INTRA- AND INTER-SUBJECT VARIABILITY IN A REALISTIC, NON-STANDARDIZED EXERGAMING SCENARIO

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The purpose of this study was to assess the variability of lower extremity mechanics related to biomechanical risk factors for anterior cruciate ligament injury. Lower body kinematics were measured in healthy subjects in a realistic, non-standardized exergaming scenario. Variability in a jump exercise were described with the coefficient of variation and leg symmetry was assessed using Welch's t-test. Inter-subject variability was moderate-high and intra-subject variability was low-moderate in all variables, while leg symmetry differed significantly for knee internal rotation and hip extension ($p < .001$), but not in the knee valgus. Athletes showing high risk knee biomechanics and high movement variability need clear instructions to prevent more extreme angles. Athletes showing low movement variability need proper recovery periods to avoid ACL fatigue failure.

KEYWORDS: Kinematics, Anterior Cruciate Ligament, Injury

INTRODUCTION: Incidence rates of Anterior Cruciate Ligament (ACL) ruptures are high. Studies on the biomechanical injury mechanism, using injury situation simulation or video analysis or investigating kinematics from athletes without prior knee injuries in standardized laboratory conditions, have shown that a combination of factors contribute to ACL injury. These factors include low hamstring muscle activity, a high knee valgus, and low knee flexion (Koga et al., 2010). Also, movement variability plays a role as the ACL can fail in response to a single large load, but also in response to repetitive smaller loads during a short time interval without appropriate recovery (Wojtys et al., 2016). If an athlete exhibits a high initial biomechanical load on the ACL, e.g. through a high knee valgus, combined with high movement variability, the probability of more extreme angles and higher load increases. Exergaming, exercise with gaming elements, can serve as a realistic training setting in which knee kinematics can be accurately measured using a marker-based system. However due to the shift of the players' cognitive focus onto the experience, variability of lower extremity mechanics might increase (Martin-Niedecken et al., 2020). Therefore, the primary aim of this study was to assess the intra- and inter-subject variability of lower extremity mechanics related to biomechanical risk factors for ACL injury in subjects without prior knee injury in a realistic, non-standardized exergaming scenario. The secondary aim was to identify differences in risk factors between the legs in such a scenario.

METHODS: 18 healthy athletes (9 female) without prior knee injury were recruited. Participants did 7.58 ± 3.41 hours per week of soccer (n = 7), floorball (n = 5), volleyball (n = 3), or handball (n = 3) and were aged 25.2 ± 3.3 years. One participant had prior experience with the ExerCube.
The ExerCube (Martin-Niedecken et al., 2020), an exergaming device providing adaptive, functional, and high-intensity interval training, was used to play the exergame "Sphery Racer" and measure lower body biomechanics (figure 1). In the exergame, participants start in the centre of the ExerCube, getting visual instructions on the next exercise that is to be performed. The different exercises require either staying in the centre of the ExerCube or to perform sidesteps to the right or left wall. Each participant played for 25 minutes after receiving a 3-minute tutorial on correct execution of the nine exercises included in the exergame and described elsewhere (Martin-Niedecken et al., 2020). The biomechanics of the jump will be analysed in this work. It is performed as a countermovement jump in the centre of the ExerCube with arms stretched into the air. The order of the exercises was the same for all

participants. Not all participants performed the same number of exercises, as the game was adaptive (game runs faster when movements are performed correctly). On average, participants performed 630 ± 43 different exercises and 82 ± 5 jumps.

Figure 1: A participant playing the Sphery Racer in the ExerCube.

Biomechanics was measured with a camera-based motion capture system (Vicon, Oxford UK, Version 2.11) based on a marker cluster set (List et al., 2013). Under supervision of the investigator, every 60 seconds a new trial was automatically recorded and saved, resulting in a total of 25 trials per participant. Post-processing of marker trajectories was performed with MATLAB (MathWorks Inc. Natick, USA, Version 2019a) applying a 4^{th} order Butterworth filter with cut off frequency of 7 Hz. The following stepwise approach was used to identify multiplanar biomechanical risk factors in each exercise:

1. Angle data in each 60-second-long trial was separated through video analysis at the most neutral position possible (upright trunk with both feet on the ground and straight legs) to get a single trial for each exercise. Incomplete recordings (exercises at the beginning or end of a 60-second-long trial) were excluded for analysis. The left leg of one participant was excluded due to sliding of marker clusters. Data were not cut, normalized, or excluded between exercises as critical angles could occur at any moment of the training.
2. Critical knee flexion angle (KFcrit) of 10-30° was identified separately for the right and left leg in each exercise as the strain on the ACL then is highest (Escamilla et al., 2012).
3. Three risk factors; the maximal knee valgus (KV; knee abduction angle), the maximal knee internal rotation angle (KIR), and maximal hip extension (Hext) were extracted in all sections during which KFcrit occurred to account for a multiplanar injury mechanism.
4. The maximal angle of all sections for each exercise was used for analysis, assuming higher angles correspond to increased ACL strain.

Statistical analysis was conducted in R (R Core Team, Vienna A, Version 4.3.2). Coefficient of variation (CV) for all outcomes were calculated to describe intra- and inter-subject variability. CV was regarded as low if CV ≤ 0.25, moderate if 0.25 ≤ CV ≤ 0.5, and high if CV > 0.5. Symmetry was assessed using paired t-tests for maximal values between the right and left leg of each outcome. Significance level was set to 0.05.

