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Use of Motion Capture in Assisted of Knee Ligament Injury Diagnosis

Radosław Bednarski, Adrianna Bielak

Lodz Univeristy of Technology
Institute of Information Technology
ul. Wólczańska 215, 90-924 Łódź, Poland
radoslaw.bednarski@p.lodz.pl
adrianna.bielak.lodz@gmail.com

Abstract. *This study treats of the use of motion capture systems as the help diagnose knee injuries. It consists of the theoretical work and the application. The written work describes a course of research includes choice of research group, selection of appropriate exercises, find useful computational methods, description created for research applications and summary results. The practical part was to create an application for physiotherapists which could help them to diagnosis potential pathology of the knee. The purpose of this study was to test whether a motion capture system dedicated to entertainment can be used in the medical aspect. This system was test for selected methods and determined to be suitable for supporting the diagnosis of knee injuries. Otherwise it has to be written what was the reason of failure. The results of the study were that after trial and error methods peeled action and created application proved helpful.*
Keywords: *motion capture, knee joint; knee injury, diagnostics.*

1. Introduction

In modern medicine, the use of IT solutions in terms of software and hardware is becoming more and more common, which is aimed at the more efficient and more complete diagnosis or rehabilitation of the patient. These types of solutions include motion capture systems that are composed of both hardware and software parts. The fields of medicine that most benefit from this type of solution are all branches based on motion biomechanics, such as physiotherapy, rehabilitation, orthopedics. In next chapter authors desribe construction and role of the knee joint, common knee injuries and use of motion capture systems to assist in the diagnosis of knee injuries. In the third chapter we present the state of the research from the point of view of the equipment used.The fourth chapter describe the research methods used in the diagnosis of knee injuries. In chapter fifth, the authors describe the research carried out on a group of professional dancers.The sixth chapter deals with the description of the method used to calculate the angle Q, used in the diagnosis of injuries. In chapter seventh, the authors describe how to conduct a study for a selected group of dancers. In chapter eighth we present the results of the research and discuss them. In the last chapter, we concluded the research.

2. Construction and role of the knee joint

The knee joint plays an important role in the human body. This feature is due to the fact that it is the largest human pond and one of the most complex. At the same time, it serves as a multifunctional structure, and as such is exposed to numerous pathologies. The knee joint has the function of stabilizing the human body vertically and also supporting its weight and cushioning it. Simultaneously, it is a structure characterized by a large range of mobility, caused by high-intensity movements such as trot, sprint, climbing, cycling, lifting weights.The knee joint is a group of hinged joints that is characterized by the movement of straightening and flexion, where the joint can be raised in relation to the lower leg while the latter is absent [1]. It is a structure connecting the femur with the tibia [2].

The description of the construction of the knee joint can be divided by the ligament system, the muscular system and the bone system [3]. Describing the ligament knee system, we can distinguish the group of external and internal ligaments [4].When discussing the muscular system, it is necessary to determine the functions it performs with respect to the knee joint. The knee joint task is to stabilize. When analysing the skeletal system of the knee joint, it is important to determine the type of bone and what bone it is. It is a hinged-rotating pose created by tibia, femur and patella. Its head is the thigh knuckles that move along the knuckles of the tibia. In this system, there is a patella (Fig. 1), which affects the shape of the femur joint surface, resembling a horseshoe, connecting the joint to the condyle of the femur. The hollow, which occurs on the tibial facet, is called the meniscus [3].

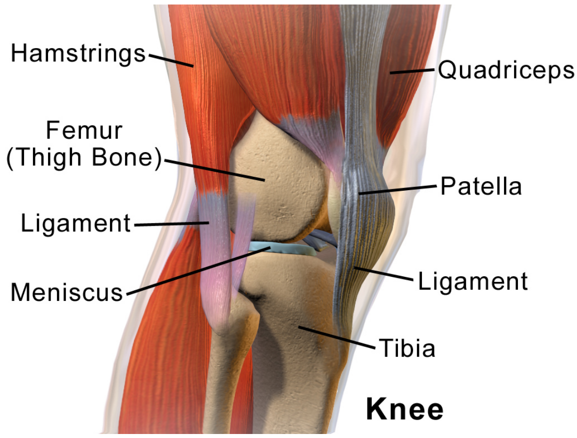

Figure 1: Knee joint structure.

The complicated construction of the knee joint and the heavy load on the quadriceps muscle of the thigh, as well as participation in dynamic movements, causes the joint to be subjected to numerous and frequent injuries [1].

2.1. Common knee injuries

Pathologies of the knee joint can be manifested either through acquired or inherited pathways. In the case of both groups, the most characteristic conditions can be distinguished [1].

Among the diseases acquired to the most common are break the meniscus, stretching of the ligaments, ligament rupture, damage to the articular capsule, joint dislocation, intestinal bone fracture in the joint or kneecap fracture. Among the innate, you can mention varus and lumbar [5, 6].

On the basis of the graphs in Fig.1, Fig.2, Fig.3, it can be seen that injuries of the knee joint are among the most common among people professionally related to physical activity as well as people doing static work [5]. This is due to the strong load on the joint with the thigh muscles, which equally affect the joint even during daily physical activity (sitting on a chair, getting up from a bed) [3]. Injury to

