Examination the relation of dynamic knee valgus without marker-less movement pattern screen tests

Abstract of PhD Thesis

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INTRODUCTION

Anterior cruciate ligament (ACL) injuries are really common in population in most countries of the world. In the most physically active 20-29 year old age group, annual ACL tears can reach up to 140/100,000 cases per year. 70% of all ACL tears are sports-related, so people who play sports are more at risk of this type of injury compared to the physically inactive population. In Hungary, more than 3000 cases of ACL replacement are performed every year and this rate is increasing.

72% of all ACL injuries occur in non-contact situations. In these cases, the most common cause of injury is valgus stress on the knee joint, which causes the knee to collapse medially. Above threshold valgus stress ACL injuries usually occur during landing from a jump, during extension or when changing direction.

The internationally commonly used movement pattern screen tests (Single Leg Test, LESS Test, Drop Jump Test) are able to detect incorrect movement techniques and movement errors in time, thus preventing lower limb injuries. By detecting poorly learned movement techniques, it is possible to correct them before injuries occur through the implementation of corrective exercises.

The evaluation of the movement pattern screening tests with a movement analysis camera system provides even more accurate feedback on the current condition of the subjects.

AIMS

In my doctoral dissertation two study results are showed. The overall aim of my research in recent years has been:

1. to develop a marker-less method for dynamic knee valgus measurement;
2. to map the characteristics of single- and double-leg movement pattern screen tests;
3. to explore correlations between these movement pattern screen tests;
4. and examination the effect of a lower limb development training on dynamic knee valgus.

HYPOTHESIS

I. Study

In the first study, we compared the Kinect Azure camera with two gold standard rated measuring devices and mapped the characteristics of the single-leg squat (SLS).

I/A Hypothesis: Kinect Azure camera is a reliable device to measure the lower limb movement parameters

I/B Hypothesis: Well-trained athletes performed smaller dynamic knee valgus during knee flexion than untrained athletes

II. Study

In the second study adolescent soccer players' lower limb movement patterns were examined, as well the correlation of movement pattern screen tests results were examined.

II/A Hypothesis: Athletes who regularly performed corrective lower-limb exercises showed smaller dynamic knee valgus values during SLS, SLJ and DJ tests than those don't receive specific lower-limb exercises.

II/B Hypothesis: The correlation is strong between the SLS and SLJ test results, however there is no correlation between SLS and DJ or SLJ and DJ test results.

METHODS

I. Study

First subtask: Comparison the Kinect Azure camera, Xsens MVN and OptiTrack movement analysis system

In the first sub-task, we compared the accuracy and reliability of the Kinect Azure (Microsoft corp. Redmond, WA, USA) camera with the gold standard motion analysis camera system OptiTrack (NaturalPoint corp., Corvallis, Oregon, USA) and the sensor-based motion analysis system Xsens MVN (Xsens Technologies BV, The Netherlands). The comparison was made to see how the Kinect Azure, compared to OptiTrack and Xsens MVN, provides data on mediolateral knee and vertical pelvic motion. These two devices are marker and sensor based, and are used in biomechanical laboratories for motion analysis, such as in gait and running analyses, musculoskeletal research and film animations.

In our study, 5 healthy and physically active subjects (female=2; age=33.6±9.4 years; body weight: 69.6±9.23 kg; height: 187.4±8.65 cm) were involved. The Xsens MVN sensors were attached to the foot, leg and thigh according to the instructions for use of the device, and the sacral marker was attached to the upper part of the shorts. After the Xsens MVN sensors were attached, the sensors were calibrated according to the device manual. The sampling rate of the Xsens MVN was 60 frames/sec.

During the examination, the Kinect Azure camera was positioned 100 cm in height and 250 cm away from the subjects, so that the Kinect recorded the frontal plane, i.e. the medial-lateral displacement of the joints. The subjects were positioned behind a line parallel to the Kinect camera's lateral axis, 250 cm away from it, so that they remained facing the camera throughout the tests. Reflective markers were applied to the external ankle, the external epicondyle of the femur, the styloid process of the ulna, and the sacrum (Figure 1).

