLR) is the standard treatment. However, more than 50% of athletes fail to return to pre-injury levels [1], indicating a rehabilitation gap. We list several shortcomings. First, rehabilitation programs focus on movement quality but lack in automating movement patterns critical for sports [2]. Second, current functional return-to-sports (RTS) screening tests that are part of a more comprehensive protocol assessing patient reported outcomes (e.g., IKDC questionnaire) and knee function (e.g., swelling, strength) do not adequately simulate sports situations, limiting their effectiveness. For example, since landing after a jump is a common situational pattern for ACL injury in soccer, a frequently used and accepted RTS screening test to evaluate movement quality is the drop vertical jump (DVJ) test [3]. During this test, patients are instructed to jump from a box, land, and immediately perform a maximum vertical jump. Since this standard protocol does not oblige athletes to anticipate or react to environmental variables, they mainly focus on their knee joint (internal focus) during the movement, which is not representative for when they return to sports [4].

This paper investigates whether non-immersive (Extended Reality XR) and immersive (Virtual Reality VR) can provide a solution to these shortcomings [5]. By making a game, a lifelike sport specific experience has been created, namely an exercise game (exergame) [6]–[8]. In such exergames, the patient's attention is directed to the environment instead of the injured knee, forcing the body to rely on automatic motor control to maintain joint-to-joint integrity. Consequently, VR related rehabilitation seems more suited to sufficiently address the automation of the movement pattern, and hereby inducing less prefrontal brain activity and more sensory-motor integration.

For the work in this paper, we designed an exergame framework providing soccer scenarios to perform RTS Screening. We evaluated this in both a non-immersive (XR) setting using projection on a big screen, and an immersive (VR) setting using a Head Mounted Display (HMD). The implemented RTS screening mimics the procedures as described in the work of

This research was supported by the Research Foundation – Flanders (FWO), IDLab (Ghent University – imec), Flanders Innovation and Entrepreneurship (VLAIO), and the European Union. Moreover, the computational resources (STEVIN Supercomputer Infrastructure) and services used were kindly provided by Ghent University, the Flemish Supercomputer Center (VSC), the Hercules Foundation and the Flemish Government department EWI. The authors would like to thanks the following master thesis students who contributed extensively to the software, clinical trials, and analysis of the results: Cornelis To, Dhibi Jasim, Dhondt Lisa, Maelfait Andrea, Naudts Michiel, Van den Bossche Margo, Van Gendt Marjolein, and Van Hootegem Alena.

Gokeler et al. [9], Paterno et. al. [10], and Della Villa et. al. [11].

This paper is organised as follows. First, Section II discusses related work. Then, the proposed framework is described in Section III. Afterwards, the results are discussed in Section IV. Finally, the paper is concluded in Section V.

II. State of the Art

Since the start of the mainstream VR technology wave, research saw potential in analyzing sports performance using virtual reality [12]. This technology has the benefit of bringing the athletes' test experience closer to real scenarios while still allowing for precise control over the experiment's parameters and a controlled environment suitable for measuring performance. An overview offering the different uses of XR and VR for musculoskeletal rehabilitation and injury prevention can be found in the work of Schuermans et. al. [13]. The work of Punt et. al. investigates the non-immersive use case by assessing the efficacy of Wii Fit exercise therapy on temporal-spatial and kinematic gait parameters in individuals with ankle sprains. [14].

Initial research has been performed in validating the use of sport-specific VR technology as a tool to assess injury risk during simulated real-world athletic performance [15]. Using a restricted sample size, these findings suggest notable enhancements in ACL injury risk factors after six weeks of focused injury prevention training, observed during the execution of a sport-specific unanticipated cutting task in VR.