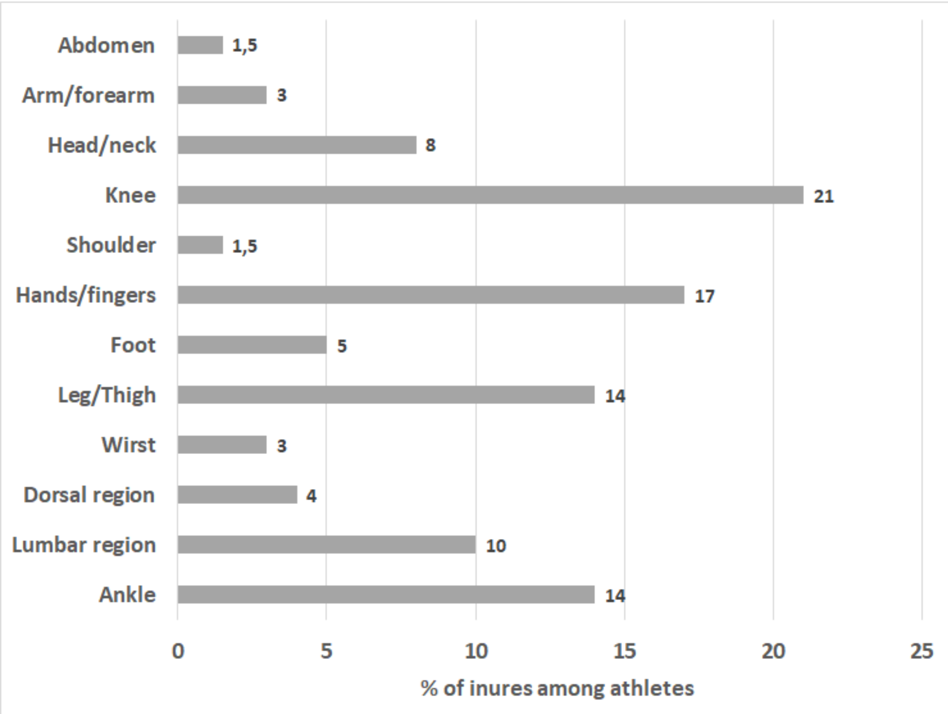

Figure 2: Graph showing the percentage of injuries among athletes [5]. Based on the graph, it can be seen that the number of knee injuries is 21%, thus fixing knee injuries as the most common in this research group.

any of the knee tissues, discussed in the previous section, affects the balance and control of the lower limb, which may result in complications [1, 2, 3].

Knee joint injuries are also called the 21st century epidemic. On the basis of the graphs shown in Fig. 4, knee arthritis is progressing with age as well as with years (in the ten years from 2004 to 2014 the number of hospitalized persons due to knee injury increased by 45,000 people). The main causes of these pathologies include vitamin deficiency, sedentary lifestyle, genetic defects of posture, poor motor habits (abnormal sitting, lifting of objects, getting up) [8]. It can be concluded that injuries of the knee are one of the most common motor ailments with dangerous and progressive effects over the years. Because of this, the pathologies of this joint are one of the best described medical issues, which is why they are often studied from a biomechanical point of view. Athletes (athletes, soccer players, basketball

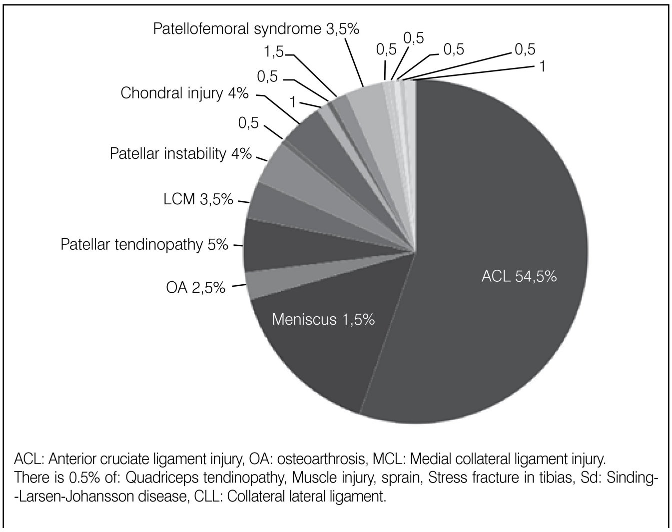

Figure 3: A pie chart showing the percentages of knee injuries among dancers [7]. The most (more than 50%) are injuries of the cruciate ligament.

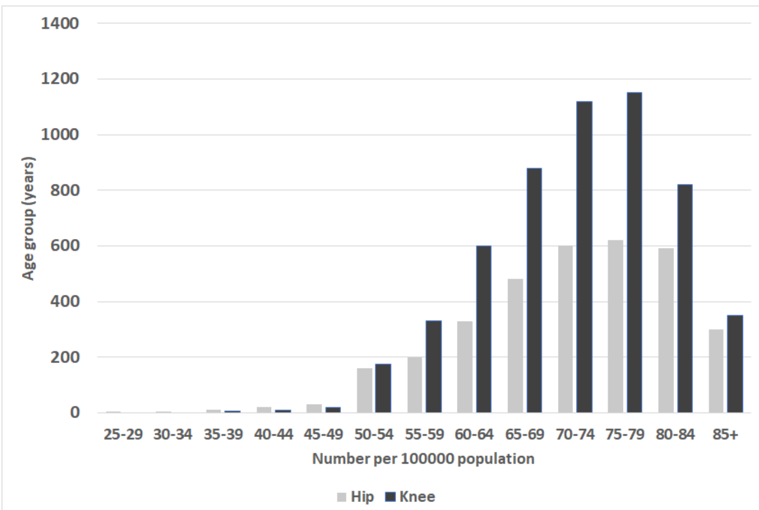

Figure 4: Diagram showing the number of people (X axis) hospitalized due to arthropathy (blue-knee, green-hip) by age (Y axis) [8].

players) and dancers, due to their specific type of movement, often cause unnatural bone formation in the knee joint, as well as greater strain on the joint due to dynamic movements[1].

2.2. Use of motion capture systems to assist in the diagnosis of knee injuries

From the beginning of the history of motion capture systems, they can be registered for use in medicine, and especially in the diagnosis of movement pathology, rehabilitation, physiotherapy, rehabilitation planning and training [9, 10]. These systems inter alia enable determining the trajectory of movement, the angles between the bones in the skeleton formed, the recording of the moment of muscle strength, the strength of the muscle and the point of application of that force, and the recording of analogue data [11]. The type of recorded data depends on the device system that is being used during the test and the format of the file to which the data is exported. The most popular formats in the context of biomechanics are C3D, CAMARC, GCD / DST, Dataq, Vicon ADC and VAD, ANA, MTS EMG [12].