For the OptiTrack, the markers placed were also used to measure the vertical displacement of the sacrum and the mediolateral movement of the knee. After the technical adjustments, subjects performed 10 to 10 single-leg squats (SLS) on both right and left legs.

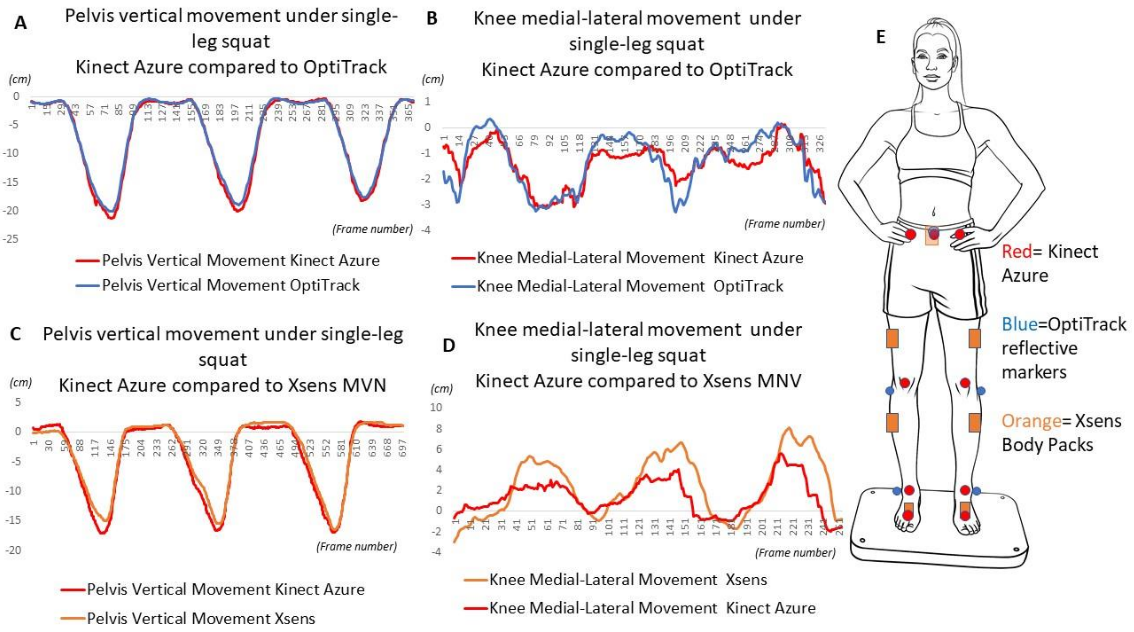

Figure 1: Comparative analysis of Kinect Azure, OptiTrack and Xsens MVN. Blue lines and blue dots show the location of the OptiTrack markers and their movement during squatting. Red represents the signals recorded by the Kinect Azure, while orange shows the location and movement of the Xsens sensors. Panels A to B show three consecutive one-leg squats of the same subject in a simultaneous comparison of Kinect Azure and OptiTrack. Panel A shows the vertical movement of the pelvis, i.e., the vertical (along the y-axis), displacement of the pelvis. The 3 lowest points of the curve are the lowest points of 3 consecutive single-leg squats. When the line in the figure touches zero, the subject was in a fully upright, single-legged standing position. Panel B, meanwhile, shows the medial-lateral knee deflection (measured along the x-axis) during the squats shown in panel A. Panels C and D follow the same pattern as panels A and B, but for the comparison of the Kinect and Xsens instruments. It is noticeable that the curves representing each instrument overlap very well, with minimal differences only at the lowest point of squatting (panels A and C). This is due to differences in measurement methodology. The differences in the medial-lateral knee movement compared to the sacrum movement are numerically very similar, the visual differences are due to the smaller limits where the

displacements are of the order of millimeters. Panel E shows the location of markers, sensors and fixed points on the human body.

