An injury to the knee ligament apparatus is a pathology that involves one or more ligaments of the knee joint [1]. It is more prevalent among young able-bodied working-age men actively engaged in sports and exercise and is one of the most common traumatic and orthopedic injuries that compel the patient to seek medical help [1, 2].

The most common injury to the capsular ligament apparatus is an anterior cruciate ligament tear, affecting 30–35 people per 100,000 population [1]. Cruciate ligaments are fibrous bands of connective tissue that connect the femur and the tibia and limit excessive tibial mobility [3].

Most often, anterior cruciate ligament injuries are noncontact and occur during sudden knee joint rotation with the foot firmly planted [1, 4]. Many isolated ligament injuries are consequences of sports injuries caused by a rotational mechanism [5].

The following procedures are used to establish a diagnosis of anterior cruciate ligament tear: history taking, the Lachman test, the Anterior and posterior drawer tests of the knee, radiography of the knee joint (anterior, posterior and lateral views), and magnetic resonance imaging (MRI) of the knee joint [4].

Motion capture analysis (MCA) of gait provides valuable diagnostic data about the patient’s locomotion patterns. It

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**Author contribution:** Mozheyko EYu formulated the hypothesis, proposed the design, defined the goals and objectives of the study, analyzed study results, wrote and edited the manuscript; Pavlov AO formulated the hypothesis and edited the manuscript; Chistov MA, Khramchenko MA searched the literature, analyzed study results, performed statistical analysis and wrote the manuscript; Gurevich VA recruited the subjects, analyzed the results and performed statistical analysis.

**Compliance with ethical standards:** the study was approved by the Ethics Committee of Krasnoyarsk State Medical University (Protocol No 89/2019 dated April 17, 2019).

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Table 1. Characteristics of gait speed and rhythm in the patient with injuries to the knee ligament apparatus and the healthy subject

| MCA parameters                  | Patient with anterior cruciate ligament tear | Healthy subject |
|--------------------------------|---------------------------------------------|-----------------|
|                                | Left leg | Right leg | Both legs | Left leg | Right leg | Both legs |
| Cadence (steps/min)            | 94,4 ± 2,91 | 96,7 ± 3,78 | 95,5 ± 3,51 | 116,88 ± 3,25 | 117,56 ± 4,12 | 117,22 ± 3,68 |
| Lead toe off (% of the gait cycle) | 62,0 ± 1,54 | 62,9 ± 2,87 | 62,4 ± 2,29 | 60,10 ± 1,79 | 60,90 ± 2,16 | 60,60 ± 1,97 |
| Initial contact, lead foot (% of the gait cycle) | 49,80 ± 1,62 | 50,10 ± 2,32 | 49,90 ± 1,96 | 49,90 ± 1,13 | 50,10 ± 1,75 | 49,9 ± 1,56 |
| Contralateral toe off (% of the gait cycle) | 12,40 ± 0,71 | 12,80 ± 0,96 | 12,60 ± 0,85 | 9,80 ± 0,94 | 10,90 ± 0,85 | 10,50 ± 0,96 |
| Single support time (s)        | 0,48 ± 0,021 | 0,46 ± 0,038 | 0,47 ± 0,031 | 0,4 ± 0,026 | 0,44 ± 0,020 | 0,43 ± 0,025 |
| Double support time (s)        | 0,31 ± 0,023 | 0,32 ± 0,020 | 0,32 ± 0,021 | 0,2 ± 0,023 | 0,25 ± 0,018 | 0,23 ± 0,021 |
| Step time (s)                  | 0,64 ± 0,031 | 0,62 ± 0,040 | 0,63 ± 0,036 | 0,51 ± 0,027 | 0,56 ± 0,028 | 0,54 ± 0,028 |
| Stride time (s)                | 1,27 ± 0,042 | 1,24 ± 0,049 | 1,26 ± 0,047 | 1,02 ± 0,044 | 1,12 ± 0,040 | 1,08 ± 0,048 |
| Step length (m)                | 0,61 ± 0,021 | 0,62 ± 0,016 | 0,61 ± 0,020 | 0,68 ± 0,033 | 0,75 ± 0,016 | 0,72 ± 0,027 |
| Step width (m)                 | 0,20 ± 0,018 | 0,20 ± 0,010 | 0,20 ± 0,015 | 0,07 ± 0,012 | 0,07 ± 0,010 | 0,07 ± 0,011 |
| Stride length (m)              | 1,21 ± 0,023 | 1,23 ± 0,030 | 1,22 ± 0,029 | 1,36 ± 0,014 | 1,51 ± 0,0071 | 1,45 ± 0,011 |
| Walking velocity (m/s)         | 0,95 ± 0,042 | 0,99 ± 0,057 | 0,97 ± 0,053 | 1,24 ± 0,028 | 1,44 ± 0,025 | 1,34 ± 0,028 |

Today, passive markers are widely used in clinical motion capture analysis. Passive markers are reflective sensors that are attached to the patient’s body; the signals emitted by the sensors are captured by the video camera. The acquired data are transmitted to the computer for further processing. Finally, a report is generated that is subsequently used to analyze the linear and angular kinematics of the patient’s movements [7].