3. Current state of the problem from the point of view of the research equipment used

By analysing published scientific articles from 2011 to 2016 on the use of capturing systems directly in the analysis of biomechanics of the knee, one can notice a certain tendency in both the direction of research and the methods. The most commonly considered topic is the risk assessment of ACL injury using a motion capture system, as a result of a well documented type of injury (described in subsection 4.3.2). The most commonly used exercise during the test is walking, sprint, climbing and climbing stairs, squat in legs apart, hips, jumps.

In the literature we studied, the following equipment and test methods were used:

- Opto-Knee (Shanghai Innomotion Inc) portable infrared optics with two infrared cameras placed approximately 50cm apart, with a camera mounted on

[1]Request formulated in discussions with orthopedists from the hospital Nicolaus Copernicus in Lodz, which took place in April / May 2016.

a mobile workstation and 8 markers arranged in accordance with the manufacturer's instructions [13]. The study assumed the usefulness of the system to assess the risk of ACL injury with a positive end result.

- Use of two systems; One based on markers, the other without markers. The markless system was made up of 10 German-based Allied Vision Technologies Prosilica GX1050C time-synchronized cameras with Spica Technology Corp.'s software and hardware. Eight of the cameras intercepted the displacement of the whole body in space, while the other two intercepted the movement of the legs (including feet). The study aimed to compare the readability of the data needed to analyze the motion of the middle knee and the center of the ankle, which could determine the risk of injury (mainly ACL) during exercise [14].

- "DynamoLab" , The Academic Laboratory of Movement and Human Physical Performance of Medical University of Lodz, which, inter alia, analyses movement, has the BTS Smart DX 7000 system for comprehensive body movement analysis. It consists of 8 TVC cameras that emit infrared radiation at a frequency of 500 Hz at the maximum resolution set. Cameras recognize markers in grayscale and are designed to perform difficult light conditions [15]. The control unit is a Dual-Core Intel® XEON® PCI-X, compatible with various system components (eg Ethernet) [16]. The calculations are done in dedicated SMART-Analyzer software, Smart-Performance, Smart-Clinic, which have implemented internationally-recognized calculation protocols (movement analysis), and enable the creation of their own protocols (using data entry blocks) 2D and 3D (Fig. 5) [17]. The system enables automatic tracking during the test, synchronization of kinetic, kinematic, video and EMG data, automatic calculation of specific parameters based on a chosen protocol, kinematic and analog data logger, 3D reconstruction with markers, real time visualization and markers editing. The advantage of this system is the ability to use it outdoors. The collected data are used to evaluate the motor system, determine motor dysfunctions, plan treatment and training and analyse the effectiveness of rehabilitation [15].

Peripheral modules used in the course of testing using motion capture systems include platforms such as AMTI, Kistler, Bertec, BTS, EMG kits including BTW, Noraxon, rehabilitation treadmills, video recording systems such as BTS Vixta [16].

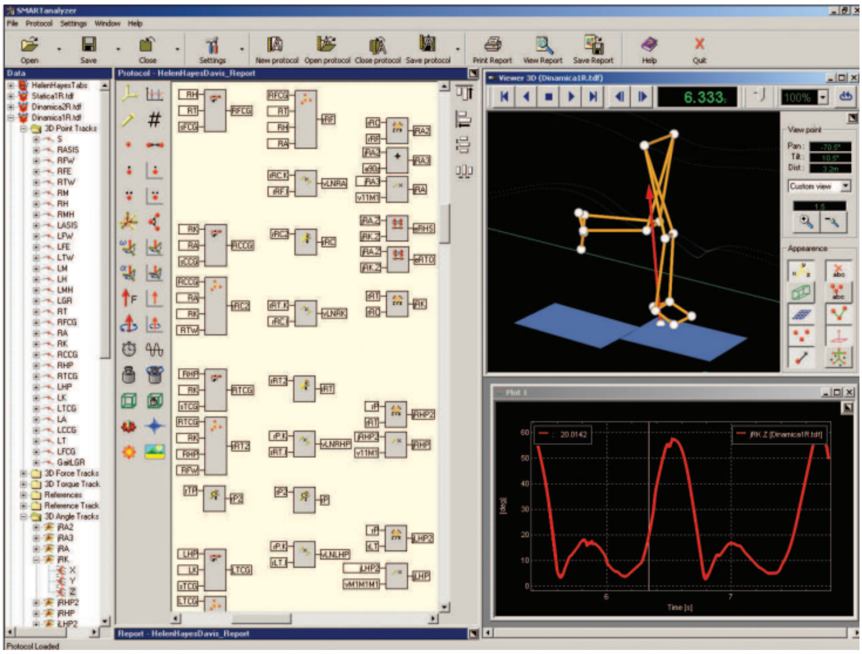

Figure 5: Drawing showing SMARTAnalyzer software dedicated to BTS Smart [17].

In order to analyse the collected and exported data, the following are predominant:

- Tools offered by Motion Labs Systems [12],
- Matlab plugins [11] for reading data from the formats mentioned at the beginning of this chapter (mainly .c3d) with implemented functions enabling faster biomechanical calculations (eg C3D MATlab access).
- Open source library compatible with popular mathematical analysis programs such as Matlab, Octave (eg Biomechanical Toolkit: Open Source framework for visualization and process biomechanical data) [18],
- Software provided by the manufacturer of the particular traffic-capture system, such as the aforementioned BTS Smart System.

4. Research methods for knee injure diagnosis

A number of studies may be used to diagnose knee arthropathy starts from the manual methods through ultrasounds and tomography. However motion capture systems are helpful when it comes to diagnosing joint mobility and the influence of specific movements on its functioning.

