Application of the Motion Capture System in the Biomechanical Analysis of the Injured Knee Joint

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Abstract. The aim of the study was to analyzed the gaits determinants and the components of the ground reaction forces in patients treated surgically with the use of arthroscopy technique due to injuries in the knee joint. For the purpose of this study, three clinical cases of people with knee joint dysfunctions were examined. The studies were carried out in a biomechanical laboratory using the BTS Smart motion capture system. From the large set of collected data, the gaits determinants and the components of the ground reaction force were taken under account. The characteristics of the parameters considered for each patient were compared. The BST Smart system allows analysis of all gait determinants and ground forces reactions, what gives many important information about state of examined patient. These data cannot be collected during classical physical examination. The obtained results indicate the tendency of unloading the lower limb operated in relation to the opposite lower limb, although the gait is normal during visual analysis.

Keywords: Biomechanical analysis · Gait · Knee joint · Arthroscopy

1 Introduction

The knee joint is the largest joint of a human body, and due to its function during the locomotion mechanism one of the most important [1]. It is a crucial element of the lower limb – in both static and dynamic position, it allows maintaining the vertical position of a person and transfers the mass of body sections above it [2]. It allows bending and straightening movement occurs and their ranges are individually different and is a resultant of the circumference of the muscles of the thigh and lower leg, age and physical conditions. It usually takes the value of 0 degrees of extension (physiological hyperextension can reach about minus 5°), the value of flexion varies between 120 and 150° [3]. Movements in the frontal plane generally do not occur. From a

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practical point of view, the knee joint has 6 degrees of freedom, of which 3 are related to translation and another 3 to rotation; these are: (1) anterior-posterior translation (forward and posterior tibia), (2) medial-lateral translation (shifting of the tibia in the medial or lateral direction) and (3) distal-proximal translation (traction, compression) and (1) bending rotation -rightly, (2) external-internal rotation, (3) adduction-abduction rotation (distortion and deformity of the joint) [3].

One of the most common injuries in the knee joint are patellar injuries. Patellar subluxation is a condition in which the patella dislodges from the intercondylar eminence most often in the lateral direction and to strain the ligaments on the side opposite to the injury. The dislocation of the patella is a permanent injury in which the joint surfaces are separated from each other and the continuity of the ligaments is interrupted. Both the lateral subluxation of the patella and its dislocation very often lead to damage to the joint surface [4].

Surgical procedures of the restoration of proper or similar to proper path of the patella to this day are not popularized by the operators, and the results of treatment are the result of the frequency of injuries, muscle strength (especially the endurance of the medial head of the quadriceps), the level of dysplasia, and joint laxity. Currently, less invasive procedures are usually proposed, which consist in the arthroscopic release of the lateral patches of the patella, plasty of the ligaments with their duplication or reinforcement in the event of discontinuity, as well as the plasticization of the medial anterior cruciate ligament [5].

The patellofemoral joint plays an important role as a quadriceps thigh muscle block, and all its abnormalities and deviations from the biomechanical norm lead to distortions of individual gait components both in terms of quality and the possibility of distance traveled [3]. One of the basic attributes of walking mentioned in the literature is the minimal energy expenditure. In order to move with the lowest possible energy loss, the deflection of the center of body mass during a walk both vertically and horizontally should be as small as possible. Movement mechanisms used by the body to reduce fluctuations of the center of body mass and to minimize energy expenditure are called determinants of gait [6]. There are six basic determinants of gait:

1. Pelvic rotation around the long axis of the body.
2. Pelvic tilt in relation to the sagittal axis.
3. Bending of the knee in the support phase.
4. Movement in the knee joint.
5. Bending in the ankle and tibia joint.
6. Side displacements of pelvic [6, 7].