The data sets recorded from the 3 devices were synchronized and combined at a sampling frequency of 30 Hz. Kinect Azure was operating with the lowest frequency (30 frames/sec), so the higher frequency data series of the other two devices (Xsens MVN 60 frames/sec, OptiTrack 120 frames/sec) had to be matched to this. When choosing the sampling frequency, we made sure that the frequency provided by the other two devices was a multiple of the Kinect Azure frequency divisible by 30, thus enabling precise synchronization of the data lines. In order to synchronize the data - in the absence of a synchronous signal - we had to find a notable point during the recording of the movement to which the data lines could be aligned and synchronized. In our case, this was the moment of starting the squat, which we could easily identify graphically and numerically, since at this moment there was a sudden decrease in the coordinate position of the sacrum compared to the one-legged standing position. The data from the Kinect Azur and Xsens MVN, as well as from the Kinect Azur and OptiTrack measuring devices could thus be compared frame by frame, and the average of the differences in centimeters was calculated from the absolute value differences per frame in the case of 100-100 squats.

Second Subtask: Examination the relationship of dynamic knee valgus and squat depth

In the second part of the first study, we looked for the answer to how we can develop a methodology that can easily and clearly measure the mediolateral movement of the knee, as well as the correlation between squatting depth and knee valgus. Twenty-two healthy and physically active subjects (female=9; age=24.5±10 years) were included in this study. Participants with mild knee complaints, such as patellofemoral pain after running, or moderate knee pain after hiking - without pathological and functional changes - were included in this research, which did not require medical supervision. Based on the Tegner scale from 1 to 10, they were on average in category 5, which means cycling, running in the city, doing recreational sports or performing heavy physical work more than 3 times a week. During the tests, we used only the Kinect Azure camera, which was placed at a height of 100 cm and at a distance of 250 cm from the test persons. The Kinect Azure recorded the frontal plane, i.e. the medial-lateral displacement of the joints (as in the first subtask). A 3 cm high platform made of plexiglass was placed on the ground 250 cm from the Kinect camera, the same as the frontal plane of the camera, which ensured that the subjects remained facing the camera the entire time. The subjects performed the SLS test standing on this platform. This setup allowed the entire body of the subjects to be seen during the recordings.

After setting up the device, the subjects were placed hip-width apart on the platform designed for this purpose, and both hands were placed on the hips. From this position, subjects first stood on their right foot, bent their left knee and pulled their heel back. After that, 4 SLS exercises were performed. The task was then repeated on the other leg. The participants were instructed to slowly try to squat down as deep as possible to the point where they could safely and stably stand up, while keeping their soles on the ground and their heels not rising.

The depth of the squats and the medial-lateral movement of the knee were recorded in centimeters. After data collection, the individual squats were analyzed individually using the Microsoft Excel program. For each subject, we examined the knee valgus value measured at 15% squat depth and the knee valgus value measured at 30% squat depth for both the right and left legs. After that, the data measured at 15% squat depth and the data measured at 30% squat depth were sorted into two separate lists per subject. The results of the right and left legs were arranged in a common list, the data were only grouped according to the 15% and 30% depth. Not every subject was able to reach the 30% squat level for both legs, but every subject reached the 15% squat depth. The 30% list thus contained less data. The data sorted into groups were tested for normality. The data in both groups showed a normal distribution, but since the 30% group contained fewer items than the 15% group, we used a one-sample t-test, where we compared the 15% group mean to the 30% group mean results.

II. Study

In this study, the lower extremity movement patterns of adolescent soccer players were examined in laboratory conditions with a Kinect Azure camera. The tests consisted of movement pattern screening tests, nominally the previously described SLS, SLJ and DJ tests.

To check the reliability of the SLS, SLJ and DJ tests, we performed a test-retest reliability study. The purpose of the reliability test was to determine whether, if the three different tests are repeated over several series, the results of each series will show the same or similar results. So we were interested in the plasticity, variability, and reliability of each test.

Subjects

In group "A" 12 (male=12; age=13.9±0.83 years; body weight=57.9±7.64 kg; height=171.27±9.12 cm) healthy, competitive athletes player were involved. The "B" group included 10 (male=10; age=14.7±0.82 years; body weight=61.8±9.28 kg; height=174.3±7.31 cm) healthy, competitive male football players.

The two groups were exposed to a similar training load and had similar weekly training numbers. In addition to the usual ball, technical and fitness training (which both teams performed equally), the fitness trainer of the "A" group had them perform specific anti-valgus, cruciate ligament support exercises twice a week at the beginning of the conditioning training for 2 months. These tasks involved various exercises performed on one leg, unstable balance positions and unilateral exercises.