The choice of the proper method and calculations depends on the purpose of the study. They can pertain to support making diagnosis off afflictions characterized by deviations from the standard such as the angle of rotation between bones in the acetabulum. On the other hand they aid determine whether particular movement (e.g. in rehabilitation) is performed correctly for improving the condition of the joint. They can also help to diagnose whether patient movements have pathogenic effects on the joint function. To determine the risk of injury it is necessary to correlate positions of the captured 3D points in each frame of the appropriate markers with the recorded force, muscle's strength and application of the force as well as ground reaction force. In this way comprehensive motor motion data can be obtained for all movements in space of particular body parts and muscles work in those parts.

One of the methods of high accuracy is to capture data using a system based on markers which contains information about among others markers positions in each frame, angles between interconnected elements of the generated skeleton, the individual markers displacement vectors calculated on the basis of positions of the markers at the beginning of the test, positions at the end of the initiation cycle and the duration of the motion, the ground reaction force, muscles strength at any given moment.

On the basis of the above an analysis is made using anthropometric parameters appropriate to the research group to calculate the centre of gravity of the body and its inertia, the local group of the examined movement organ and the Newton-Euler equation, which described the dynamic equation of motion for each segment of the body that can be subdivided into several subgroups such as torque, moment of gravitational force or the point of force application what is used in knee arthroplasty analysis based on data recorded by the motion capture system which can be useful to specify:

- risk of knee and hip joint injuries in specific phases of motion,

- risk of ACL injury due to excessively high torque in the knee joint during a given phase of movement,
- risk of muscle overload in a given phase of motion.

It can be done by capturing marker data in 3D space (which can be dropped into 2D space later but is not necessarily and dependents on the selected local group also the potential injury which is analysed) and using the EMG [19]. It is possible to compile equations of motion by synchronizing these data in time. On their basis there is potential to accomplish biomechanical analysis with the probability of finding the risk of pathology (with using anthropometric, international data relevant for the research group) [12, 18]. There are also methods that are based only on capturing positions of the markers in each frame and then finding the equations using analytical geometry (most often striving to determine the angle of movement of a given skeleton segment in a given joint)[10].

5. Research for a group of dancers

The research presented in this chapter, consultation and software development took place from the beginning of March to the end of August 2016. The study included a literature review of hardware and software used in biomechanics, documentation on the .c3d format, also motion capture and knee injuries materials. In addition the study consisted of consultations with the manager and staff of DynamoLab[2], orthopedists from The Copernicus Hospital in Lodz (Poland), a physiotherapist, dancers and computer scientist[3]. The dancers movements were recorded then analysed in the software which has been created for the study.

5.1. Research group

The first research group consisted of people with high risk of knee injury from the Lodz city (Poland) (18 people including dancers, volleyball players, manual

[2]DynamoLab – The Academic Laboratory of Movement and Human Physical Performance of Medical Uniwersity of Lodz, Poland.

[3]Consultations with the doctors from the Lodz University of Technology in Poland from The Institute of Information Technology.

workers, trainers). After the first month since the commencement of motion capture had begun it was decided that at this stage of the work selected motions and methods that let achieve the goal by using parameters after recording motions of people with different motor motivations was unfeasible. Considering the measuring dynamic angle Q value method which was determined by the type of software it was necessary to find people with similar motor characteristics and with the medically diagnosis of the knee injury. For this reason a group of 9 dancers with different knee injuries was selected and contained:

- a dancer just before the operation of reconstruction of the cruciate ligament (rupture of the ligament),
- a dancer just after knee rehabilitation (recurring anterior cruciate ligament injury from childhood),
- a dancer during rehabilitation (lateral cruciate ligament),
- a dancer with overload of the left knee joint,
- 5 dancers with periodic overload of knees.

Specifying the group made it possible to select a specific set of exercises (subsection Chosen exercises) that could be used to select a proper method to accomplish the goal.

5.2. Consulting with specialist

During the study several groups were consulted. The following describes which issues were discussed with each group and how the consultation impacted work flow:

- Talking to the manager and staff of DynamoLab - as a result it was suggested to get additional literature as well as to make a correction of the topic, purpose of the research and the exercises list. It was also expressed willingness to cooperate for the future.
- Interview at Nicolaus Copernicus hospital in Lodz (Poland) - as a result it was identified the most common knee arthritis, provided information about equipment and software in the area of motion capture in biomechanics and it was proposed to use additional literature.

- Interview with physiotherapist - evaluation of the final selection of exercises, evaluation of the suitability of the program from the point of view of the physiotherapist.
- Conversations with dancers - setting up the finals exercises from the ballet dance technique that contribute to knee injuries or discomfort, sharing information about the most common knee injuries in dance theatres.
- Discussion with computer scientist - getting help with orientation of the purpose of work, suggesting additional literature, defining opportunities for work development, assistance in using equipment and software.

5.3. Capturing and analayzing data

Prior to the study it was necessary to define the research method and to select the appropriate exercises. The selection was determined by the type of data captured by the system which consisted of positions in a three-dimensional system for each marker in each frame. The motion capture technology that was used was dictated by availability during the course of the study. After correcting the purpose of the study the appropriate set of exercises was initially selected. The next step was to select the appropriate calculation method, which was the calculation of dynamic angle Q value, and define how it correlated with the mentioned above captured data. Determining this correlation was the most important aspect in the conduct of the study because it influenced the design of the application which had to implement the aforementioned calculations and a simple expert system that ultimately determines the risk of pathology. This aspect was mainly related to the need to extract relevant parameters from the exported data namely the position of the specific markers in each frame described in the chapter "Method of calculating Q-angle", which would prove to be good for the purpose and risk of the disease after processing.

Initially, a method based on the patterns at the beginning of that subsection was selected. Based on it the choice of such analytical calculations would be relevant if the EMG was to use. Vicon Blade software available during the study did not allow the EMG service which automatically prevented full use of these computational methods. Having a point cloud saved with high accuracy in each frame it was necessary to select a computational method, which was in that case the calculation of Q-angle, that would allow the risk of a disease to be determined by moving a given marker or group of markers relative to another marker or another group of markers and using analytical geometry. Due to the above, the range of mobility of the knee joint and the accompanying measurements during the diagnosis of this mobility were considered. The dominant methods are manual methods for checking the mobility of the patella with the possible use of the goniometer[4][20], which determines the angles of swing in the knee joint rotation according to the respective axis.

