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Kinect Azure–Based Accurate Measurement of Dynamic Valgus Position of the Knee—A Corrigible Predisposing Factor of Osteoarthritis

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Featured Application: Lateral disposition of the knee under load in the single-leg squat (SLS) test is widely used for screening functional instabilities of the knee under load, which is associated with elevated risk of lower limb injuries and early onset of osteoarthritis. We identified that approximation of the Quadriceps angle at the lowest point of squat is error-prone and not suitable for comparing patients or monitoring progress, as it is highly dependent on squat depth and muscle strength. The current study shows that the Kinect Azure–based Dynaknee software is able to simultaneously measure squat depth and the dynamic valgus position of the knee. We suggest that valgus shift, measured at 15% squat depth and expressed in percentage of lower limb length, may be a more reliable parameter for evaluating dynamic valgus in an orthopedic or physical therapy office.

Abstract: (1) Dynamic knee valgus is a predisposing factor for anterior cruciate ligament rupture and osteoarthritis. The single-leg squat (SLS) test is a widely used movement pattern test in clinical practice that helps to assess the risk of lower-limb injury. We aimed to quantify the SLS test using a marker-less optical system. (2) Kinect validity and accuracy during SLS were established by marker-based OptiTrack and MVN Xsens motion capture systems. Then, 22 individuals with moderate knee symptoms during sports activities (Tegner > 4, Lysholm > 60) performed SLS, and this was recorded and analyzed with a Kinect Azure camera and the Dynaknee software. (3) An optical sensor coupled to an artificial-intelligence-based joint recognition algorithm gave a comparable result to traditional marker-based motion capture devices. The dynamic valgus sign quantified by the Q-angle at the lowest point of the squat is highly dependent on squat depth, which severely limits its comparability among subjects. In contrast, the medio-lateral shift of the knee midpoint at a fixed squat depth, expressed in the percentage of lower limb length, is more suitable to quantify dynamic valgus and compare values among individual patients. (4) The current study identified a new and reliable way of evaluating dynamic valgus of the knee joint by measuring the medial shift of the knee-over-foot at a standardized squat depth. Using a marker-less optical system widens the possibilities of evaluating lower limb functional instabilities for medical professionals.

Keywords: osteoarthritis; ACL rupture; dynamic knee valgus; single-leg squat; motion capture; Kinect Azure

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1. Introduction

Dynamic knee valgus is an abnormal position of the lower extremity; the weight bearing knee tilts to the medial side from the midline of weightbearing, causing uneven weight distribution and sheer forces within the joint. Dynamic knee valgus is an often-observed musculoskeletal disorder in sports and daily life. According to recent studies the most common reasons for dynamic knee valgus are the lack of adequate gluteus strength, [1–3] weak quadriceps muscle [4] or weak hamstring muscle [5]. Excessive knee valgus is a predisposing factor in osteoarthritis (OA) [6] and patellofemoral pain syndrome (PFP). The dynamic knee valgus position may also lead to typical sport injuries. Studies show that ball games, martial arts and skiing are the most dangerous types of sports with regard to knee injuries [7,8]. Furthermore, the dynamic valgus position is one of the most common causes of non-contact Anterior Cruciate Ligament (ACL) rupture [7,9]. Knee valgus position during exercise may appear at landing from jumps or losing and re-gaining balance [10,11]. This is an injury risk because the joint capsule is overloaded while the ACL is elongated, and when the load is overwhelming the ACL might be ruptured. ACL injuries are widespread in the world; for example, each year one out of 3500 people in the United States suffers from ACL injuries. About 70% of all ACL injuries are the results of sports participation: 15% of ACL injuries occur in soccer, 10% to 13% in skiing, 9% to 15% in football, 9% to 10% in baseball, and 8% to 15% in basketball [12]. ACL rupture alone is a predisposing factor for knee osteoarthritis [13]. Moreover, long-term sequelae of ACL injury includes knee osteoarthritis in up to 90% of the patients [14]. Finally, ACL-injured athletes develop knee osteoarthritis symptoms significantly earlier than those without ACL injuries [15]. In summary, excessive dynamic knee valgus coupled with sports activities can lead to an ACL elongation and rupture, which in turn results in premature osteoarthritis of the knee. Since dynamic valgus is a corrigible risk factor, early and accurate evaluation is crucial.

There are several methods to measure dynamic knee valgus in an office setting. Clinicians, coaches and physical therapists commonly use single-leg functional tests such as step-up, hop, drop jump or squat to evaluate the momentary condition of the knee shift in the horizontal plane [16]. A simple observation is fast, easy and inaccurate, while using dedicated kinesiometry systems is unfeasible for this particular task. Several video analysis–based systems have become available recently for monitoring the dynamic valgus of the knee; however, the standardization of these measurements is not yet available [17]. Motion capture systems using markers are accurate, but they are expensive and are only suitable in motion capture laboratories. Therefore, there is a need for reliable evaluation of knee dynamic valgus that can be performed in a medical or physiotherapy office.