Other work investigated that after undergoing ACLR, patients immersed in a VR environment exhibited knee joint biomechanics similar to those of the control group. These findings suggest that a lifelike VR setting could divert patients post-ACLR from conscious motor control [16]. The work of DiCesare et al. compared a standard DVJ test to a VR guided DVJ performed as part of a simulated corner-kick [4]. In contrast to the standard DVJ, the VR-guided test provoked an aberrant landing pattern, which was associated with a higher force impact on the ACL and subsequently, a higher risk of ACL-injury [4]. In conclusion, the biomechanical risk profile for (re)injury was more provoked during VR screening, probably due to the external focus of attention through immersion. All things considered, although still in its infancy, VR seems to be promising for both rehabilitation and screening purposes compared to conventional rehabilitation and clinical assessment procedures.

III. Proposed Framework

The goal of the proposed study is to let participants perform (1) cutting maneuvers, and (2) vertical jumping or heading maneuvers. We aim to investigate whether we can observe differences between the reference clinical (non-XR and non-VR) conditions compared to the proposed VR and XR conditions.

A. Reference Clinical Trials

In the non-XR and non-VR settings, participants were simply instructed to perform cutting and jumping maneuvers without any visual sport-specific context. During these trials, participants start at a certain starting position in the back of the room, approximately four meters from the point where a cutting or jumping maneuver takes place. They are then prompted by a start signal and run to the front of the room. After one second, one of three Lummic reaction lights illuminates, which indicates the maneuver that needs to be performed. That is, the light on the left or the right indicates a left or right cutting maneuver, respectively. The light in the middle represents a vertical jump. As such, we are able to study the participant's performance in the maneuvers.

B. Proposed XR & VR Trials

In both the XR and VR setting, participants are presented with a simulated soccer scene. This scene was modelled and animated within the Unity game engine. Players from the same team are blue and players from the opposite team are red.

1) Vertical Jump: For the scenario to trigger a vertical jump or heading, the player starts facing the corner flag where a teammate is ready to take the corner kick. After a few seconds, the referee's whistle blows, and the teammate kicks the ball towards the region above the user's head. Fig. 1a and Fig. 2a give an example on how the users perform a vertical jump when the ball is on its way towards the region above their heads. In order to make the exercise less repetitive, we implemented several variations. There are three possible behaviors for the non-playable characters (NPCs) receiving the corner kick: following the ball, waiting at the edge of the penalty area, or jumping with the ball. Additionally, for this scenario, we implemented five variations involving the starting positions of the player and the side from which the ball is kicked. As such, the user may be more motivated to perform a vertical jump exercise.

2) Cutting Maneuver: To trigger the cutting maneuver, a passer and an interception is simulated.

In the passer scenario (used in both XR and VR scenario), the user is part of the attack. The ball starts at the user's feet and is automatically passed straight to a teammate. The teammate, with an opponent on their back, passes the ball back to the user. By ensuring that the pass is hard enough, the user must move explosively to reach the ball. To add realism and dynamism, the defender slides towards the blue player, prompting the user to anticipate the quick return pass.

For the interception maneuver (only used in the VR scenario), the user begins facing an opponent who is dribbling towards them with the ball at their feet. After a few seconds, the opponent passes to a teammate, and the user must move out to intercept the ball. This scenario is suitable because it immediately immerses the user in the action, clearly showing the opponents attacking and the user's need to prevent it.

In both cutting scenarios, the ball can be played to the left or right, and the user does not know beforehand. Therefore, they must make a sudden and powerful movement. Fig. 1b and Fig. 2b depict the cutting maneuver at the moment the ball is played for the XR and VR case, respectively. In these figures, the user must respond by moving to the left and right, respectively.

C. Experimental Setup

1) Non-immersive (XR) Conditions: In the XR setting, the vertical jumping task involved the participant's response to a virtually simulated corner-kick situation, aiming to head the ball towards the goal. A cutting maneuver is executed in response to a ball passed by a team player, directed randomly and explosively to either the participant's left or right side. These two maneuvers in the XR environment are shown in Fig. 1a and Fig. 1b, respectively.