MCA requires that, since a plane is defined by 3 points, there should be at least 3 reflective markers in the field of view of at least 2 cameras [8].

To measure the physical characteristics of the studied body segments, calibrating markers are attached to the subject. So far, reference standards have been elaborated for movements of the foot, tibia, femur, pelvis, spine, wrist, forearm, and shoulder [9].

At present, MCA is being actively used to uncover the mechanisms of noncontact injuries to the anterior cruciate ligament of the knee joint [10]. 3D MCA has been proposed for adoption into clinical practice as a tool for monitoring rehabilitation in patients with knee joint injuries and assessing the risk of re-injury [11].

The clinical case described below illustrates a personalized MCA-based assessment of locomotor function in the patient with anterior cruciate ligament tear.

**Clinical case**

Patient I., aged 21 years, was diagnosed with a complete anterior cruciate ligament tear of the left knee joint and a partial posterior cruciate ligament tear. On January 19, 2021 the patient...
underwent arthroscopy of the left knee joint, resection of the remnant anterior cruciate ligament tissue, reconstruction of the anterior cruciate ligament with a peroneus longus autograft and autograft fixation with 19 PEEK Interference Screws (Arthrex; USA). The postoperative course was unremarkable. The patient received conservative treatment, which included antibiotics, analgesics, anticoagulants, and dressings. The knee joint was immobilized with a knee brace; the patient was using crutches for support when walking. On discharge, the patient’s condition was satisfactory.

Preoperative MRI performed on December 3, 2020 revealed an impression fracture of the lateral femoral condyle; trabecular edema of the lateral tibial condyle, the intercondylar area and the medial femoral condyle; synovitis and suprapatellar bursitis; MR features of injury to the anterior cruciate ligament and ligamentitis of the medial collateral ligament; moderate degenerative changes of the anterior and posterior horns of the medial meniscus; periarticular soft tissue edema.

Subject V., aged 22 years, had no health complaints regarding their musculoskeletal system, no medical history of lower limb surgery or injury and was comparable with patient I in terms of their anthropometric characteristics.

The patient and the healthy subject were tested at the Laboratory of MCA at the Federal Siberian Research and Clinical Center (FMBA, Russia) using a Vicon Motion Capture Systems (Vicon; UK). The system consisted of 12 infrared T20 video cameras, 3 force plates, a Vicon GigaNet connectivity device, a computer with installed software for video signal capture and processing (Nexus ver. 1.7.15) and software for generating reports (Polygon ver. 3.5.1).

The testing included several stages. First, anthropometric measurements were taken to map the sizes of the patient’s body segments to the computer model. Then, reflective markers were attached to the subject’s bony landmarks. The patient and the subject were asked to walk at their usual speed on 3 force plates. During the test, the video cameras captured the spatial positions of the markers and the force plates recorded the ground reaction force. Each participant performed at least 10 gait cycles on 3 force plates.

The following changes in gait characteristics were observed in the patient with an anterior cruciate ligament tear vs the healthy subject:

- **Angle 1**
  - Patient with injured knee ligament apparatus: \([-13.71; -18.08]\)
  - Healthy subject: \([-17.79; -16.28]\)

- **Angle 2**
  - Patient with injured knee ligament apparatus: \([23.3; 24.43]\)
  - Healthy subject: \([34.52; 32.66]\)

- **Δ**
  - Patient with injured knee ligament apparatus: \([37.62; 42.68]\)
  - Healthy subject: \([50.1; 48.84]\)

**Table 2.** Mean hip flexion and extension angles and amplitudes during one gait cycle in the patient with injuries to the knee ligament apparatus and the healthy subject

| Angle 1 | Patient with injured knee ligament apparatus | Healthy subject |
|---------|---------------------------------|----------------|
| Left leg | Right leg | Left leg | Right leg |
| Angle 1 | –13.71 | –18.08 | –17.79 | –16.28 |
| Angle 2 | 23.3 | 24.43 | 34.52 | 32.66 |
| Δ | 37.62 | 42.68 | 50.1 | 48.84 |