Making the final calculations leading to the same results as those obtained with a goniometer would be a duplication of the diagnostic method rather than enrichment which would result in failure of the goal and assumptions. Due to the limitations of the Vicon Blade software which is dedicated to capturing motion for entertainment (films, games, postproduction) and not medical (such as Vicon Nexus 2) the pool of meaningful computational methods has been considerably narrowed. Finally, the method of calculating dynamic angle Q[5] was chosen.

At the end of software development one more method was used for calculations based on points displacement such as patellar track and passive patella rotation. Both tests involve performing a number of minor manual tests I.e.flexion and straightening in the knee during which the patella is observed. Some norms of displacement values and angles are generated in the local coordinate system in the knee joint which help to diagnose joint injury [21]. To undertake research using the same system and software it would be required to attach several tens of small markers only on the surface of the knee joint and to create a dedicated skeleton and markers in Vicon Blade. This issue is described in subsection Results and discussion as one of the potential developments in that study.

5.4. Chosen exercises

As in the case of the research group the selection of exercises was changing with the analysed literature, research and consultations.

Initially, motion was captured during the execution of a small and large squat with feet spaced parallel to the width of the hips in the rhythmic pulse. This is an exercise that causes discomfort on the part of the injury and determines whether

[4]Used to measure angles.

[5]Meaning the angle Q and how to calculate it is described in the Method of calculationg Q-angle subsection.

there is a risk of deepening it. It would be necessary to precisely place the patella markers and create a model in Vicon Blade to analyse the position of the markers only from its areas. This method would allow you to use the method of calculating instability of the patella. In spite of this surgery the measurements would not be very accurate with respect to the quicker, simpler method, namely the goniometer and therefore would not be helpful in determining the diagnosis of a knee injury.

Squats in parallel position were changed to walking in the same for each person pulse. On the basis of the exported data this was tried to check if there is a phase of gait which arrived the pathological swing of the position of one of the knee markers relative to the point position halfway between the front marker of the anterior iliac spine of the selected side of the bone and a marker in the back of the same bone. This method has not produced the expected results for this research group because no one had strong degenerative changes in the knee joint which could let to find the high amplitude between the positions of the markers described above.After two series of research that did not produce the result, the manager and the staff of the DynamoLab were consulted. The correction was suggested on the topic of the study, purpose of the research and selecting exercises for the new research group.

During the consultation it was stated that although traumatic ligament injuries are factually and extensively described in scientific publications, it has been noted that motion capture systems do not capture data from which it would be possible to make a diagnosis of any knee arthritis unambiguously due to the inability to scan the construction of the knee joint. For this purpose ultrasound, X-ray and magnetic resonance are used which return proper data to make diagnosis. At the same time it was noted that the aforementioned methods are not able to determine whether the knee joint has no motor defect despite the correct tissue structure after rehabilitation. In this situation motion capture methods are helpful.

There were also suggested few exercises that could be the best for the new purpose of the research namely: squats and get up and go down the stairs. A new series of captured data has been launched on the aforementioned research group. This time squats were modified from the parallel position for two squats from the ballet dance technique i.e. demi plié[6] and grand plié[7] in the first ballet position of legs (Fig.6).

[6] A small ballet squat.
[7] A grand ballet squat.

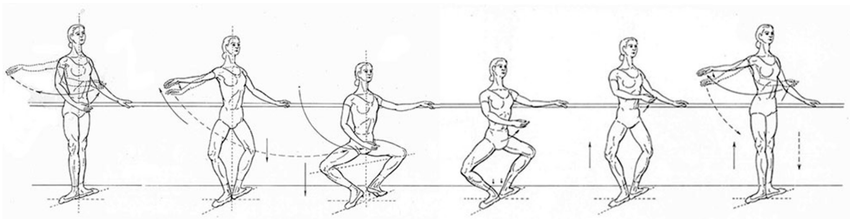

Figure 6: A drawing which depicts the demi plié and the grand plié in the first ballet position of feet [22].

The choice of these two exercises was dictated by three reasons. The first was that classical dance technique has precisely defined angles of rotation in the joints to which dancers should strive. This is a compulsory technique for professional dancers regardless of the motor technique. This has made it possible to choose one method with the same range of values for dynamic Q-angle calculation, because it involved dancers of the same motor technique with similar motor characteristics and with basics of ballet dance technique, including the selected exercise, which reduced the probability of data corruption. The second reason was the injury-prone movement associated with ballet dance. From the biomechanical point of view the ranges of joint mobility (mostly lower body part) and the angles of rotation in those joints, to which a trained dancer must strive, are contradictory to the anatomy of the human body. The above exercises which require unnatural twisting of the bones in the hip joints are the cause of knee joint injuries (most often ACL which is referred to in subsection Common knee injuries). The third reason was the need to use the dynamic Q-angle calculation method because of the ability to capture only 3D points without EMG data. With the above exercises, especially the grand plié, there was a greater probability of capturing the abnormal value of this angle.

The second exercise that was chosen was to get up and go down the pouf three times in the cameras' view bounds. This exercise imitated the movement phase of the skeleton while get up and go down the stairs

6. Method of calculating Q-angle

Q-angle is formed by the line leading from the anterior superior iliac spine to the middle of the patella and the path that crosses the line of the second line extending from the centre of the patella to the tibial tuberosity [23] (Fig.7). By default the Q-angle is measured in a static manner e.g. using a goniometer. It turns out that the specific dynamic movement can enlarge the value of this angle. Then this angle is called the dynamic Q-angle [24].