The visualizations were displayed on a 7m x 4m projection screen originating from a 12.000 lumen 4K projector. The projection took place at the Arts and Sound Interaction Lab (ASIL) located in 'De Krook', Ghent, which is a research facility affiliated with Ghent University. This is a 10m x 10m room and spans the height of two floors (6m). Participants were located between seven and three meters in front of the screen and the camera perspective, focal length and lens shift were modified to match the perspective of the participant from a fixed four meter distance from the screen.

2) Immersive (VR) Conditions: In the VR setting, participants wore an HMD showing various soccer match scenarios. As such, the participants were required to react with vertical jumps (in corner situations) or cutting maneuvers. These two maneuvers in the VR environment are shown in Fig. 2a and Fig. 2b, respectively.

For the type of headset, we opted for a Meta Quest 2 because it provided the lowest weight on the participant's head. Combined with the untethered setup, this device provided enough freedom and flexibility to perform the tests.

IV. Experimental Results

A. Overall Test Setup

Motion capture data from each trial were saved and processed using Qualisys Track Management (QTM) post hoc analysis. The analysis focused on the push-off moment. For the cutting trials, this was from the leg of interest contacting the floor to the other leg's contact. For jumping maneuvers, it focused on the initial ground contact to full extension of both knee joints. Subsequently, the data were exported to Visual3D in C3D format, for participant model creation and calculation of segment and joint angles during cutting and jumping.

Three-dimensional (3D) kinematics of the lower limbs and trunk were measured and analyzed during cutting and jumping maneuvers using QTM for optical motion tracking, in all settings. To capture trunk and lower limb motion, participants were fitted with 44 infrared reflective markers on specific anatomical structures (anatomical markers) and lower limb segments (tracking markers) to collect kinematic data and generate a 3D model for subsequent analysis (see Fig. 3). A setup of 14 infrared cameras captured participants' movement quality during VR and non-VR guided cutting and header maneuvers.

Initially, a static measurement was taken with participants in the anatomical position. Subsequently, four functional measurements were taken, two for each knee (flexion-extension) and hip (flexion-extension, abduction-adduction, circumduction). These functional trials were essential for constructing a 3D model for each participant, enabling quantification of kinematic curves during cutting and header trials. Participants were randomly assigned to either start with the VR or control (non-VR) condition. Before kinematic measurements began, eight markers were removed, and two inertial measurement units (IMUs) were affixed to both feet to define contact phases for kinematic analysis.

The relevant measurements we made were knee flexion, knee valgus, and knee internal rotation. Knee flexion refers to the bending of the knee joint, typically measured in degrees, indicating the angle between the thigh and the lower leg. Knee valgus describes the inward angling of the knee towards the midline of the body, often observed during activities such as squatting or jumping. Knee internal rotation refers to the rotational movement of the tibia (shinbone) in relation to the femur (thighbone) within the knee joint. It involves the inward twisting or rotation of the lower leg bone around its longitudinal axis.