Protocol

Before the tests, the participants performed a general and a lower limb warm-up. The warm-up consisted of 3 minutes of running, jumping exercises, hip, knee and ankle circling, 20 two-legged squats and one-legged squats. For familiarization, subjects performed the SLS, SLJ, and DJ exercises as many times as they wanted. Typically, this meant 4-5 ungraded repetitions per exercise. The test subjects could supplement the warm-up with other exercises according to their own needs, but we drew their attention to not getting tired during the warm-up, and the warm-up should not last more than 10-12 minutes in total. The exercises were presented in the following order: SLS, SLJ, DJ. In the case of the "B" group, we performed the Test-Retest variability test for the SLS, SLJ and DJ tests. This meant that in the first series, subjects performed the SLS, SLJ, and DJ tests, and after a 15-minute rest period, they repeated the exercises in the same order and number of repetitions in the second series.

RESULTS

I. Study – First Subtask

The absolute mean difference in the vertical movement of the pelvis between Kinect and OptiTrack was only 1.3±0.7 cm, while in the lateral movement of the knee it was 0.7±0.3 cm. When comparing Kinect Azure and Xsens, the difference measured in the vertical movement of the pelvis was 1.5 ± 0.7 cm, while the average absolute difference in the lateral movement of the knee was 1.5 ± 0.9 cm.

I. Study – Second Subtask

Based on the previously described methodology, we measured the lateral displacement of the right and left knees of 22 subjects during single-leg squats to analyze the relationship between squat depth and dynamic knee valgus. Analyzing the squatting depths compared to the lateral movements of the knee, we found that the degree of dynamic knee valgus gradually increases with the squatting depth. Figure 2 shows the squatting of 6 test subjects. 3 people keep their knees relatively stable while squatting, while 3 participants' knees significantly tilt into valgus while performing the task. Although the degree of knee valgus was smaller at 15% squatting depth than at 30%, the trends are clearly observable. Those who had significant knee valgus at a squat depth of 30% had knee valgus at 15%, but those who could keep their knees stable above their feet at 15% had less knee valgus at 30%.

The results were also analyzed using statistical tests. The knee valgus data series of the 15% and 30% levels were tested for normality, during which we determined that the data follow a normal distribution. Given that the data series followed a normal distribution, we used a t-test. The average knee valgus degree at 15% squat depth was 2.63 ± 2.63%, while at 30% depth it was significantly higher, 4.5 ± 3.59% (t (27) = 2.77, p = 0.01), see Figure 2.