RESULTS: The CV in the three outcomes for each participant separately (intra-subject variability) as well as the inter-subject variability is displayed in Table 1. Inter-subject variability was moderate in the maximal KV and high in the maximal KIR and HExt. In all outcomes intra-subject variability ranged from low to high.

Table 1: Coefficient of variation (CV) for each outcome and each participant (N = number of observations for both legs combined).

Subject	N	CV of maximal KV	CV of maximal KIR	CV of maximal HExt
01	150	0.37	0.47	-0.26
02	156	0.31	0.51	-0.18
03	160	0.18	0.24	-0.39
04	139	0.28	0.73	-0.55
05	165	0.23	1.10	-0.10
06	166	0.27	0.30	-0.14
07	162	0.24	0.19	-0.36
08	143	0.17	0.23	-0.49
09	176	0.36	0.25	-0.41
10	171	0.26	0.40	-0.13
11	170	0.60	0.75	0.22
12	166	0.38	0.55	-0.27
13	160	0.22	0.62	-0.14
14	156	0.31	0.73	-0.67
15	168	0.79	2.21	-1.36
16	180	0.57	0.42	-0.63
17	170	0.23	0.26	-2.42
18	184	0.25	0.44	-0.61
Inter-subject	164	0.48	0.69	-1.10

Significant differences were found in maximal KIR and maximal HExt during the jump, but no significant difference was found for KV (Table 2).

Table 2: Comparison between the right and the left leg for the maxima or minimum of the outcomes between 10° and 30° knee flexion during the jump.

Side	Maximal KV	t-test (p-value)	Maximal KIR	t-test (p-value)	Maximal HExt	t-test (p-value)
Right	5.93	T(1, 1367) = 0.15, p = 0.88	7.14	T(1, 1367) = -11.05, p < .001	8.52	T(1, 1366) = 4.84, p < .001
Left	5.74		8.77		8.15	

DISCUSSION: The primary aim of this study was to assess intra- and inter-subject variability of biomechanical risk factors for ACL injury in healthy subjects during a jump exercise in a realistic, non-standardized exergaming scenario. The secondary aim was to identify differences in risk factors between the right and the left leg. For all three biomechanical risk factors, the intra-subject variability ranged from low – high, while the inter-subject variability was moderate - high. HExt showed the highest inter-subject variability, followed by KIR and KV. High inter-subject variability in KIR and HExt, and high intra-subject variability present in several subjects in KV, KIR, and HExt, can be explained by different movement strategies such as high or low knee flexion during the lunging motion or high or low jumping height. The exergame allowed several strategies to register correct execution of the jump exercise. Also, variability could be a result of the variability in game speed. Higher or lower game speed could have led to adapted exercise execution and therefore adapted biomechanical movement patterns and higher variability thereof. A separate analysis is needed to confirm or negate this relationship. During 25 minutes of high-intensity training athletes get fatigued, possibly leading to altered muscle activation or biomechanical movement patterns. However, up to date no fatigue protocols have shown consistent effects on biomechanical risk factors for ACL injury. In contrast, it has been shown that athletes land with more favourable movement strategies when fatigued hence increasing variability but decreasing ACL loading (Bourne et al., 2019).
Only moderate inter-subject variability in KV might be a result of jump training with a clear focus on knee movement in the frontal plane in many subjects showing low intra-subject variability.

Consequently, focus on the sagittal and transverse plane is lower resulting in higher variability in these planes. However, high variability (inter-subject or intra-subject) does not automatically lead to high ACL loading. If the maximal angle of a biomechanical risk factor (KV, KIR, HExt) is high, high movement variability results in a greater probability for even more extreme angles. Thus, resulting in high loads on the ACL in a small number of repetitions. However, if the maximal angle of a biomechanical risk factor (KV, KIR; HExt) is low and movement variability is low, loading on the ACL is lower but more focused on a specific region of the ACL. Thus, possibly requiring more repetitions over a short time interval without proper recovery to rupture. Hence, in athletes showing both high knee angles and movement variability more extreme angles should be prevented for example by more detailed instructions and athletes showing low movement variability should consider long recovery times to avoid ACL fatigue failure (Wojtys et al., 2016). There were significant differences between the right and left leg for the KIR as well as the HExt, but not for KV. A possible explanation of this finding is that, due to the previous exercise, participants were moving from a side wall to the centre of the ExerCube which results in asymmetrical movement of the right and left leg. However, as athletes were trained well, they might have learned how to jump with a symmetrical KV and therefore it did not result in significant differences between the legs. Fatigue, possible learning effects, and adaptive game speed limit this study. Fatigue accumulates during the training and was not measured, which is why no specific timepoint from which fatigue affected movement behaviour, and hence data could be investigated separately, can be determined. Moreover, learning effects during the training session could lead to altered movement patterns.

CONCLUSION: Performing a jumping exercise in an exergaming scenario leads to moderate-high inter-subject variability in movement execution. Athletes showing high risk knee biomechanics as well as high movement variability should be instructed in detail to prevent extreme angles possibly resulting in ACL rupture. In athletes showing low movement variability, proper recovery periods should be considered to avoid ACL fatigue failure. The right and left leg need to be considered separately as movement is not symmetrical.

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