In the case of the test to obtain the value of the angle Q it was necessary to

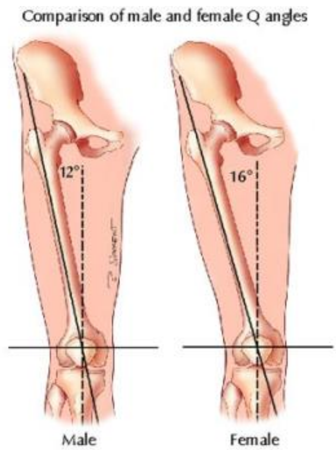

Figure 7: Static Q-angle values for men and women [24].

perform the calculations in the following steps which have been designed by the authors:

1. Select the markers which were needed for calculations namely the RKNI (Right Inner Knee), LKNI (Left Inner Knee), RBWT (Right Back Waist), LBWT (Left Back Waist), RFWT (Right Front Waist), LFWT (Left Front Waist), RKNE (Right Outer Kee), LKNE (Left Outer Knee), RSHN (Right Shin), LSHN (Left Shin), RHIP (Right Hip), LHIP (Left Hip)[25].

2. Calculate the position of the centre of the right and the left patellar defining the middle of the segment between pairs of RKNE, LKNE and RKNI, LKNI markers.

3. Calculate the position of the right and left anterior iliac spine by calculating the position of the point between the pair of RFWT, RBWT and LFWT, LBWT.

4. Calculate the position of the tibial tuberosity by calculating the position of the point in one of sixth of segment which is situated between the centre of

the right patella and the RSHN marker from the centre of the patella and performing analogical calculations for the left leg.

5. Determine the vector vr1 and vl1 from the centre of the patellar calculated in the second step to the centre of the anterior iliac spine calculated at third step independently for both legs with a direction to the anterior iliac spine.
6. Set vector vr2 and vl2 from the centre of the kneecap to the tibial tuberosity independently for both legs with the direction to the tibial tuberosity.
7. Calculate the arccosinus of the obtuse angle between the normalized vectors and convert the resulting value to an angular value.
8. Value obtained in the seventh step deducted from 180°.

Finally, the authorial formula based on the steps above and used to calculate the Q-angle can be written as follows:

$$Q = 180^\circ - (\cos^{-1}(\overrightarrow{RCCRH} \cdot \overrightarrow{RCCTTR}))(\frac{180^\circ}{\Pi}) \tag{1}$$

Q – Q-angle for right leg,
RCC – point in the centre of the patella of the right knee,
RH – position of the right anterior iliac spine,
$\overrightarrow{RCCRH}$ – normalized vector from the centre of the patella to the anterior iliac spine,
TR – tibial tuberosity position in the right knee,
$\overrightarrow{RCCTTR}$ – normalized vector from the centre of the patella to the tibial tuberosity.

The Q value for each leg is finally obtained by calculating the steps above. These calculations had to be performed for each leg in each frame to be able to observe changes in the dynamic angle Q. Based on these values and internationally standards of static angle Q values it was possible to determine which movement and which phase caused a significant increase in this values. This is going to affect the risk of injury. The value of the Q-angle which goes beyond the norm may be indicative of genu valgum or bowleg. The standard for men is the 14° with a margin of error of 3° and for women 17° with the same margin of error. In addition to the abovementioned diseases the wrong Q-angle may also be the tensile strain of the flexor retinaculum, the external rotation of the tibia, the increased anteversion of femur [23]. Those diseases are determined by the static Q-angle. In the case of the study, i.e. the calculation of the dynamic Q-angle, the out-of-range values are the starting point for assessing the correctness of the exercise and the risk of injury as a result of the sudden increase in the angle.

7. Description of author's application supporting knee injury diagnosis

The study was conducted using 10 Vicon T40s cameras. The cameras were connected to a dedicated Giganet MX computer which was also connected to a computer with Vicon Blade software. Vicon Blade is software designed for capturing motion-based entertainment such as games and movies. The default skeleton implemented in the software included 53 markers.Markers were attached to a special, matched, black matte costume dressed by a dancer (Fig. 8, Fig. 9).

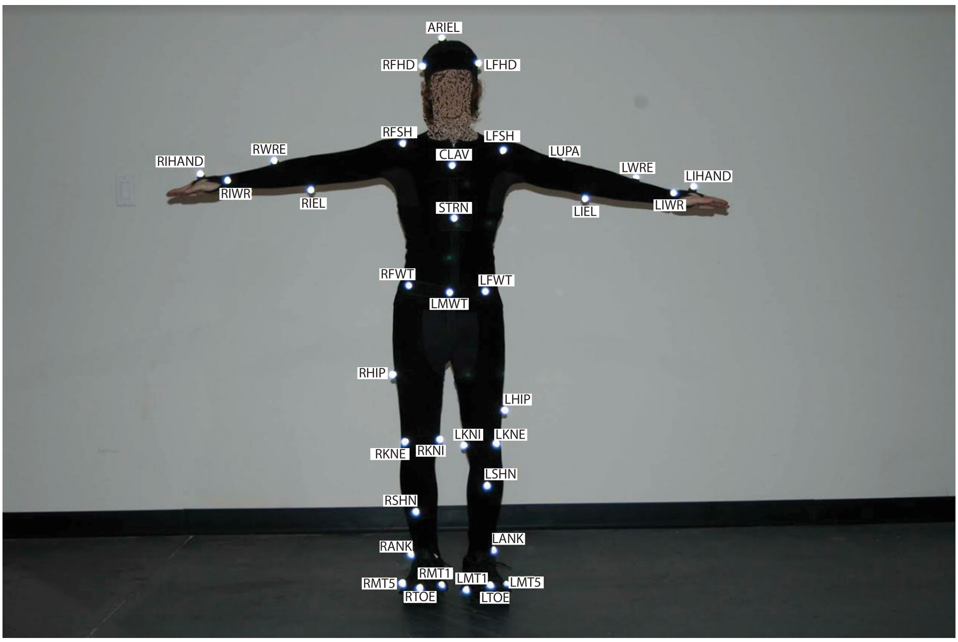

Figure 8: Arrangement of markers in front of the body [26].