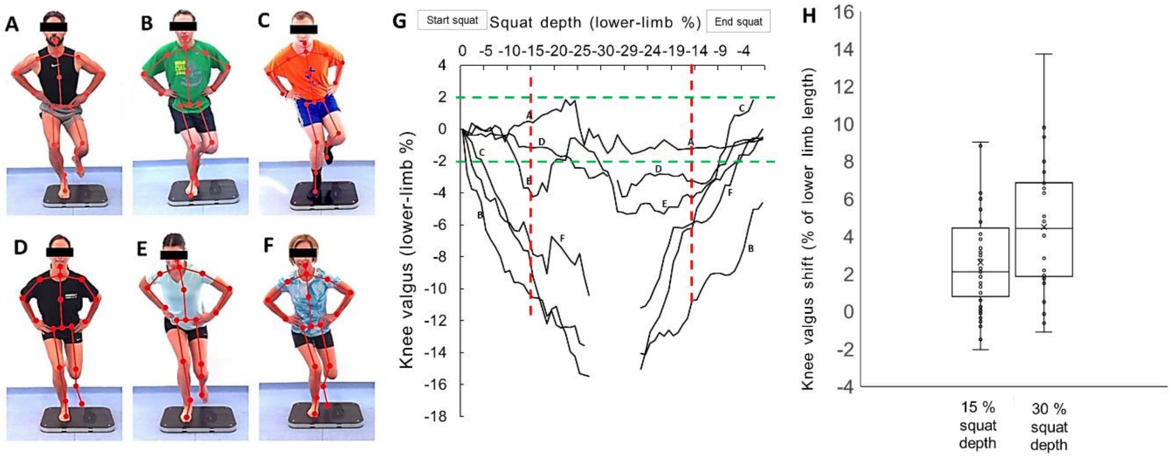

Figure 2: Illustration of the relationship between squat depth and knee valgus in 6 subjects. The left panel shows the 6 subjects' single-leg squats of varying quality, from very excellent to very poor. In the middle panel, the black lines represent the lateral knee motion of the subjects, the X-axis shows the squat depth and the Y-axis shows the knee valgus/varus. In the majority of cases, the black lines break off steeply, leaving only 1-2 lines in the green corridor representing 2% lateral displacement. The knees of those remaining in or approaching the green corridor all remained very stable in one position throughout, while the others had significant lateral knee valgus. The far right panel shows the knee valgus values measured at the 15% and 30% squat levels, showing that the deeper position has significantly higher valgus than the lower level.

II. Study – Results of SLS, SLJ and DJ test

The second study compared the SLS, SLJ and DJ scores of Group A and B. The aggregated results are shown in Figure 3. Group A had better valgus scores than Group B on all tests and this difference was significant on the right side in SLJ_I (U(22)=20, Z=

-2. 638, p=0.008), and in SLJ_II phase also on the right side (U(22)=18, Z= -2.558, p=0.011) and in DJ_II, on the left side (U(22)=31, Z= -1.912, p=0.056).

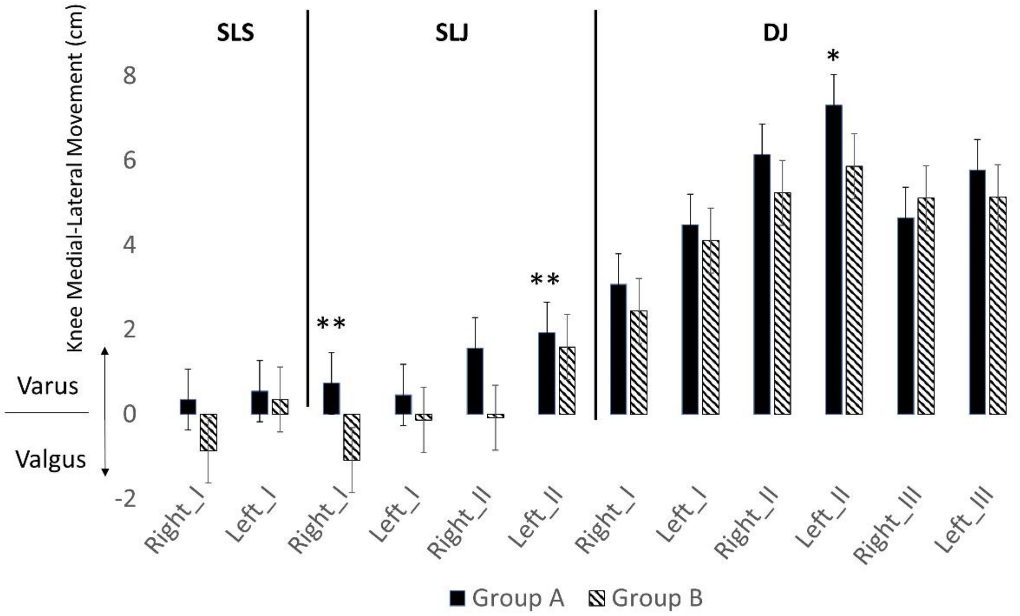

Figure 3: Mean knee valgus/varus values recorded during SLS, SLJ and DJ tests comparing Group A and B. In almost all cases, Group A members performed better results than Group B members. The difference was significant in 3 cases. Based on the Mann-Whitney U test, * indicates a significance level of p<0.05 and ** indicates a significance level of p<0.01. The difference is presumably due to the fact that members of group A had received separate lower limb correction exercises for a longer period prior to the survey, while members of group B had not. Positive values indicate movement in the varus direction, while negative values indicate movement in the valgus direction.