The first determinant of gait is related to alternate pelvic turns to the right and to the left depending on the gait phase. This results in an increase of the effective length of the limb at the interface between support and swing phase, and also reduces the amplitude of the deviations of the center of mass of the body while walking, which leads to reduction of energy expenditure. At a gait speed of approx. 5 km/h, the angular value of the revolutions around the vertical axis should be 4–5° for each side [7, 8]. The second determinant describes the pelvic fallout in the sagittal plane on the side of the lower limb currently in the phase of swing, and elevation on the side of the lower limb being in the support phase. Similarly to the first determinant, there is a reduction in the amplitudes deviations of the center of mass of the body, as well as an increase in the effective length of the limb during gait. This leads to a further reduction of energy expenditure during the gait. The range of alternating pelvic tilts in the sagittal axis is about 5º [7, 8]. The third determinant of gait is the bending of the knee joint in the support phase. At the beginning of the support phase, a slight bend occurs in the knee joint, which increases until the foot is laid flat on the ground. Then the bend reaches the maximum value equals about 15–20º. Next, the knee is straightened, but at the end of the support phase, the knee is re-bent to move the foot above the ground. The mechanism described makes the path of the center of gravity moving further flattening while the energy expenditure decreases [7, 8].

The first three gait determinants described above perform the same role and lead to the flattening of the motion paths of the center of mass of the body. Pelvic rotation described in the first gait determinant leads to elevations of the path of center of mass. On the other hand, the second and third gait determinants increase the radius of the arches of this path during walking, what leads to further flattening [5]. The fourth and fifth determinants of gait are interrelated mechanisms of movements of the feet, ankles and knee joints. When the heel comes into contact with the ground, the foot is dorsally bent. With full contact of the foot with the ground, draws the arch over the foot performing movement in the ankle joint. At the same time, there is a slight flexion in the knee joint. During the unloading of the foot, it performs plantar flexion. Synchronization of knee and foot movements during the support phase allows the body's center of mass to be kept as close as possible to straight line and allows for a smooth transition of the support phase into the swing one. The sixth gait determinant is the lateral displacement of the pelvis in the vertical plane due to the alternating loading of the lower limbs. The lateral dislocation of the pelvis is on the side of the lower limb loaded. In addition, it is accompanied by a several-degree adduction of the thigh in the hip joint. Unlike the other gait determinants that reduce movement of the center of mass in the vertical direction, the lateral pelvic displacement compensates for the center of the body and makes it easier to maintain body balance.

The aim of the study is to analyze the gaits determinants and the components of the ground reaction forces in patients treated surgically with the use of arthroscopy technique due to injuries in the knee joint.

2 Methodology

For the purpose of this study, three clinical cases of people with knee joint dysfunctions were examined. The studies were carried out in a biomechanical laboratory using the BTS Smart motion capture system. Before the examination, information about diseases and the course of treatment of each of the considered persons was collected. Basic information collected during interview are presented in Table 1.

Before starting the gait analysis using the BTS Smart system, markers reflecting infrared light were glued on the subject's body. A total of 17 markers were glued at the appropriate points on the skin of the subject. Measuring error as a results from the displacement of soft tissues on the bone points of the body can be assessed for about 5 mm. The correct placement of markers allows to create a model that is essential to

Table 1. Basic clinical information about patients

Patient	Treated lower limb	Diagnosis	Treatment	Mass of the body [kg]
1	Left	Dysplasia of the knee joint, condition after injury	Non-surgical treatment	49
2	Left	Excessive lateral pressure syndrome, condition after patellar dislocation	Cut of the lateral patellar retinaculum, duplication and sewing of the medial patellar retinaculum	104
3	Right	Damage of the anterior cruciate ligament (ACL)	ACL reconstruction using muscle tendons in the dorsal part of the thigh	62

isolate individual segments of the lower body. For this purpose, characteristic points were selected symmetrically on both sides of the body. The selected points are: anterior superior iliac spine, greater trochanter, middle of the patella, axis of knee joint, tuberosity of tibia, lateral malleolus, calcaneal tuberosity, great toe. Additionally, a point on the sacrum was marked. For each of the respondents, the gait examination contained of 50 registrations of activity consisting in free passage at any speed along the designated path. In the middle part of the path there were two dynamometric platforms that collected information about ground reaction forces. The positions of all markers during movement were recorded. Recordings containing incomplete data were rejected and the remaining ones analyzed.