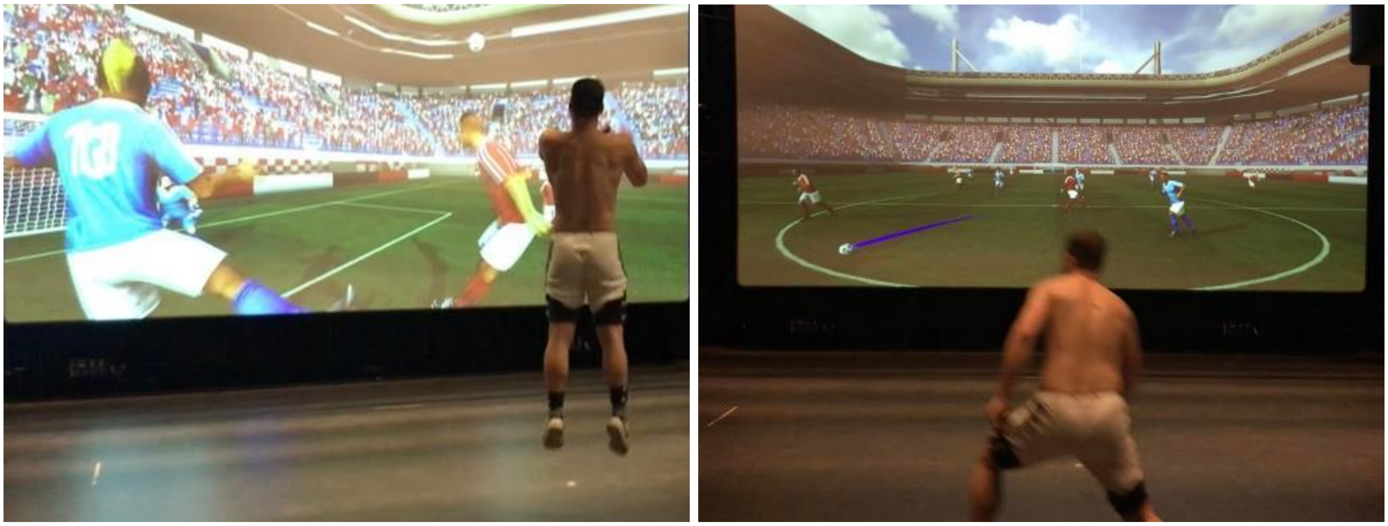
B. XR Results

In the XR study, 11 male soccer athletes were enlisted, with mean ± standard deviation values for age of 24.3 ± 3.6 years, a height of 180.6 ± 5.6 cm, weight of 77.4 ± 5.8 kg; 6.7 ± 2.7 hours engaging in sports per week, and 14 ± 4 months duration of RTS. These individuals had experienced an ACL tear associated with soccer within the preceding three years and had completely resumed sports activities at the time of assessment. The effect of condition (clinical non-XR and non-VR compared to the VR and XR conditions) on the lower limb kinematics during cutting and header maneuvers was investigated with linear mixed models. Analyses were executed with participants as a random factor and conditions as fixed predictors. Post hoc analyses were performed with Bonferroni corrections. The effect of possible covariates was investigated (age, sex, BMI, and sports level) but did not have an effect and are therefore not included as covariates in the analyses. The residuals of the linear mixed model were checked for normal distribution and homoscedasticity. The level of significance was set at ($a = 0.05$).

Table I presents the XR (vs. non-XR) Visual 3D (V3D)[1] measurements, for the involved leg of all participants. This table displays group averages and standard deviations (SD) per variable, with statistically significant differences ($p < 0.050$) between the two conditions highlighted in bold.

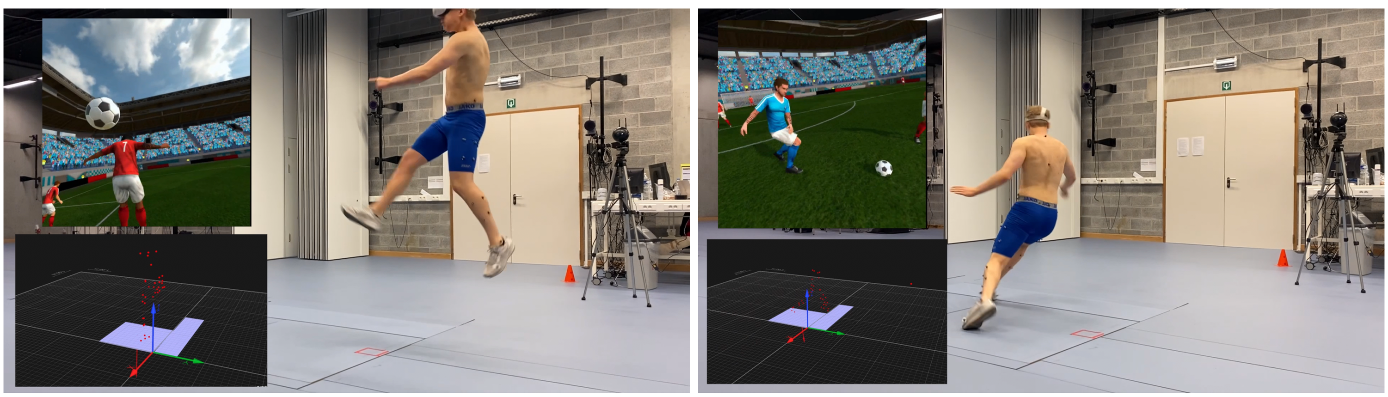
As can be observed in Table I, the heading maneuver resulted in insignificant increases in knee flexion and knee valgus. More interesting is that during the push-off phase of a side cutting maneuver, there was notably more knee

