Analysis of the biomechanical characteristics of the knee joint with a meniscus injury

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The knee joint is one of the most important joints in the human body. The meniscus is a half-moon cartilage which locates between the medial and lateral condyle of the thighbone and the medial and lateral condyle of the shin in the knee joint, and it has multiple functions such as bearing load, cushioning and stabilising joints. It is easy to be injured because of its complex structure and functions. In this study, the physical fitness of patients with meniscus injury was tested using kinematic measurement, and the data were collected for biomechanical analysis on the parameters such as the angle and stress when the patient’s bent knees during sports. The results demonstrated that the average values of bending angle, the rotation angle of the knee joint and intensity of pressure of the patients with meniscus injury were remarkably different with those of people without meniscus injury. Biomechanical characteristics are of extensive values to the treatment of meniscus injury.

1. Introduction: Knee meniscus is mainly used to redistribute the contact force passing the tibia–femur joint [1]. Meniscus injury of the knee is a common sport-induced injury. In the daily exercise, there are instant changes of direction, sudden takeoff and striding, all of which cannot be done without the flexion and extension of the knee. Meniscus plays an important role in the control of compound biomechanics of the knee joints [2] as it can protect the stability of knees, absorb shock, transfer load and control motion [3]. Frequent, large-range actions make the knee joint meniscus bear the huge load, and long-time load can induce excessive fatigue of meniscus and strain. Meniscus injuries are common among athletes and general populations [4]. Patients with meniscus injury may have pain, swelling or mechanical symptoms, and often need surgical operation [5]. If no treatment is carried out, it will increase the risk of degenerative changes of the knee joints [6]. Meniscus injuries are common among sportsmen, especially sportsmen in the fields involving frequent rotation, such as basketball, soccer and American football [7].

Zedde et al. [8] found that meniscus injury of young basketball players was induced by pressure and bending rotation of the knee joints through analysed the traumatic meniscus injury of basketball players. Remitting pains through meniscus repairing, biological replacement implantation and implantation of donor meniscus are beneficial to the recovery of competitive activities and long-term stability. In the study of Astur et al. [9], football players with meniscus injury were trained. They found that the effects on the plays were negative, the sports which could increase the risks of meniscus injury included running, volleyball and weightlifting. The absence of meniscus may result in higher incidence of degenerative changes of the knee joints [6] and induce osteoarthritis. There are structural, mechanical and biological changes of the knee joints after the occurrence of a meniscus injury, which may be greatly affected by local or global inflammation [10]. Jones et al. [11] found through investigation that the incidence of meniscus injury increased with the increase of age, the incidence of meniscus injury among people who aged over 40 years were four times that of people under 20 years. Guess et al. [12] developed a calculation model to explore the relationships between the compression degree of the meniscus and biomechanical functions by adjusting the relaxation degree of meniscus accessory. He found that the compression on meniscus increased when the relaxation degree of tibial accessory increased and moreover the increase of relaxation degree could result in the dysfunction of the meniscus. In this study, special quality testing was performed on patients with a meniscus injury, and various parameters of the knee joints during sports were measured using kinematic measurement, and a biomechanical analysis was carried out. This study investigated the effects of meniscus injury on the kinematics of the knee joints [13].

2. Exercise induced injury on the knee joints: The knee joints with biomechanical functions which can bend and rotate keep stable in daily activities and spread strength [14]. The activities of the knee joints are three-dimensional which follow the forward and backward movements of the thighbone and axial internal rotation of tibia instead of single flexion and extension. The flexion, extension and twist of the knee joints mainly rely on the relative movement of the thighbone and tibia. The flexion and extension of the tibia are between 0° and 150°, and the twist of the tibia is realised by taking the vertical axis of the knee joint as the centre. Condyles of femur provide a stable pathway for the sliding of the patella. The arm of force of the muscle group of the knee joints changes along with the variation of the flexion and extension of the knee joints and is stable when the angle was between 90° and 135°.

Exercise induced injury on the knee joints is usually related to the meniscus. A meniscus injury can reduce the stability of the knee joints and increase the stress on the knee joints during flexion and extension, which may affect the functions of other tissues of the knee joints and is prone to cause some slight injuries. The accumulation of slight injuries can induce compensative changes in different tissues and result in the strain of the whole knee joint.

The biomechanical analysis of the knee joints was made by performing dynamic stereo photography, image sampling and data calculation [15].

2.1. Test equipment: Test equipment included Vicon 3D motion capture system, reflective ball sensors, a stress sensor, a WNQ treadmill, biomechanical analysis software, SPSS ver. 12.0 and a computer installed with WINDOWS.