3 Results

From the large set of collected data, the gaits determinants and the components of the ground reaction force were taken under account. The characteristics of the parameters considered for each patient were compared.

The first of the presented parameters is the second determinant of gait, the pelvic tilt in relation to the sagittal axis. Angle measurement required the assumption that positive values were obtained in the situation when the left lower limb was in the front, and negative values in the reverse situation. The measured variable reaches the maximum when the left heel is placed on the ground, i.e. at the beginning of the stance phase of the left lower limb and the minimum with the start of the stance phase for the right lower limb. These characteristics for three examined patients are presented in the Fig. 1.

One can observe in the Fig. 1, that for all patients asymmetrical characteristics were obtained. In first case, the maximum value, when the left heel touched the ground, was about 4°, and in the case of the right foot it was almost 6°. The shape seems to be close to a sinusoid, but there is some flattening before the contact of the left foot with the

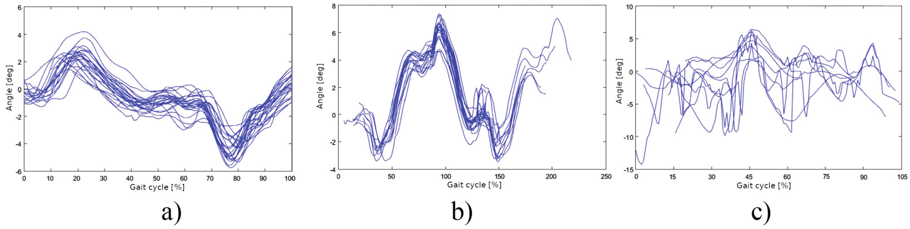


Fig. 1. Pelvic tilt in relation to the sagittal axis during gait for 3 examined patients – (a) first patient, (b) second patient, (c) third patient.

ground. In the second case, an atypical course of the second determinant can be seen, in which the moment before the pelvic tilt around the sagittal axis reaches the local minimum, a small increase of this value can be noticed. Analogically, the maximum is preceded by a slight decrease of the value of the measured angle. Patient No. 3 achieved very irregular shapes of curves. In addition, they did not overlap with each other. Larger values were recorded at the moment when the right lower limb was at the front. In extreme cases, they were even two times bigger than in the case of the left lower limb. These results may also suggest that the patient has a pelvic or hip joint dysfunction.

The second considered parameter of the gait was flexion in the ankle joint. Negative values in the charts indicate the plantar flexion of the foot, while the positive values correspond to the dorsal flexion. In the Fig. 2, there are presented characteristics of flexion angle in both feet for first patient.

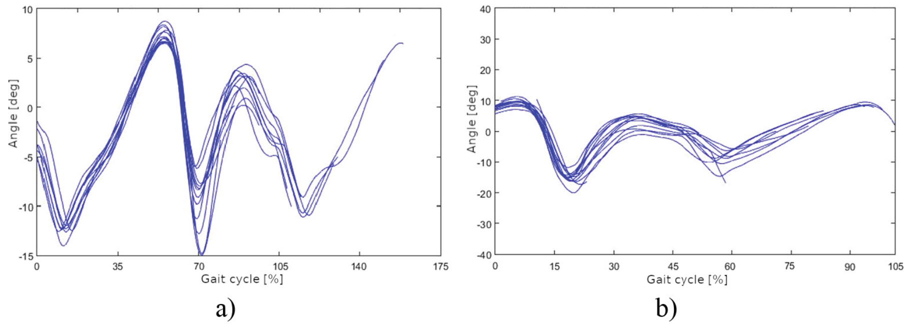
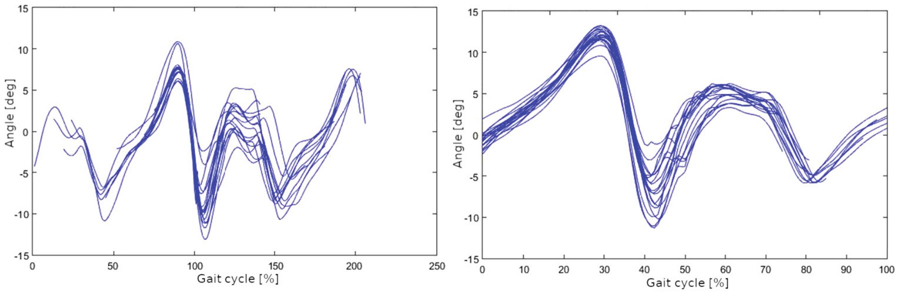