[1]https://bassettbiomechanics.com/visual3d/



(a) Vertical jumping (b) Cutting (to the left)

Fig. 1. The maneuvers performed within the XR environment.



(a) Vertical jumping (b) Cutting (to the right)

Fig. 2. The maneuvers performed within the VR environment. In each figure, the left top inset is the view as seen from within the HMD, and the left bottom inset is the motion captured data.

bending observed in the XR condition compared to the non-XR condition ($p = 0.044$). Specifically, participants exhibited an average knee flexion of 47.59° (± 5.33) in the virtual environment and 44.96° (± 6.88) in the real environment, indicating a mean difference of 2.62 [95% CI, 0.09-5.15].

In addition, significant differences were observed in both average ($p = 0.029$) and maximum ($p = 0.012$) frontal plane knee ranges during the respective phases. In the XR condition, an average valgus (knee moving inward) of 17.38° (± 4.73) was recorded, compared to 15.78° (± 4.70) in the non-XR condition, resulting in a mean difference of 1.59 [95% CI, 0.20-2.99]. Furthermore, maximal valgus angles were measured at 22.46° (± 4.50) in the virtual environment and 19.78° (± 5.01) in the real environment, showing a mean difference of 2.67 [95% CI, 0.73-4.61]. In other words, comparing the XR condition with the non-XR condition, significantly increased knee flexion and knee valgus can be observed for the cutting maneuver.

TABLE I
V3D MEASUREMENTS (MEAN ± SD) FOR XR AND NON-XR CONDITIONS.

V3D measurements (°)	Non-XR cond.	XR condition
Head knee flexion average	53.43 ± 10.97	55.06 ± 8.94
Head knee flexion maximum	68.35 ± 11.87	68.77 ± 10.74
Head knee valgus average	11.42 ± 6.15	11.86 ± 7.04
Head knee valgus maximum	16.74 ± 6.10	17.48 ± 7.85
Head knee internal rot. avg.	9.13 ± 8.64	4.85 ± 11.95
Head knee internal rot. max.	12.42 ± 10.85	9.74 ± 11.22
Cutting knee flexion average	**44.96 ± 6.88**	**47.59 ± 5.33**
Cutting knee flexion maximum	55.44 ± 8.17	56.06 ± 6.83
Cutting knee valgus average	**15.78 ± 4.70**	**17.38 ± 4.73**
Cutting knee valgus maximum	**19.78 ± 5.01**	**22.46 ± 4.50**
Cutting knee internal rot. avg.	13.05 ± 5.78	13.68 ± 6.16
Cutting knee internal rot. max.	17.14 ± 4.68	16.56 ± 9.03

Based on these elevated flexion and valgus amplitudes

Fig. 3. Motion capture setup using reflective markers.

during the push-off phase of a cutting maneuver we conclude that participants in the virtual environment appeared to replicate movements more aligned with the mechanism of an ACL rupture, characterized by increased flexion, valgus, and external rotation from the tibia towards the femur, with the first two components proving statistically significant. Consequently, XR integration in screening processes introduces more provocative movements in the affected leg within a virtual soccer simulation, emphasizing the added value of XR. Such testing, particularly in an XR setting, directs less attention to movement mechanics and more towards gameplay, potentially increasing the risk of ACL re-tear due to amplified knee flexion and valgus, as confirmed by Alentorn-Geili et al.'s study [17] examining ACL tear risk factors. XR's ability to elicit such risky positions, akin to real-world change of direction movements on the soccer field, underscores its enhanced value in traditional RTS screening methodologies.