Fig. 2. Knee flexion and extension during one gait cycle in the patient with injuries to the knee ligament apparatus (top) and the healthy subject (bottom)
Table 3. Mean knee flexion and extension angles and amplitudes during one gait cycle in the patient with injuries to the knee ligament apparatus and the healthy subject

|                  | Patient with injured knee ligament apparatus | Healthy subject |
|------------------|---------------------------------------------|-----------------|
|                  | Left leg | Right leg | Left leg | Right leg |
| Angle 1          | 1,39     | -2,89     | 1,7     | 5,3       |
|                  | [1,04; 2,37] | [-3,32; -2,36] | [1,33; 2,26] | [5,02; 5,67] |
| Angle 2          | 45,07    | 52,82     | 61,89   | 63,73     |
|                  | [42,61; 48,18] | [51,2; 54,59] | [60,82; 63,34] | [63,4; 64,86] |
| Δ                | 43,16    | 56,01     | 60,85   | 58,39     |
|                  | [40,54; 46,55] | [54,89; 57,09] | [58,47; 61,57] | [57,73; 59,17] |

Fig. 3. Ankle flexion and extension during one cycle in the patient with injuries to the knee ligament apparatus (top) and the healthy subject (bottom)
Table 4. Mean ankle extension and flexion angles and amplitudes during one gait cycle in the patient with injuries to the knee ligament apparatus and the healthy subject

|                      | Patient with injured knee ligament apparatus | Healthy subject |
|----------------------|---------------------------------------------|-----------------|
|                      | Left leg | Right leg | Left leg | Right leg |
| Angle 1              | –9,24    | –15,65    | –9,59    | –9,18     |
|                      | [-9,41; –7,01] | [-17,19; –14,37] | [-12,05; –7,8] | [-10,39; –8,52] |
| Angle 2              | 13,48    | 10,79     | 19,76    | 23,52     |
|                      | [12,99; 14,71] | [9,25; 11,47] | [18,26; 20,49] | [22,11; 24,22] |
| Δ                    | 21,9     | 26,21     | 29,33    | 32,26     |
|                      | [20,98; 22,85] | [25,16; 27,07] | [28,58; 30,28] | [30,83; 33,91] |

We also found that the degree of left knee joint rotation was significantly lower than in the right knee joint (Fig. 4, Table 5). Rotation asymmetry in the knee joint was observed in the healthy subject, too, but it was slight.

Discussion clinical case

A study reported the use of MCA during a single leg hop test for assessing recovery of static and locomotor function in athletes after anterior cruciate ligament repair [12]. The following parameters were evaluated: knee flexion at initial contact, peak knee flexion, knee flexion range of motion, and knee valgus range of motion in the frontal and sagittal planes. The speed and rhythm of the gait were not studied. The authors concluded that MCA could be recommended as a simple and accurate method for assessing knee joint stability and predicting changes of returning to sports after anterior cruciate ligament reconstruction [12].

Another study employed MCA to assess the risk of injury in athletes following anterior cruciate ligament reconstruction [13]. The researchers performed the motion analysis of leg movements and assessed stability of the knee joint during walking, running, kicking the ball with moderate force and ball lashing. In addition to the speed and rhythm of gait, the researchers measured the ratios of flexion and extension angles in the operated and healthy knees during running and ball kicking. The angular characteristics of movements were not studied. It was concluded that MCA could be used as independently and as a complementary tool for gait analysis [13].

Another study was conducted in female athletes with anterior cruciate ligament injury; MCA was applied to analyze the mean knee flexion and the mean valgus angles during the initial contact, the internal and external rotation angles of the knee joint, and the mean peak vertical ground reaction force. The anterior cruciate ligament injury was attributed to a combination of valgus loading and internal knee joint rotation [14].

In another publication, the mechanisms of a slip-catch injury to the anterior cruciate ligament were investigated using MCA. The following parameters were analyzed: the knee...
Table 5. Mean knee rotation angles and amplitudes during one gait cycle in the patient with injuries to the knee ligament apparatus and the healthy subject

|                  | Patient with injured knee ligament apparatus | Healthy subject |
|------------------|---------------------------------------------|-----------------|
|                  | Left leg | Right leg | Left leg | Right leg |
| Angle 1          |          |           |          |           |
|                   | -5.83    | -14.55    | -7.28    | 0.57      |
|                   | [-7.48; -4.96] | [-15.73; -13.37] | [-8.23; -5.12] | [-0.84; 1.16] |
| Angle 2          | 2.41     | 4.12      | 14.27    | 17.78     |
|                   | [1.78; 2.79] | [3.13; 5.54] | [13.91; 15.17] | [17.02; 18.9] |
| Δ                | 8.15     | 19.01     | 21.59    | 17.05     |
|                  | [7.04; 9.58] | [17.2; 20.69] | [19.54; 22.75] | [16.03; 18.8] |

CONCLUSION

3D MCA is an informative method for the analysis of subtle changes in the biomechanics of walking in patients with anterior cruciate ligament injuries. The method generates valuable data about the amplitude and angular parameters of motion, and the speed and rhythm of gait.

Further research is needed to clarify how long the pathologic changes to the gait may persist and whether they can be managed through rehabilitation.

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