II. Study – Results of Test-Retest reliability examination

Pearson's Correlation Coefficient shows the strength of the relationship between the first and second set of SLS, SLJ and DJ tests. If the value is closer to 1 that means strong correlation between the two factors. However, if the value of r approaches 0, it means that there is no or only a weak relationship between the two values. Table 1 shows that in most of the tests examined, there is a strong or very strong correlation between the first and second set of scores.

Table 1: Results of the reliability examination of SLS, SLJ and DJ tests.

	SLS Right	*SLS Left*	***SLS ∑***	*SLJ R. I.*	*SLJ L. I.*	*SLJ R. II.*	*SLJ L. II.*	***SLJ ∑***	*DJ R. I.*	*DJ L. I.*	*DJ R. II.*	*DJ L. II.*	*DJ R. III.*	*DJ L. III.*	***DJ ∑***
Pearson correlation (r)	*.715*	*.612*	***0.664***	*.872*	*.910*	*.560*	*.649*	***0.748***	*.732*	*.940*	*.906*	*.697*	*.892*	*.883*	***0.841***
p	*.020*	*.060*	***0.04***	*.002*	*.001*	*.117*	*.059*	***0.045***	*.016*	*.000*	*.000*	*.025*	*.001*	*.001*	***0.007***

II. Study – Correlations between SLS, SLJ and DJ tests' results

The strength of the correlations between the SLS, SLJ and DJ tests was determined using Pearson's correlation coefficient. Figure 4 presents the results. Strong correlations were found between SLS and SLJ I (r=0.788) and SLS and SLJ II (r=0.725). No or weak correlations were found between SLS and DJ and between SLJ and DJ.

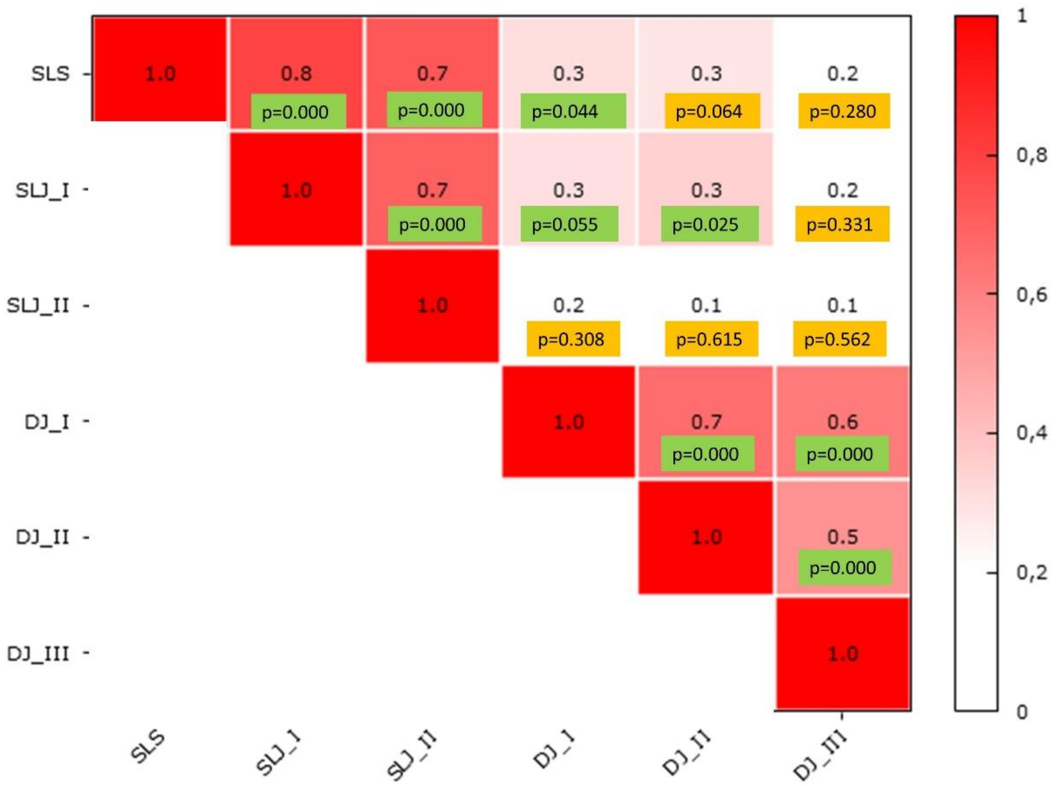

Figure 4: Correlation matrix showing the strength of the relationship between SLS, SLJ and DJ test scores. The figure shows the strength of the correlation between each test result. The shaded red colours indicate a strong or very strong correlation between each phase of the SLS and SLJ test, while only a weak correlation is observed between the one-leg exercises and the DJ test.