The Kinect Azure 3D camera advantages over gold standard systems are that the Kinect camera is able to detect joints and capture motion without markers. Furthermore, the Kinect Azure camera is portable, easy and quick to use, and it is a low-cost solution compared to medical equipment standards. Although the previous Kinect version had acceptable applicability in motion analysis [18–20], the Kinect Azure system provides higher accuracy [21,22] and is technically comparable to those of standard motion capture systems, OptiTrack or MVN Xsens. [23–26]. The aim of the current study was to design a reliable assessment method of the single-leg squat (SLS) test with a second generation Kinect Azure 3D camera.

2. Materials and Methods

The experimental procedures were approved by the ethics committee of University of Physical Education of Budapest, Hungary (Ethical license number: TE-KEB/No43/2019).

2.1. Participants

Twenty-two (Female = 9; Age = 24.5 $\pm$ 10) healthy and physically active participants were involved in this study. Participants enrolled in the study experienced minor knee complaints, without any obvious pathology or a condition that may require medical attention. Minor knee complaints mean slight patellofemoral pain after running or mild knee pain after hiking. The knee condition was assessed by the Lysholm questionnaire; participants who had a score less than 60 were excluded from the study. Participants also filled out the Tegner activity scale, where the exclusion criteria was a score lower than 4 to exclude sedentary patients. Participants were asked to wear a tight T-shirt or undershirt and shorts without covering the knees. The measurement was performed barefoot, and the subjects did not wear knee braces or kinesiotape. The overall well-being of the subjects was assessed by the standard SF-36 score [27], the level of sports activity was evaluated by the Tegner score [28] and subjective knee function by the Lysholm score [29].

2.2. Microsoft Kinect Azure Camera System and Evaluation

Kinematic parameters were evaluated with a Microsoft Azure Kinect camera system (Microsoft Corp. Redmond, WA, USA). Originally, the Kinect camera was developed for video games to improve the gaming experience. Kinect Azure contains an RGB (red, green and blue) camera and a three-dimensional infrared depth sensor; thus it is able to measure the full body kinematics. Kinect Azure estimates 3 coordinates of every major joint of the human body in 3 planes without any marker or other supplemental equipment. Kinect provides cost-effective, quick and user-friendly lower limb examinations. During the examination, the camera was set up 250 cm away from the subjects at a 100 cm height from the ground. This camera placement provided ideal circumstances to capture a full-body image of the subjects. All data were collected with the help of a custom software (Dynaknee, OrthoSera Kft, Budapest, Hungary) for Windows 10 operation system that allowed data management, recording and analysis. The Kinect camera recorded 3 coordinates of every major joint of the human body in 3 planes without any markers or on-body sensors: the X coordinate in medial-lateral, the Y coordinate in vertical and the Z coordinate in anterior-posterior direction [21]. The origin of the coordinate system is the center of the IR camera in Kinect. Thus, Kinect Azure automatically detects the location of the hip, knee and ankle joint centers and records 3 coordinates of every major joint of the human body [21]. Microsoft uses an encrypted software, which can detect human joint centers through an artificial intelligence-based algorithm [21,30]. In this study, only the lower-limb functions were examined; thus we analyzed the following variables: time_stamp, wrist_right/left_X_Y, pelvis_Y, hip_right/left_X_Y, knee_right/left_X_Y, ankle_right/left_X_Y and foot_right/left_X_Y coordinates.

2.3. Validation of Microsoft Kinect Azure Camera with Xsens MVN and OptiTrack Motion Capture Systems

In the current study, the Kinect Azure camera accuracy and reliability was compared to a gold standard motion capture system, OptiTrac, and a high accuracy inertial measurement unit, MVN Xsens. The XSENS MVN inertial motion capture system is an easy to use, completely portable system, which is based on state-of-the-art miniature inertial sensors and wireless communication solutions combined with advanced sensor fusion algorithms, incorporating synchronized video data. Instant graphical output is provided, including joint angles [31]. OptiTrack is a widely used motion capture system and considered as one of the most accurate [23,24]. These two systems can be regarded as gold standard marker-based systems; they are installed in movement analysis laboratories for the purposes of gait analysis, musculoskeletal research and animation.

Five (Female = 2; Age = 33.6 $\pm$ 9.4 years) healthy and physically active participants were involved in the comparative examinations. On the first testing day the Xsens body packs were fixed on the participants' extremities as they stood in front of the Kinect Azure camera. Only lower leg functions were examined, with markers placed on the pelvis, calves, thighs and feet (Figure 1). Participants executed 10 single-leg squats on each side while the Kinect camera and Xsens were recording at the same time. On the second testing day the participants were examined in an OptiTrack movement laboratory. They wore reflective markers on their pelvis, knees and ankles (Figure 1). In both tests, during the examinations, the knee medial-lateral and pelvis vertical movements were recorded with each pair of motion capture systems simultaneously. Recorded data streams were synchronized and resampled to 30 Hz frequency. Data from the instruments were compared frame to frame, and means of differences were calculated from absolute differences in cm.