C. VR Results

In the VR study, 31 male soccer athletes were enlisted, with mean ± standard deviation values for age of 21.68 ± 3.17 years, a height of 182.42 ± 6.78 cm, weight of 77.13 ± 10.31 kg, 5.98 ± 2.45 hours engaging in sports per week, and 16.00 ± 12.96 months duration of RTS. Among them, 14 had a history of ACL reconstruction (ACLR), while 17 were matched controls. Initially, there were a total of 39 participants; however, 8 withdrew from the study due to various reasons.

Table II presents the VR (vs. non-VR) V3D measurements, for the involved leg of all participants. Just as in Table I, this table displays group averages and standard deviations per variable, with statistically significant differences ($p < 0.050$) between the two conditions highlighted in bold.

TABLE II
V3D MEASUREMENTS (MEAN ± SD) FOR VR AND NON-VR CONDITIONS.

V3D measurements (°)	Non-VR cond.	VR condition
Head knee flexion average	**54.47 ± 8.10**	**52.95 ± 7.79**
Head knee flexion maximum	75.25 ± 9.72	73.22 ± 12.48
Head knee valgus average	**13.73 ± 16.78**	**14.04 ± 7.48**
Head knee valgus maximum	**17.83 ± 12.51**	**22.45 ± 9.87**
Head knee internal rot. avg.	17.44 ± 33.73	6.23 ± 32.60
Head knee internal rot. max.	21.38 ± 46.91	10.26 ± 47.52
Cutting knee flexion average	**46.63 ± 6.38**	**49.47 ± 6.44**
Cutting knee flexion maximum	58.84 ± 8.76	61.32 ± 8.26
Cutting knee valgus average	**11.55 ± 7.52**	**14.33 ± 7.84**
Cutting knee valgus maximum	**16.21 ± 11.07**	**19.73 ± 10.46**
Cutting knee internal rot. avg.	10.69 ± 9.65	11.92 ± 9.11
Cutting knee internal rot. max.	16.15 ± 12.12	16.52 ± 13.70

The header maneuver shows a significant decrease in knee flexion average and a significant increase in knee valgus. No concluions can be drawn from these measurements.

During the side-cutting maneuver, the non-VR condition exhibited notably less knee flexion ($p = 0.001$) and knee valgus range of motion (ROM) compared to the VR condition. Both the average (p = 0.010) and maximum (p = 0.025) values for knee flexion and valgus differed significantly. Specifically, the average knee bending ROM was 46.63° (± 6.375) in the non-VR condition compared to 49.47° (± 6.44) in the VR condition, indicating a mean difference of 3.55 [95% CI, 1.53 - 5.56].

Similarly, the average knee valgus ROM was 11.55° (± 7.52) in the non-VR condition compared to 14.33° (± 7.84) in the VR condition, with a mean difference of 3.01 [95% CI, 0.81 - 5.21]. In terms of maximum knee valgus, it was 16.21° (± 11.07) in the non-VR condition and 19.73° (± 10.46) in the VR condition, showing a mean difference of 4.30 [0.60 - 8.01].

The findings of this VR study indicate a notable increase in average flexion and valgus range of motion (ROM) in the VR testing condition compared to the non-VR condition. Currently, there exists only limited literature discussing the potential benefits of VR in RTS screening protocols. Athletes often face lower-limb injury risks due to biomechanical shortcomings, which VR-based assessments can address within a sport-specific context. This approach holds promise for improving the evaluation of skill transfer to the sport, thereby aiding future injury prevention strategies.

Specifically, our study highlights higher average flexion and valgus ROM in the matched leg during the push-off phase of side-cutting maneuvers in the VR condition. These results suggest that subjects in the VR condition replicate movements resembling those involved in ACL rupture mechanisms. These significant findings indicate that sport-specific testing prompts greater motion amplitudes. When soccer players undergo VR testing, their focus shifts from movement patterns to simulated game scenarios, potentially resulting in increased knee flexion and valgus, associated with heightened ACL tear risks.