Fig. 2. Flexion in the left (a) and right (b) ankle joint depending on time during gait of patient 1.

Obtained characteristics for each of the lower limbs are similar, which indicates a high regularity of gait. However, charts for the left lower limb (injured one) and for the right lower limb differ. In both cases, the dorsiflexion of the feet have similar angular values of the range of motion. However, when feet perform plantar flexion, there were larger differences. It can be observed that for the left lower limb the plantar flexion is smaller than for the right one.

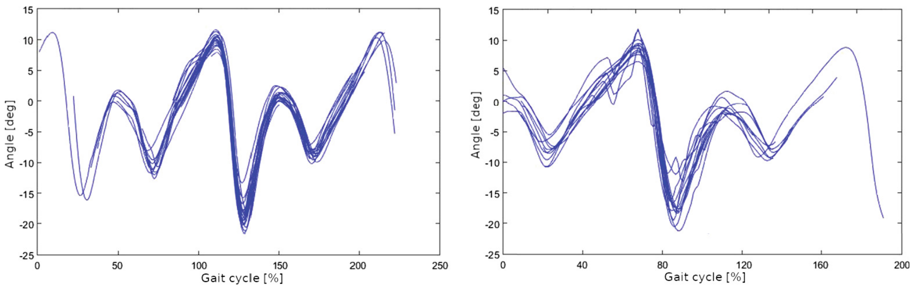
In patient 2 case (Fig. 3), the values of both dorsal and plantar flexion for both limbs are very similar. The only clearly visible difference between the right and the lower limb is the repeatability of changes in the angle of the ankle angle. For the left foot, the individual runs differ significantly more than in the case of the right foot. This difference is most evident when foot is dorsally bending.



a) b)

Fig. 3. Flexion in the left (a) and right (b) ankle joint depending on time during gait of patient 2.

In the case of third patient, the values of both the dorsal and plantar flexion of the feet for both lower limbs are very similar (Fig. 4). In the case of the right lower limb (injured one), it can be seen that there are less regular shapes with visible sudden and momentary jumps or decreases in the angular value of ankle bending. This is probably due to load compensation in the knee or hip joint.



a) b)

Fig. 4. Flexion in the left (a) and right (b) ankle joint depending on time during gait of patient 3.

The third parameter that should be mentioned is the side component of the ground reaction force. In this case, the results obtained by the first and second examined patient were presented in the form of graphs (Fig. 5). To make it possible to compare the results obtained by individual subjects, the components of the reaction force of the substrate are given in terms of percentage of body weight (% BW).

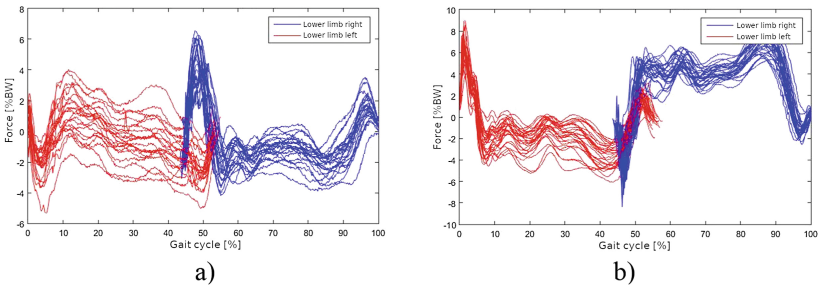


Fig. 5. Side component of the ground reaction force obtained during gait for patients 1 (a) and 2 (b).