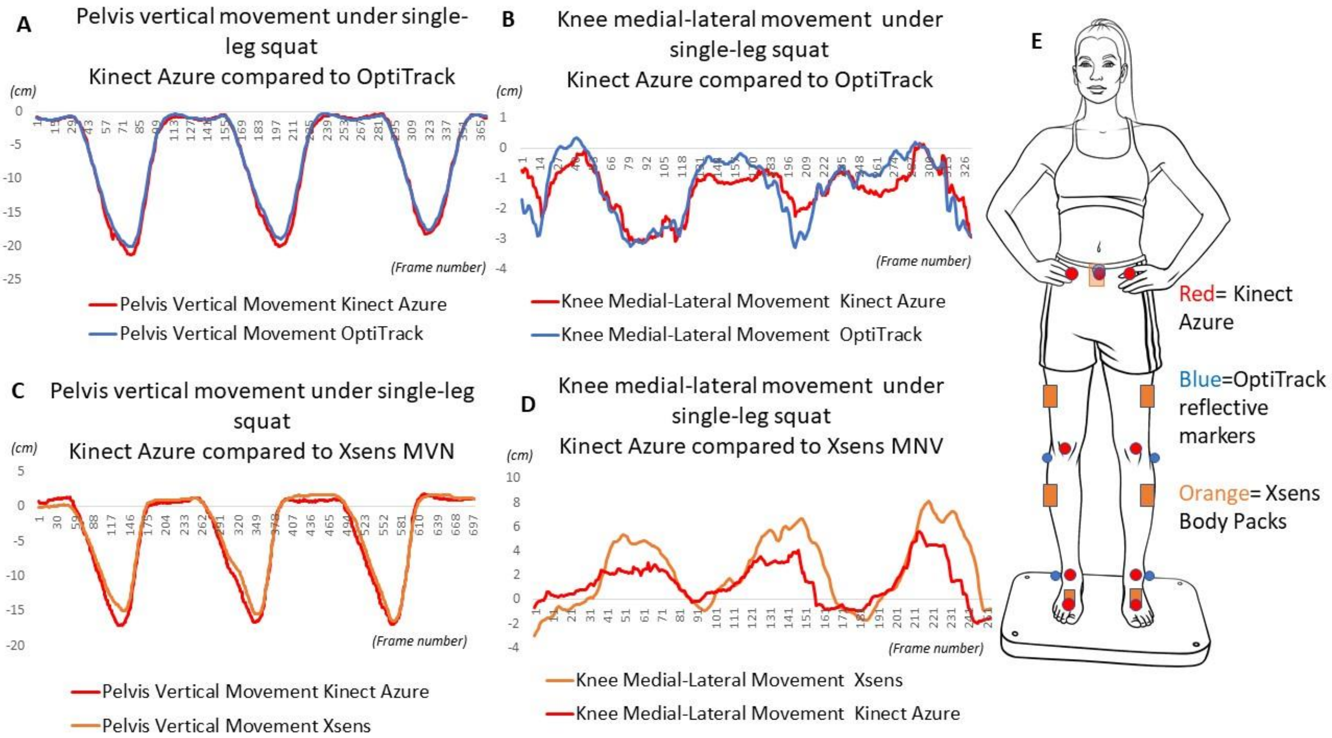

Figure 1. Blue lines and markers show the OptiTrack sensors and recordings, red color shows Kinect Azure, and orange color shows Xsens. On Panels (**A**–**D**) three consecutive single-leg squat recordings are shown by a representative subject. Note that pelvis vertical movements (Panels **A** and **C**) are tightly coupled by the separate systems; there are only small discrepancies around the lowest point of squat. Knee medio-lateral movements are even closer to each other numerically (Panels **B** and **D**); however, these recordings are more "noisy", probably due to balancing micro-movements during a squat. Panel (**E**) shows the locations of the markers on the human body (red dot = Kinect Azure; blue dot = OptiTrack; orange rectangle = Xsens MNV).

2.4. Procedure

The participants performed four well-executed single-leg squats on each side. The starting position was standing with hands on hips. Following the instructions, the subjects bent their left knee and pulled their left heel up and backward; they slowly performed single-leg squats as deep down as possible while their heel and foot kept in contact with the floor. The squats were considered valid when participants sustained their balance under the whole repetition with their hands on their hips and did not step away during the examination. In case of an improperly executed test, the subjects were asked to repeat the session. Squat depth and knee movement results were calculated in centimeters and converted to a percentage of lower-limb length, as measured by the Kinect system. After converting the data, each squat was analyzed separately.

3. Results

3.1. Validation of Kinect Azure Versus Marker-Based Systems

The vertical tracking of the pelvis was very close among the three different systems, with only the lowest points showing discrepancy, probably due to a tilt in the hip at this position (Figure 1). The lateral movement of the knee was less smooth but numerically closer among the various systems (Figure 1). The absolute average difference in the case of pelvis vertical movement between Kinect Azure and OptiTrack was 1.3 $\pm$ 0.7 cm, and the difference between knee lateral-medial movement was 0.7 $\pm$ 0.3 cm. Meanwhile, the average pelvis difference was 1.5 ± 0.7 cm, and the average knee lateral-medial movement was 1.5 ± 0.9 cm between Kinect Azure and Xsens MVN (Figure 1).