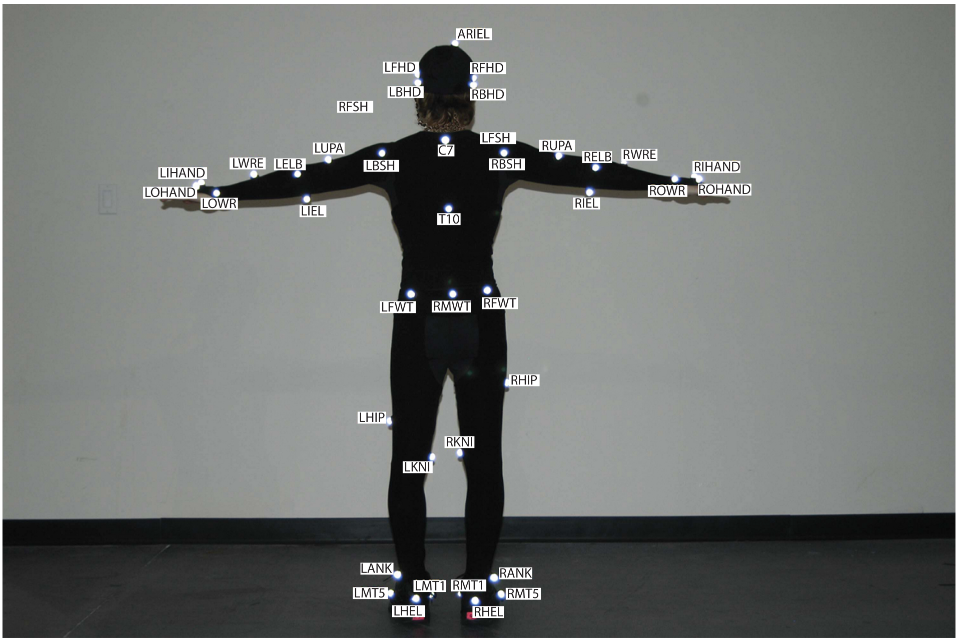

Figure 9: Arrangement of markers on the back of the body [26].

Markers form the upper part of the body were attached in an approximate manner consistent with their location in the default skeleton of Vicon Blade. Markers from the lower part of the body were also attached according to the basic framework implemented in the program but with simultaneous accuracy to the anatomy of the bone structure of the dancer.

The RKNI and RKNE markers were positioned exactly on the sides of the centre of the knee so that the centre of the knee was exactly in the middle of the distance between them in the resting state during standing (analogous to LKNI and LKNE markers). The RSHN and LSHN markers are placed exactly on the outside of the calf midway between the centre of the ankle and the middle of the patella. The RHIP marker was placed exactly halfway between the anterior iliac spine and the centre of the knee on the outside of the thigh (analogously for LHIP marker). The RFWT and RBWT markers were placed so that the anterior iliac spine was exactly in the middle between them where the first was in the front of the body and the second one the back of the body (analogous for LFWT and LBWT markers).Captured data has been reconstructed and cleared (by removing unnecessary markers appearing in some frames and correcting some markers). Then these data were exported to .c3d format.

Based on the analysis and data obtained, the authors created the application called ”Q angle analyser” which implements load any .c3d file, automatic calculation of the dynamic Q-angle for both legs based on the file loaded by the user, expert system that qualifies the value of the calculated dynamic Q-angle as normal or abnormal, displaying the Q-value which is beyond the norms, display information about a knee injury risk. Authors also includs a free, open-source C3D.NET DataViewer program that visualizes the position of each point in the .c3d file on charts. The program is provided by the developer of the .c3d library in C# language which is described below. The visualization may be helpful to the therapist/physician to determine the phase of movement in which the dynamic Q-angle reaches dangerous values.

The programming development environment was Microsoft Visual Studio 2013 with added free open C3D.NET library that allows to load .c3d files, reads the distinguished files and their names, reads the 3D position for each point in each frame and camera's settings for each one as well as adding or removing a frame which was not needed in this area. The programming language was C# with .NET 4.0 platform. The program is designed for PC with Windows system.

The main functionality of the application "Q-angle analyzer" is to load data from the selected file in .c3d format. The application displays only files that are saved in .c3d. The formula (1) is performed in the program.

The input data of the created application are any files saved in .c3d format. The output values which are returned in the program window depict dangerous dynamic Q-angles values beyond the standard and information about the potential risk. The input data of the included C3D.NET DataViewer application are any files saved in .c3d format. The output is the label of the saved parameters, the camera's setting for each of them, the 3D positions in each frame and the analog data if any of them were recorded.

The code consists of several classes where there are two the most important i.e. the Form1 class, which handles events derived from the user interactions and the Main.cs class which contains the method of calculations described in Method of calculating Q-angle subjection. The program uses the Microsoft.Xna.Framework library to store point items saved in a .c3d file into vectors. These vectors are stored in dynamic lists where each list corresponds to the position of the marker in all frames where the first item of the list is the position of the marker in the first frame and the last item of the marker in the last frame (Listing 1). Marker positions are arranged in chronological order. The number of elements in each list assigned to a marker is equal to the number of frames saved. Values of vectors calculated on the basis of the algorithm described in subsection Calculations (Listing 2). They are also stored in dynamic lists.Each list is re-initialized after loading the next .c3d file.