DISCUSSION

The main goal of this dissertation was to lay the foundations for a new, cost-effective motion analysis tool that is fast, simple and easy to use in practical situations. I see the practical utility of the research in the timely, efficient, accessible and quantifiable screening of dynamic knee protein, which causes the majority of knee joint injuries and cruciate ligament tears, and then correcting them after identification. Recognition of dynamic knee valgus is very important for the prevention of ACL tears, as this in itself places a significant burden on the athlete, the healthcare system and the athlete's sporting club. It should also be remembered that in later life, athletes who have previously injured their ACL are much more likely to develop knee osteoarthritis.

Comparison of Kinect Azure, Xsens MVN and OptiTrack systems

In our examination, we compared the artificial intelligence-based Kinect Azure, the OptiTrack camera system using reflective markers, and the radio frequency-based Xsens MVN device. The evaluated results of the vertical pelvis movement were very similar for all three devices. When plotting the medial-lateral movement of the knee on a graph, little overlapping curves were obtained, but the difference is more of a visual origin due to the small scaling range. When the narrower interpretation range of a few centimeters is magnified, larger excursions are seen than for the much larger displaced sacrum. On reflection, it becomes clear that the displacements in the enlarged graph are predominantly millimeter-scale.

From the overall results, and from the literature studied, it appears that the Kinect is absolutely suitable for the purpose for which it was intended - i.e. mainly for the investigation of vertical pelvic and lateral knee movements.

Correlation between dynamic knee valgus and squat depth

A new finding of the research is that squat depth has a strong effect on the magnitude of dynamic knee valgus. In general, the deeper the squat, the greater the lateral knee valgus, so the range of motion of the subjects performing the exercise is a not insignificant issue in the evaluation of each movement pattern screening test, as it can have a major impact on the final "diagnosis". The assessment of dynamic knee valgus should start at a minimum of 15% of the lower limb length, but our research outlines that a squat depth of 30% is even more optimal for athletes/athletes. Many studies in the literature have used the previous Kinect V2 camera, testing the new Kinect Azure camera in this respect is also novel.

Our results show that test subjects with adequate muscle strength and neuromuscular regulation are able to keep their knees above their feet at the 15% squat level. It appears that, when correctly executed in single-leg squats, the knee remains in a 2% lateral "corridor of motion" throughout, which means that regardless of the depth of squat, their knee does not make more than 2% mediolateral movement. This phenomenon is illustrated in Figure 2. The really well-trained athletes were able to keep their knees in the 2% lateral corridor at both the 15% and 30% squat depths, but the knees of the untrained individuals continued to tilt medially as the squat depth increased.

Test- retest results

During the test-retest examination, we were curious to see what differences we get between the test results if the individual tests are carried out 15 minutes apart in 2 series in a row, without any intervention or affecting the condition of the person examined. So how strong will the correlation be between the results of 2 identical tests performed one after the other, i.e. how much will they allow us as practicing coaches to be led to the same conclusion. In the case of the SLS exercise, the correlation between the series was strong ($p=0.664$), in the case of the SLJ it was even stronger ($p=0.748$), and in the case of the DJ test it was very strong ($p=0.841$). This also shows that, while the variability of the two-legged jump test is relatively small, the one-legged exercises showed high variability among the surveyed football players. An interesting measure from the point of view of training preparation or training goal can be the reduction of variability between the results of single-leg exercises. Therefore, a higher level of fitness, more precisely the regulation, muscle strength, stability and mobility of the right lower limb can be a measure of correct squat execution, if the variability of the result of one-legged squats also decreases, so the correct lower limb movement patterns are consolidated in such a way that they automatically appear in a similar image in any state of fatigue or in any game situation.