3.2. Results of the Kinect Azure Methodological and Biological Examinations

Participants were healthy and active individuals with good overall scores on the SF-36 wellbeing scale. Their typical level of sports activity on the Tegner scale of 1 to 10 was "5—Competitive sports (bicycling, cross-country skiing, recreational sports running on uneven surface more than 2 times a week or heavy labor (building, forestry)". Their average Lysholm knee score was about 81 on a scale of 1–100, showing mild knee complaints (Table 1).

Table 1. Descriptive values of subjects.

Age, Years	**26.5**	**±12.43**
Male, n	13	
Female, n	9	
Weight, kg	69.54	±10.38
Height, cm	174.81	±9.99
Lysholm	82.92	±15.72
Tegner	4.67	±1.96
SF36		
Physical functioning	87.50	±18.52
Role limitations due to physical health	77.08	±29.11
Role limitations due to emotional problems	86.00	±26.59
Energy/fatigue	54.17	±20.76
Emotional well-being	72.67	±20.59
Social functioning	78.00	±20.83
Pain	67.50	±20.46
General health	71.67	±15.42

Note. Means ± SD; SF36 Short Form Health Survey, which is a standardized international well-being test [27].

A selected participant showed a correctly executed single-leg squat and some incorrectly performed squats in order to demonstrate the room for dynamic valgus shift in a healthy joint during a complete single-leg squat. The participant was asked to consciously make only one typical mistake during each squat. Hip, knee and foot X coordinates were fixed in single-leg-stance position; this was the reference state. In the first case, when the participant executed a technically correct squat, there was a minimal difference in the knee medio-lateral movement compared to the single-leg stance; thus the athlete could hold his knee over his foot (Figure 2). In the second case, the subject dropped his hip down (Trendelenburg sign), while in the third case, the participant executed the squat with a pronated foot. In both of these cases the knee moved significantly to the medial side from the knee-over-foot position (Figure 1). During the last case, the subject pushed his knee to the medial side as much possible in order to demonstrate the maximum room for change in a healthy joint during a single-leg squat.

Several variables can define the medial/lateral knee movement during squatting. First, the knee angle was defined based on wrist_X, knee_X and ankle_X coordinates; the Kinect wrist point was used as an approximation of the anatomical point of the Spina Iliaca Anterior Superior. Second, the knee angle was evaluated by the Kinect hip_X, knee_X and ankle_X coordinates. Third, the knee medial-lateral shift was measured (Figure 3). The different evaluation methods of knee valgus are shown in Figure 3. The wrist-point-based approximation of the quadriceps angle is rather variable in this setting, since the wrist point may move independently as the subject adjusts her hand during the squat. The hip-point-based Q-angle evaluation is anatomically less accurate, as the Kinect's definition of 'hip' falls farther away from the anatomical point than the hand; however, the measurement is less noisy (Figure 3). The lateral movement of the knee, measured from the ankle midpoint, is the most reliable as it is calculated from two rather than three measured parameters, i.e., ankle and knee vs. ankle-knee-hip (Figure 3).