Listing 1: Execute a method in the Main.cs class that initializes the list and writes the corresponding parameters to it.

```
internal void GetDataFromLabel()
{
    UInt16 firstFrameIndex =
      fileC3D.Header.FirstFrameIndex;
    UInt16 pointCount =
      fileC3D.Parameters["POINT:USED"].GetData<UInt16>();
    String[] pointLabels =
      fileC3D.Parameters.
       GetParameterData<String[]>
        ("POINT", "LABELS");
    RKNI = new List<Vector3>();
    LKNI = new List<Vector3>();
    RMWT = new List<Vector3>();
    LMWT = new List<Vector3>();
    ...
    for (Int32 i = 0; i < fileC3D.AllFrames.Count; i++)
     for (Int32 j = 0; j < pointCount; j++)
      if (pointLabels[j].Contains("RMWT"))
       RMWT.Add(new Vector3
        (fileC3D.AllFrames[i].Point3Ds[j].X,
         fileC3D.AllFrames[i].Point3Ds[j].Y,
         fileC3D.AllFrames[i].Point3Ds[j].Z));
      else if(pointLabels[j].Contains("LMWT"))
       LMWT.Add(new Vector3
        (fileC3D.AllFrames[i].Point3Ds[j].X,
         fileC3D.AllFrames[i].Point3Ds[j].Y,
         fileC3D.AllFrames[i].Point3Ds[j].Z));
     ...
}
```

Listing 2: A method for calculating the positions of the relevant structures specified in the algorithm contained in subsection Method of calculating Q-angle based on the position of the markers in each of the frames. The items received are saved as Vectory3D and stored in dynamically generated lists.

```
internal void FindProperPositions(int count)
{
   for (int i = 0; i < count; i++){
     rightPatellaPos.Add (
      new Vector3(
        (RKNI[i].X + RKNE[i].X)/2,
        (RKNI[i].Y + RKNE[i].Y)/2,
          (RKNI[i].Z + RKNE[i].Z)/2) );
         leftPatellaPos.Add(
          new Vector3(
            (LKNI[i].X + LKNE[i].X) / 2,
            (LKNI[i].Y + LKNE[i].Y) / 2,
              (LKNI[i].Z + LKNE[i].Z) / 2));
              rightTibialPos.Add(
               new Vector3(
                 (RKNE[i].X + RSHN[i].X) / 5,
             (RKNE[i].Y + RSHN[i].Y) / 5,
                 (RKNE[i].Z + RSHN[i].Z) / 5));...}}
```

8. Result and discussion

Based on the recorded motions and the data returned by the application the risk of injury in the grand plié exercise was finally determined among all dancers. In the demi plié risk of injury was determined in the case of 4 people (the dancer with ACL and before surgery, dancer during rehabilitation, dancer with recurrent knee injuries and dancer who is currently not injured). In the exercise of get up and go down the pouf the risk was established for one dancer (with ACL injury). A graph (Fig. 10) below is drawn up based on the dynamic Q-angle value of the performance of the grand plié for all dancers.

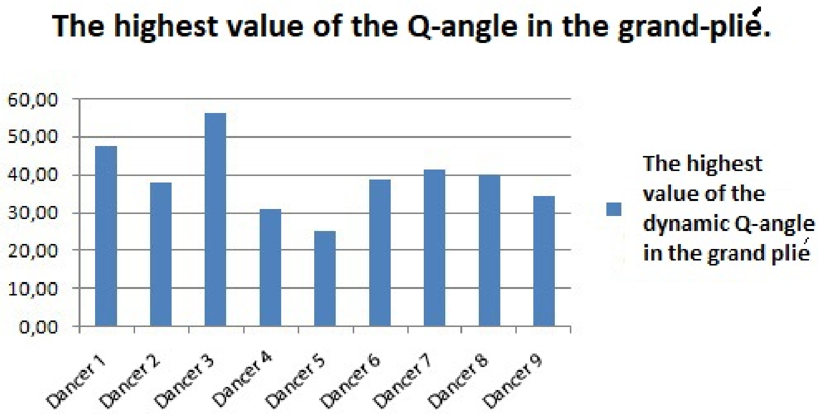

Figure 10: The highest value of the dynamic Q-angle for all dancers during the grand plié.

The above values are obtained in the middle of the exercise cycle which means the deepest squat. According to fact this exercise is one of the most pathogenic moves in ballet dance the values of the calculated Q-angle in the program has returned data that has a real confirmation. All dancers in the grand plié had dangerous levels of dynamic Q-angle. The highest value of this angle was obtained by a dancer with ACL injury (Dancer 3) and a dancer during rehabilitation (Dancer 1). They had got the most serious injuries in the research group, so the results returned by the app also have real confirmation. The phase of movement where each of the dancers obtained the dangerous value of the Q-angle was different for everyone, so this parameter was omitted in the summary.

In the demi plié the value of the dynamic Q-angle beyond the standards was obtained by the dancers with the most serious injuries as well as the dancer with recurring injuries. Among the group was also the dancer with overload but without injury. In the case of the first three persons the result may suggest joint pathology caused by injury. In the case of the last dancer this information may suggest the risk of injury during regular that kind of exercises.

By analysing the results returned from the data captured while get up and go down the pouf the value of Q-angle beyond the norm was obtained by one dancer with ACL injury, which confirms that serious injury affects simple movement mechanics. The assumption of too high Q values for the dancer during rehabilitation was not accurate. This result may be due to the fact that the dancer's injury does not affect the mechanics of simple movements or may be due to lack of accuracy of the data.

9. Conclusions

The method in both motion capture, matching exercises and calculations is a method that is not 100% accurate. This lack of accuracy is due to the use of the default skeleton available in the Vicon Blade software and the overalls provided with the kit. Using the suits had was a risk of slight movement of the marker during exercise which could have been overlooked. Referring to the above it is proposed to broaden the research in this area by adopting the same set of exercises and calculation methods but using a different software skeleton and the placement of markers specifically for the study. In potential the smallest markers attached directly to the smooth surface of the skin would be used and the placement of these markers would only be limited to the local system i.e. from the ankle to the hip.

Despite lack of data accuracy after consulting with a physiotherapist who is professionally involved in the rehabilitation of athletes as well as dancers and demonstrating the work of the application it has been found that the application helps to identify the phase of motion that may be dangerous for knee joint. It has also been recognized that the output is helpful for this type of diagnosis. The above statement confirms the realization of the goal of using the motion capture system used in entertainment in helping to diagnose knee injuries.

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