Correlations between the SLS, SLJ and DJ tests'results

When comparing the SLS, SLJ and DJ tests, we found higher varus values for the DJ test and higher valgus values for the single-legged exercises. We found a strong relationship in the lateral movement of the knee between SLS-SLJ_I ($r=0.788$) and SLS-SLJ_II ($r=0.725$) in adolescent male soccer players. On the other hand, there was a weak correlation between SLS and DJ ($r=0.305$), and there was no correlation between DJ and

SLJ (r=0.161). From this we can conclude that the use of a multi-aspect series is essential for determining the overall lower limb movement patterns of athletes. The application of a single test is not enough to realistically determine the current condition of our athlete's lower limbs, for comprehensive feedback, the combined application of several tests is necessary. Athletes would perhaps produce a normal amount of medial-lateral knee movement during the DJ test, thus placing them in an optimal category, but single-leg tests reveal deviations and movement errors in the athletes' lower limb functions. For a comprehensive condition assessment, it is recommended to use the one- and two-leg tests together.

Comparison the results of Group A and B

Comparison the results of groups A and B shows that the members of Group A had better lower extremity performance during the tests than the members of Group B. The special additional lower extremity exercises resulted in more precise technical execution among the members of group A. Target-specific tasks, such as squatting, one-legged squats, one-legged balance positions, special strengthening of the muscles around the hips, and one- and two-legged exercises, performed with the correct technique, effectively improve the quality of movement and reduce the incidence of ACL injuries.

CONCLUSION

Decisions about the Hypothesis

I/A Hypothesis: Kinect Azure camera is a reliable device to measure the lower limb movement parameters

The hypothesis is accepted. Kinect Azure was compared to two internationally accepted and widely used "gold standard" motion analysis systems. The comparative tests showed that there is an average difference of 0.7-1.5 cm in the measured joint points between the

3 devices we used, making the Kinect Azure camera suitable for our study purposes (Figure 1).

I/B Hypothesis: Well-trained athletes performed smaller dynamic knee valgus during knee flexion than untrained athletes

The hypothesis is accepted. A comparison of individuals with mild knee complaints but with an active lifestyle showed that, in general, as the squat depth increases the degree of knee valgus also increases. There is a significant difference between squat depths of 15% and 30% for dynamic knee valgus. Well trained athletes who can maintain their knee in the knee over foot position or laterally outwards from it throughout the squat, regardless of vertical movement, with almost no lateral movement of the knee, are above average (Figure 2). This gives them a high degree of stability, which significantly reduces the chance of ACL injury.

II/A Hypothesis: Athletes who regularly performed corrective lower-limb exercises showed smaller dynamic knee valgus values during SLS, SLJ and DJ tests than those don't receive specific lower-limb exercises.

The hypothesis is accepted. Members of group A, who regularly performed corrective and ACL support exercises, scored better on all the tests used to assess mediolateral knee motion than members of group B, who did not perform any additional exercises (Figure 3). The difference was significant in several cases.

II/B Hypothesis: The correlation is strong between the SLS and SLJ test results, however there is no correlation between SLS and DJ or SLJ and DJ test results.

The hypothesis is accepted. Based on our results, there seems to be a strong correlation between the results of the single-leg exercises, and the results of each phase of the SLS and SLJ tests are highly correlated. But the SLS and SLJ results do not converge or converge only minimally with the DJ test results. Thus, it is possible to perform well on the bipedal exercises while performing poorly on the monopedal tasks. Therefore, for a *complete lower limb movement pattern assessment, multi-aspect, multi-test testing is essential (Figure 4).*

AUTHOR'S PUBLICATIONS:

Publications related to the topic of thesis

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Uhlár, Á., Ambrus, M., Kékesi, M., Fodor, E., Grand, L., Szathmáry, G., … Lacza, Z. (**2021**). Kinect Azure–Based Accurate Measurement of Dynamic Valgus Position of the Knee - A Corrigible Predisposing Factor of Osteoarthritis. Appl Sci. 11(12).

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Publications not related to the topic of thesis

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of armed forces and services personnel using artificial intelligence. Sci Sec, 3(3), 166–175.

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