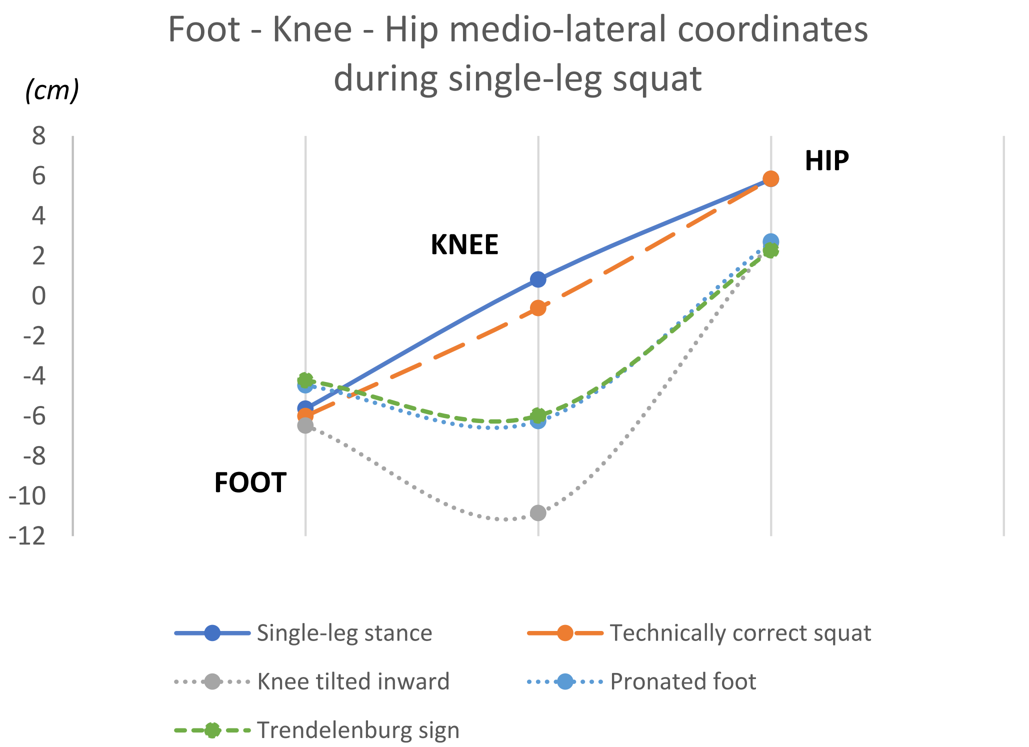

Figure 2. Representative changes of the knee medio-lateral coordinates under the single-leg stance and during technically good and poor squats as demonstrated by a healthy athlete. The y axis shows the medio-lateral positions of the respective joint midpoints during stance and squats. In the case of standing or a technically correct squat, the three joints form a straight line, indicating that the load is centered on the midline of the knee. In the case of the Trendelenburg hip or the pronated foot tests, the knee moves to the medial side from the midline; however, one can produce a higher level of valgus by keeping the knee in a deliberate valgus position throughout the squat.

We measured the lateral shift of the knee over the midpoint of pressure for the left and right knees of 22 participants during a single-leg squat in order to gain insight into the interrelation of squat depth and dynamic valgus. It became evident that there is a fairly large variation among subjects on what is felt as the deepest possible squat: some people hardly bent their knees, while others descended all the way until touching the floor. Analyzing the depth versus lateral shift curves, it was clear that the size of the valgus is very dependent on squat depth, which was not taken into account in previous studies. Figure 4 shows six representative subjects: three remained relatively stable and three showed a clear valgus shift (Figure 4). We also observed that all subjects were able to demonstrate a 15% squat depth, measured in percentage of lower limb length; however, only a small subset was able to reach 30%, which corresponds to what can be considered sufficient by subjective evaluation. Nonetheless, although the magnitude of valgus is smaller at 15% squat depth than at 30%, the trends are the same; i.e., those who have a prominent valgus at 30% already do so at 15%, and conversely, those who are stable at 15% remain stable at 30% (Figure 3). The average valgus value at 15% squat depth was 2.63 $\pm$ 2.63%; meanwhile, the average valgus value at 30% squat depth was significantly larger, at 4.5 $\pm$ 3.59% (t (27) = 2.77, p = 0.01); see Figure 4. Table 2 shows the valgus data of the 22 participants.