V. DISCUSSION & CONCLUSION

The outcomes of our study illustrated significantly greater average flexion and valgus range of motion in both the non-immersive (XR-guided) and immersive (VR-guided) testing conditions compared to the non-XR and non-VR conditions, respectively. Moreover, there was a significant increase in maximal valgus ROM in the XR and VR conditions.

We hypothesize that using the sports context, participants exhibited less focus on their movement patterns and were more engaged in the simulated game scenario. This external focus contributed to increased knee flexion and valgus, which heightens the risk of ACL tears.

Our findings are consistent with Ghaderi et al.'s [18] research on the impacts of neuromuscular training with external focus cues in male athletes post-ACLR, showcasing enhanced landing biomechanics. Initial studies validate the benefits of external focus, supporting our findings. Notably, biomechanical differences were evident between testing conditions but not between injured and matched control groups, indicating that VR testing is more discerning than clinical assessments, even detecting anomalies in healthy individuals.

Several limitations are pertinent to acknowledge in this study. Firstly, the participation of only 11 individuals in the XR test renders the sample size insufficient for deriving definitive conclusions. Secondly, for all experiments, the experimental protocol exclusively involved men aged between 17 and 30 years. Notably, the highest incidence of ACL ruptures occurs with females between 14 and 18 years, while males typically experience less incidents with a peak between 19 and 25 years. Given the substantial biomechanical differences between sexes and age groups, the findings of our study cannot be extrapolated to female athletes or youth athletes. At this point, it is impossible for us to prove that variations stem from the sporting environment rather than the method utilized to convey the actions required. We noticed that some participants would react with a movement making a sharper angle using the VR setting as compared to the clinical setting. This will be further investigated in our followup work. Moreover, it is important to note that this study focuses specifically on soccer players, analyzing sport-specific movements. Therefore, conclusions drawn from this research cannot be extended to athletes in other sports. In the future, we plan to explore factors that may influence participants' movement patterns, such as the design of the virtual scenario or feedback mechanisms. Finally, future work should consider a longitudinal study design to track participants' progress over time, especially those who have undergone ACL reconstruction surgery. This would provide insights into the long-term effects of XR and VR interventions on rehabilitation outcomes and injury prevention.

Despite these limitations, this observational study already thoroughly assesses the additional benefits of incorporating a non-immersive (XR) and immersive (VR) exergame into RTS screening post-ACLR.

References

[1] N. Van Melick, R. E. Van Cingel, F. Brooijmans, C. Neeter, T. van Tienen, W. Hullegie, and M. W. Nijhuis-van der Sanden, "Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus," *British journal of sports medicine*, 2016.

[2] M. V. Paterno, L. C. Schmitt, K. R. Ford, M. J. Rauh, G. D. Myer, B. Huang, and T. E. Hewett, "Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport," *The American journal of sports medicine*, vol. 38, no. 10, pp. 1968–1978, 2010.

[3] W. Welling, A. Benjaminse, K. Lemmink, and A. Gokeler, "Passing return to sports tests after acl reconstruction is associated with greater likelihood for return to sport but fail to identify second injury risk," *The knee*, vol. 27, no. 3, pp. 949–957, 2020.

[4] C. A. DiCesare, A. W. Kiefer, S. Bonnette, and G. D. Myer, "High-risk lower-extremity biomechanics evaluated in simulated soccer-specific virtual environments," *Journal of Sport Rehabilitation*, vol. 29, no. 3, pp. 294 – 300, 2020.

[5] J. Schuermans, A. Van Hootegem, M. Van den Bossche, M. Van Gendt, E. Witvrouw, and E. Wezenbeek, "Extended reality in musculoskeletal rehabilitation and injury prevention - a systematic review," *Physical Therapy in Sport*, vol. 55, pp. 229–240, 2022.