In the lateral component of ground reaction force, a large divergence of the waveforms can be distinguished. Some curves, despite their similar shape, do not coincide with each other. This may mean instability of the knee joint. It is probably caused by a knee dislocation. Despite the discrepancies, the shape is similar to the results described in the literature [7, 8]. The charts of force components of the ground reaction forces obtained for second patient also had an approximation to patterns known from the literature. Discrepancies were still large, but smaller than for the first patient. One can also observe, that fluctuations are slightly greater for the first recorded step.

4 Discussion and Conclusions

The analysis of the obtained results was started from the second gait determinant. The first examined person obtained an asymmetrical characteristic. The maximum deflection values differ by 2°. The waveform is slightly different from the normal one. There is some flattening of the curves' shape just before the contact of the left foot with the ground. Second patient obtained a very unusual characteristics. Just before global extremes, there was a local maximum, both in the case of contact of the right foot with the ground and the left one. This may indicate a certain gait abnormality. In the case of the third patient, as in the case of the first determinant, very irregular, non-overlapping shapes were obtained. Excessive values were obtained when the right lower limb was tilted forward. These values were even 2 times higher than in the case of the left lower limb. These results suggest a pelvic or hip joint injury.

The fifth determinant is defined by the flexion in the ankle joint. First patient obtained curves overlapping each other, but different for the left (injured) and right limb. The biggest differences can be seen in the case of plantar flexion of feet. The angle value is smaller for the lower limb that suffered an injury. This may be due to functional disorders within the knee joint that limit movement in the joint or the mechanism of preventing the occurring pain. For second patient, the ranges of bending movements for both the right and left lower limb are similar. However, in the case of the left lower limb, some irregularities can be noticed at the dorsal flexion of the foot. The third examined person also obtained similar values of flexion of the dorsal and plantar foot in both extremities of the lower limbs. In the case of a damaged lower limb, the waveforms obtained slightly differ from the normal values. This may be due to an attempt to compensate loads by the hip or knee joint.

One of most important parameters, that is usually taken under consideration during gaits analysis are component of ground reaction forces. It is usually unique and can be completely different for any individual [9, 11, 12]. After taking into account the lateral component of the ground reaction force, it was found that in the case of patient 1, a large discrepancy in the waveforms of data collected for the damaged lower limb can be observed. This means instability of the knee joint. The existing condition should be explained by an acute injury of the knee joint which occurred a few days before the biomechanical examination (information obtained from the patient during the collection of the interview). This may explain the shape of the obtained waveforms. In the case of the second patient, the characteristics were similar to those contained in the literature data. However, the values obtained for one and the other lower limb were not equal. At the instant of contact of the foot with the ground, the values were similar, however, during the support phase for the first lower limb (injured one) the values are about 2% lower than for the second lower limb (uninjured), which is a significant difference in the lateral component of the reaction force. This means that the patient loads the undamaged lower limb more than, lower limb after surgical treatment.

One can conclude, that the BST Smart system allows analysis of all gait determinants and ground forces reactions, what gives many important information about state of examined patient. These data cannot be collected during classical physical examination. The obtained results indicate the tendency of unloading the lower limb operated in relation to the opposite lower limb, despite the fact that during the visual gait assessment, the patient does not show any distance from the normal gait stereotype.

In this paper only some chosen parameters were presented. Typical biomechanical analysis consists all of trajectories, velocities obtained for all points of considered model together with angular characteristics and angular velocities of all segments. We've decided to present only these parameters with untypical or interesting characteristic. As one can observe, such approach can brings lot of important information about state of a patient. However, other crucial information about condition of lower limbs and especially knee joints could be obtained by EMG examination [10].

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