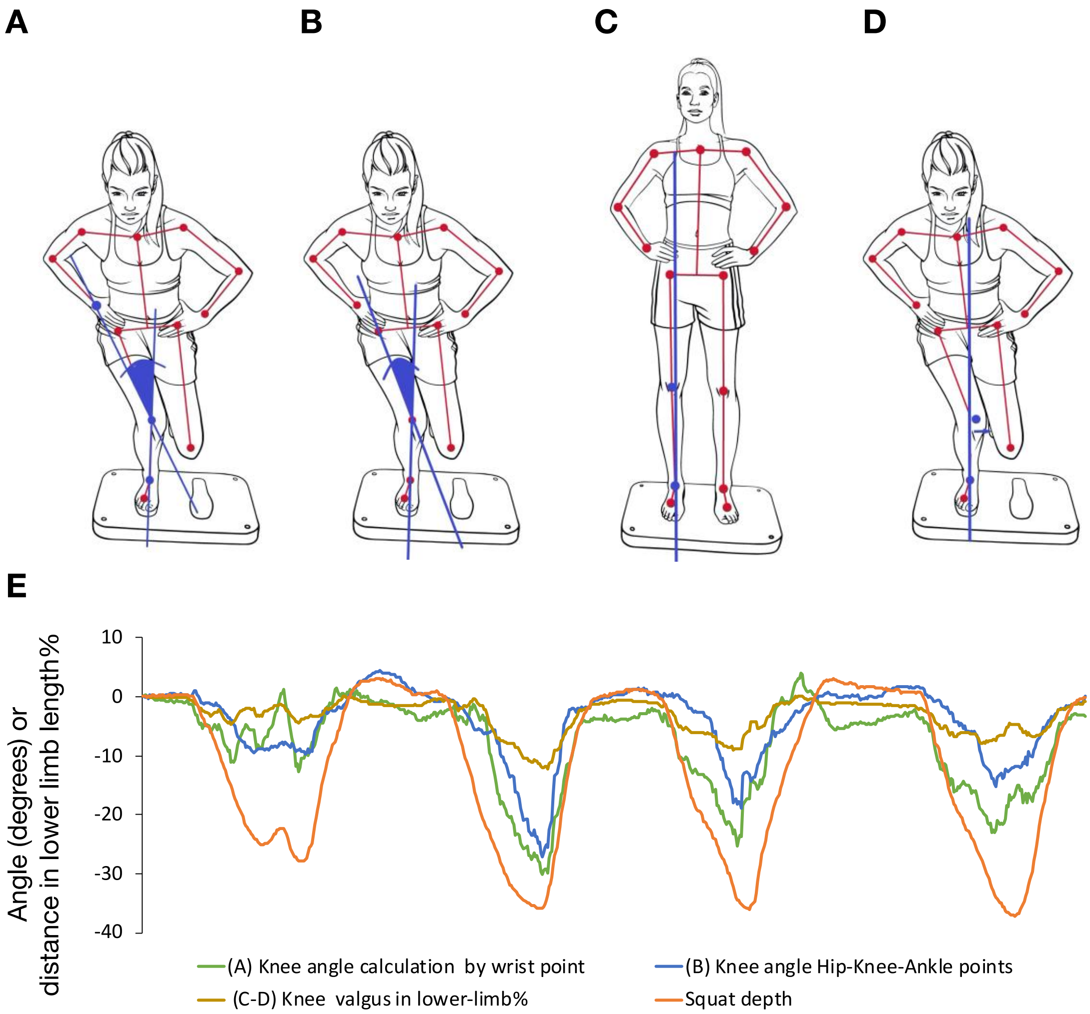

Figure 3. Different types of knee deviation calculations and squat depth changes under the single-leg squat test. Methods of knee valgus measurement. (**A**) Knee angle measurement is based on hip_X, knee_X and ankle_X coordinates. (**B**) Knee angle measurement is based on wrist_X, knee_X and ankle_X coordinates. (**C**,**D**) Knee valgus measurement is based on relative medial-lateral knee_X deviation compared to the standing position. Panel (**E**) shows four representative squats performed by a single subject evaluated by these methods simultaneously. Squat depth is also plotted as a reference. Note that using the Kinect wrist point as a reference for 'hip' is rather noisy (green line), while the hip-point based Q angle and the knee-over-foot lateral shift variables move more in parallel with each other.

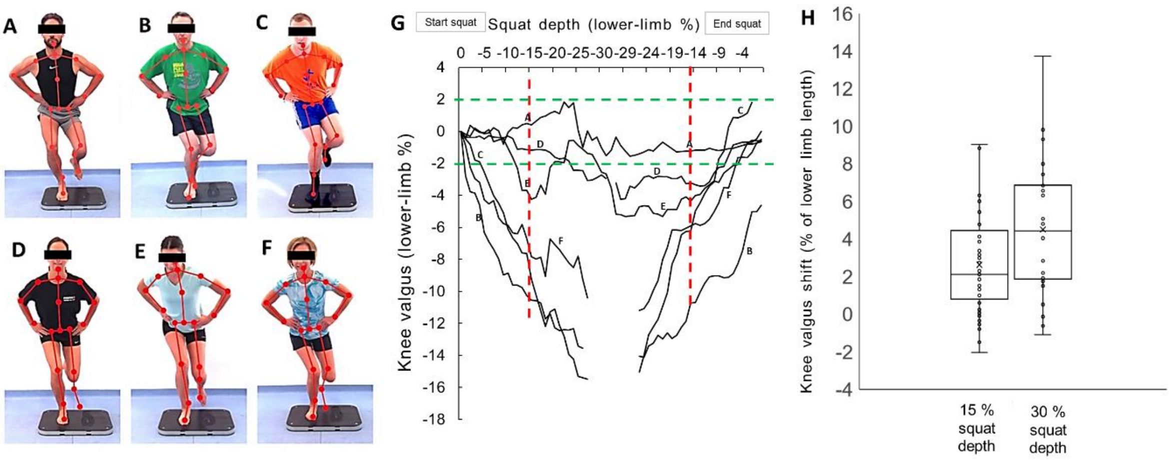

Figure 4. Representative recordings of single-leg squats vs. squat depth in six subjects. Panels (**A**–**F**) show three male and three female subjects at exactly 15% squat depth; note that although the knee is only slightly bent, the valgus tendency is evident in those who are prone to this deviation (**B**,**C**,**F**). Panel (**G**) shows the valgus shift vs. squat depth plot of these individuals; letters on the curves correspond to the image shown. Squat depth is measured on the horizontal axis, and knee deviation on the vertical; the lines that are not continuous indicate that the subject didn't reach the maximum squat depth at 30%. Vertical dotted lines show the 15% depth mark, where the valgus or stable tendencies can already be observed. Panel (**H**) shows the distribution of valgus shift at 15% and 30 squat depths in 44 knees. The line represents the median.

Table 2. Knee valgus values of subjects.