[6] B. Shroeder, M. Kunanec, B. Kroese, O. Pollard, O. Sadoon, B. Kapralos, J. Brennan, E. Leach, and J. Jenson, "Rapid recovery: a kayaking-based exergame for shoulder rehabilitation and physical fitness," in *2014 IEEE Games Media Entertainment*, pp. 1–4, 2014.

[7] R. Haghighi Osgouei, D. Soulsbv, and F. Bello, "An objective evaluation method for rehabilitation exergames," in *2018 IEEE Games, Entertainment, Media Conference (GEM)*, pp. 28–34, 2018.

[8] A. Barenbrock, M. Herrlich, and R. Malaka, "Design lessons from mainstream motion-based games for exergames for older adults," in *2014 IEEE Games Media Entertainment*, pp. 1–8, 2014.

[9] A. Gokeler, W. Welling, S. Zaffagnini, R. Seil, and D. Padua, "Development of a test battery to enhance safe return to sports after anterior cruciate ligament reconstruction," *Knee surgery, sports traumatology, arthroscopy*, vol. 25, pp. 192–199, 2017.

[10] M. V. Paterno, M. J. Rauh, S. Thomas, T. E. Hewett, and L. C. Schmitt, "Return-to-sport criteria after anterior cruciate ligament reconstruction fail to identify the risk of second anterior cruciate ligament injury," *Journal of athletic training*, vol. 57, no. 9-10, pp. 937–945, 2022.

[11] F. Della Villa, M. Buckthorpe, A. Grassi, A. Nabiuzzi, F. Tosarelli, S. Zaffagnini, and S. Della Villa, "Systematic video analysis of acl injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases," *British journal of sports medicine*, vol. 54, no. 23, pp. 1423–1432, 2020.

[12] B. Bideau, R. Kulpa, N. Vignais, S. Brault, F. Multon, and C. Craig, "Using virtual reality to analyze sports performance," *IEEE Computer Graphics and Applications*, vol. 30, no. 2, pp. 14–21, 2010.

[13] J. Schuermans, A. Van Hootegem, M. Van den Bossche, M. Van Gendt, E. Witvrouw, and E. Wezenbeek, "Extended reality in musculoskeletal rehabilitation and injury prevention-a systematic review," *Physical therapy in sport*, vol. 55, pp. 229–240, 2022.

[14] I. M. Punt, S. Armand, J.-L. Ziltener, and L. Allet, "Effect of wii fit exercise therapy on gait parameters in ankle sprain patients: A randomized controlled trial," *Gait & posture*, vol. 58, pp. 52–58, 2017.

[15] A. W. Kiefer, C. DiCesare, S. Bonnette, K. Kitchen, B. Gadd, S. Thomas, K. D. Barber Foss, G. D. Myer, M. A. Riley, and P. Silva, "Sport-specific virtual reality to identify profiles of anterior cruciate ligament injury risk during unanticipated cutting," in *2017 International Conference on Virtual Rehabilitation (ICVR)*, pp. 1–8, 2017.

[16] A. Gokeler, M. Bisschop, G. D. Myer, A. Benjaminse, P. U. Dijkstra, H. G. van Keeken, J. J. van Raay, J. G. Burgerhof, and E. Otten, "Immersive virtual reality improves movement patterns in patients after acl reconstruction: implications for enhanced criteria-based return-to-sport rehabilitation," *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 24, pp. 2280–2286, 2016.

[17] E. Alentorn-Geli, G. D. Myer, H. J. Silvers, G. Samitier, D. Romero, C. Lázaro-Haro, and R. Cugat, "Prevention of non-contact anterior cruciate ligament injuries in soccer players. part 1: Mechanisms of injury and underlying risk factors," *Knee surgery, sports traumatology, arthroscopy*, vol. 17, pp. 705–729, 2009.

[18] M. Ghaderi, A. Letafatkar, A. C. Thomas, and S. Keyhani, "Effects of a neuromuscular training program using external focus attention cues in male athletes with anterior cruciate ligament reconstruction: A randomized clinical trial," *BMC Sports Science, Medicine and Rehabilitation*, vol. 13, no. 1, pp. 1–11, 2021.