Participants	Right Knee Valgus at 15% Squat Depth (%)	Left Knee Valgus at 15% Squat Depth (%)	Right Knee Valgus at 30% Squat Depth (%)	Left Knee Valgus at 30% Squat Depth (%)
1	−0.28	1.31		
2	5.43	−0.35	6.96	0.66
3	4.85	2.30	9.31	6.32
4	9.02	−0.55	13.74	−0.62
5	3.15	−0.10	7.44	−0.14
6	1.85	−2.05	1.91	−1.11
7	2.12	0.24	2.83	1.50
8	−1.50	0.18	0.51	2.22
9	3.37	1.11	2.88	5.07
10	8.83	6.01		6.41
11	6.12	4.12	9.81	8.00
12	4.77	3.11	6.57	4.04
13	2.11	1.95	6.38	7.49
14	6.05	1.55		
15	6.37	1.89		
16	6.32	4.90		6.85
17	3.85	1.52		
18	3.41	1.95		
19	2.98	0.99		
20	0.60			
21	2.73	−0.79	4.80	2.19
22	1.51	0.06	2.21	1.75
Average	2.63		4.50	
SD	2.63		3.59	

4. Discussion

The Kinect Azure system was compared to two well-known motion capture systems during single-leg squat tests. Kinect automatically detects the 'spine base' anatomical point, while OptiTrack and Xsens monitor markers on the sacrum. At the lowest point of the squat, some participants bent forward, which resulted in a discrepancy among the

Spine Base point of the Kinect and the Xsens and OptiTrack markers that were fixed on the sacrum. Therefore, the three systems were technically very accurate as compared to one another, and the observed numerical difference is the result of the non-simultaneous anatomical points that were followed by each system, i.e., dorsal sacrum versus spine base. A similar phenomenon was observed in the knee: the Xsens sensor followed the medial tibia and extrapolated the 'knee' point from these data. The OptiTrack monitored the lateral epicondyle of the femur. In contrast, the Kinect system used the contours and the depth dimension of the knee area and used artificial intelligence to calculate a knee midpoint, arguably providing a better approximation of the mid-patellar point than the other two systems. Moreover, during the single-leg squat test, the calculated midpoint of knee may be a better choice than the lateral epicondyle of the femur. Nonetheless, although further refinements of the motion tracking systems may be possible in the future, the accuracy of the current Kinect Azure system is adequate for studying lateral knee and vertical spine base shifts during a single-leg squat.

The major aim of this study was to establish a novel Kinect Azure–based method to evaluate the knee medial-lateral movement under a single-leg squat (SLS) test, in order to create a simple and reliable method for evaluating excessive knee valgus, a predisposing factor for ACL rupture and osteoarthritis [8,11,13,15,16,32,33]. We identified that lateral shift of the knee over foot can be more reliably measured with Kinect than Q-angle. A key new finding in the present study is that squat depth has a major impact on dynamic valgus, and thus it has to be taken into account during any dynamic valgus assessment. We suggest that valgus shift can be reliably measured at 15% squat depth, defined relative to lower-limb length. Kinect validation, a subtask of this study, was performed in order to be sure that the Kinect system is an appropriate and reliable device for medical examination rooms, orthopedic physiotherapy practices or even gyms. Most studies in the literature with Kinect-based movement tracking systems use the earlier V2 camera [34–36], whereas in the present study we used the completely redesigned Kinect Azure, which has an advanced Time-of-Flight depth sensor and AI algorithm to identify joint midpoints. The validation of this camera system—even if it is limited to the single-leg squat—is a valuable resource for other investigators who are experimenting with the novel capabilities of Kinect Azure in various research settings. Our study applies a novel method, the artificial-intelligence-based Kinect Azure camera, which is able to monitor and follow the major human joints during exercise without any markers. Therefore, this system is suitable for quick and reliable assessment of dynamic knee valgus shift.

Previous studies applied the frontal plane projection angle appellation and referred to frontal plane knee valgus in their video analysis methods. In these studies, the patients executed single-leg squats, which were recorded in the laboratory by video. After the examination, the operator replayed the movie and stopped the video when the patient's squat reached the deepest point; then, the operator took out a frame from the movie. On this frame, the knee medial/lateral deviation was defined by digital goniometer [37,38], which measures the two-dimensional position of knee, called the frontal plane projection angle [39]. This procedure only measures the momentary condition of the knee. There are several issues with this procedure, which we also used in preliminary studies on more than 500 knees (unpublished observations). First, it is not possible to monitor the whole squatting process and knee medial/lateral deviation from the beginning to the end of the exercise, since only one freeze-frame can be analyzed. In this case, a huge amount of information is lost. Squat depth also includes important information about the patient's lower limb functionality, mobility and strength; therefore, it is an important parameter for the examiner. Furthermore, the patient's lower-limb side-to-side asymmetry is meaningful data for the assessment. However, with the use of only one frame on each side it is not possible to repeatably determine differences between the two body sides. Since sport movements are dynamic activities, knee valgus must be measured during a dynamic situation. No study to date has explored the knee valgus position range as a function of squat depth. The Dynaknee system is a novel Kinect Azure–based instrument, which can record, analyze, display and evaluate lower-limb functions during a single-leg squat, which can be further expanded to single-leg drop jump or single-leg step-down tests. For more accurate data and exact feedback, there is a need for a fast, simple, practical and cost-efficient kit to monitor the knee medial/lateral movement and the squat depth under the entire span of the examination.

Our results showed that the participants had appropriate neuromuscular regulation and appropriate lower-limb strength to hold their knee over their foot at 15% squat depth. It seems that, in the case of a perfectly executed single-leg squat, the lateral shift of the knee stays within the 2% range. Limiting the measurement to 15% squat depth on the way down is optimal, as all subjects in our cohort were able to squat this deep and the valgus tendencies were already evident at this point. The 44 knees examined in this study provide a pilot dataset to suggest this cut-off level; however, further studies are needed on a large number of subjects to set representative reference values for the valgus shift of the knee under load. An important novel finding of the present study that was not described earlier in the literature is that the dynamic valgus shift is very much dependent on the depth of the single-leg squat, and so the widely-used lowest point does not provide comparable metrics unless all subjects perform the squat to the same relative depth—which is hardly the case, especially in a postoperative or osteoarthritic population. Now that we have established this new variable, i.e., lateral knee shift at fixed squat depth measured in the percentage of lower extremity length (e.g., 15%), it is justifiable to recruit a large number of healthy and osteoarthritic subjects to establish exact cut-off values in a future study. It must be noted that there are no gold standards with any method to define dynamic valgus instability of the knee. Even static valgus cut-off values are debated in the literature, let alone the yet to be established dynamic ones. Future studies should define reference values for different populations, such as healthy young adults who possess no valgus or varus deformities as judged by orthopedic surgeons. Based on this reference group, knee lateral movement range and symmetry indices can be established and considered 'normal' values. The current study established that such evaluations can be performed with adequate accuracy using a portable system, opening the possibility for a wide-scale evaluation of dynamic knee valgus.

It is well-known that the single-leg squat is not only widespread in sports medicine and sports science to assess injury risk [16,40], but also commonly applied by clinicians, physiotherapists and orthopedics [38,41,42]. Excess knee valgus is the first observable step in a chain of events that may ultimately lead to symptomatic knee osteoarthritis. Dynamic knee valgus is an imbalance that results in excess shear force in the knee joint, which overloads the joint faces; in some patients, it is already associated with mild symptoms such as patellofemoral pain under load. When this imbalance lasts for years or is overloaded with demanding physical activity or sport, a destructive process develops. Furthermore, most non-contact ACL injuries in sports happen during landing with excessive knee valgus [12]. Several studies reported that the ACL-injured and -torn subjects have a greater risk for osteoarthritis [13,33]. Cimino et al. showed that the long-term sequelae of ACL injury includes knee osteoarthritis in up to 90% of patients [14]. Moreover, Johnson et al. found osteochondral lesions in more than 80% of patients who underwent acute anterior cruciate ligament ruptures [43]. These considerations together highlight the importance of early and accurate measurement of dynamic knee valgus when it is still corrigible.

Based on the scientific literature, there is a need for a relatively low-cost, reliable and user-friendly motion analysis system that is capable of injury risk screening in the orthopedic practice. The Dynaknee software, along with Kinect Azure, incorporates a low-cost, user-friendly and quick instrument, without reliance of on-body markers, that is easily applicable in GP offices, orthopedic physiotherapy practices or even in gyms. The Kinect Azure camera is the newest Microsoft Kinect product, and it can accurately monitor major joint positions during exercise. Our results have shown that the relative evaluation of medial-lateral knee movement seems to be an appropriate method to determine the range of the dynamic knee valgus.

Several studies proposed the use of Kinect in other medical fields. It could be a good choice in walking and running analysis during rehabilitation [21,44] or in hip disorder treatment [19]. Kinect provides data about lower limb functions, such as mobility and safety. The gait parameters of step length, step width and cadence can also be monitored and improved by Kinect-based protocols. Several tests, e.g., the Matthias posture test and rotator cuff mobility and strength test, are potential diagnostic routes that would benefit from the improved accuracy of Kinect. Furthermore, recent studies reported Kinect exergames to have a significant positive effect on balance performance in elderly people [45].

Kinect Azure provides an opportunity in the field of marker-less motion analysis, though it has several limitations compared to classical marker-based motion capture systems, which can provide more extensive and accurate data regarding human motion through selected marker points of the body. Undisputed advantages of the marker-based systems are that the experts can precisely follow the movements of extremities and segments through markers or sensors adhered to the skin over well-defined anatomical locations. The disadvantage of the Kinect Azure camera is that it can only measure the outer shape of the human body, and it deducts major joints from this large dataset. The Kinect-generated 'joint midpoint' is not an exact anatomical location; however, it can be reliably used in answering questions of joint movements along a single axis such as the SLS test.

The cut-off value for normal vs. pathological dynamic knee valgus shift cannot be established at the current phase of research. Future studies should establish reference values for the healthy population in both genders and also for specific pathologies; the aim of the current study was one step earlier, i.e., establishing the appropriate metrics that adequately describe the dynamic valgus phenomenon and what can be reliably measured with a marker-less system.

In conclusion, the current study shows that in order to reliably monitor dynamic valgus of the knee, medio-lateral shift of the knee over foot at a fixed squat depth is far more suitable than the previously suggested Q-angle at the lowest point of a squat. This variable can be automatically recorded with a marker-less optical camera and software system, allowing a novel diagnostic tool for evaluating osteoarthritis risk factors in the routine orthopedic practice. Future studies may extend the use of this hardware–software combination to follow other joints; however, each joint will require a different set of control measurements and even disease groups.

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