2.2. Experimental grouping: Twenty-four regular people with an exercise-induced meniscus injury and 24 healthy volunteers were selected and set as an injury group and a healthy group. There were 12 males and 12 females in each group. In the healthy group, the subjects aged between 15 and 38 years...
(average 26.9 years); the average body mass index (BMI) was 20 kg/m². In the injury group, the subjects aged between 17 and 33 years (average 23.7 years); the average BMI was 22 kg/m². The comparison of the distribution of age and BMI between the two groups suggested no remarkable differences. All the volunteers had no history of knee joint injuries and diseases; moreover, injury and pathological changes of degeneration have been excluded using X-ray and magnetic resonance imaging. They signed informed consent.

The condition of meniscus injury of the patients in the injury group is shown in Table 1. All of them underwent arthroscopy. The average disease course was (23.4 ± 32.6) months.

2.3. Physical fitness test: Tests of standing triple jump, 100-m running, 2000-m running and one-minute rope skipping were carried out in the College of Physical Education of Central South University of Forestry and Technology, Hunan, China. The maximum value, minimum value, average value and standard value were calculated. Standing triple jump could reflect the explosive power and rapid force; 100-running could reflect an instantaneous burst of speed; 200-m running could reflect speed endurance; one-minute rope skipping could reflect the coordination of the lower limbs.

2.4. Tests on flexion angle and stress during exercise: The meniscus of each subject was examined in the department of radiology of Henan Provincial People’s Hospital, Henan, China. The stressed area inside the knee joints under different angles was measured. Moreover, bone anatomy markers were labelled on the femoral lateral greater trochanter, femoral medial and lateral condyle, tibial plateau, tubercle of the tibia, lateral fibular head, medial malleolus and lateral malleolus. Two reflective ball sensors were installed on the near end of the tibia and the far end of the femur. Each subject jogged on a treadmill for 2 min. Then data were collected in 50 frames/s for 20 s. The parameters such as the introduction and extraversion angles of the femur of the knee joint relative to the tibia, internal and external rotation angles and offset were recorded and analysed using biomechanical analysis software called Visual3D; the stress and pressure per unit area inside the knee joints were calculated.

3. Experimental results

3.1. Analysis of physical fitness: Table 2 shows that the performance of the subjects in the injury group was poorer than that in the healthy group in all the tests; in the test of 2000-m running, the average time of the healthy group was much superior to that of the injury group (8.16 min versus 10.76 min), indicating that meniscus injury had a large influence on long-time endurance exercise; as to the performance of 100-m running, the injury group spent 2.83 s more than the healthy group, suggesting a great reduction of speed explosiveness. The comparison of the average performance of the subjects in the tests of standing triple jump and one-minute rope skipping demonstrated that meniscus injury could reduce explosive power, rapid force and coordination of the lower limbs.

3.2. Comparison of movement angles of the knee joints: The movement angles of the knee joints during walking were measured using the sensor. As shown in Table 3, there were no apparent differences between the injury and healthy groups in the maximum introversion and extraversion angles; the maximum internal and external rotation angles of the injury group were much smaller than those of the healthy group; the minimum flexion angle of the injury group was significantly larger than that of the healthy group, but the difference of the maximum flexion angle had no statistical significance. Table 2 shows that the range of the internal and external rotation angles of the injury group was much smaller than that of the healthy group (10.5° ± 1.2° versus 15.1° ± 1.0°); there were no notable difference between the two groups in the introversion, introversion and flexion angles of the knee joints.

3.3. Comparison of femoral offset: Table 4 exhibits that there was no notable difference between the injury and healthy groups in the maximum and minimum upward displacements and minimum outward displacement of the femur, while the maximum antedisplacement, retrodisplacement and outward displacement of the injury group were significantly lower than those of the healthy group. Table 3 shows that the ranges of the antedisplacement, retrodisplacement, inward displacement and outward displacement of the knee joints in the injury group were smaller than those of the healthy group; but the difference of the ranges of upward and downward displacement had no statistical significance.

3.4. Comparison of stress under different flexion angles: Table 5 shows that the stressed area of the knee joints decreased with the increase of the flexion angle, and the pressure on the knee joints increased with the increase of the flexion angle. When the flexion angle increased from 0° to 120°, the average stressed area of the knee joints of the healthy subjects decreased from 12.468 to 5.443 cm², and the average pressure increased from 56.251 and 128.669 N/cm²; the stressed area of the knee joints of the injured subjects decreased from 11.541 to 4.770 cm², and the average pressure increased from 48.202 to 147.268 N/cm². Thus the average stressed area of the knee joints of the injury group was apparently smaller than that of the healthy group under any flexion angles; the average pressure of the injury group was

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Table 1 Condition of meniscus injury of the 24 patients in the injury group

| Site       | n  | Medial injury | Lateral injury | Medial and lateral injuries |
|------------|----|---------------|----------------|----------------------------|
| left knee  | 8  | 3             | 4              | 1                          |
| right knee | 16 | 5             | 9              | 2                          |
| total (n)  | 24 | 8             | 13             | 3                          |

Table 2 Comparison of physical fitness between the injury and healthy groups

| Group         | Index                  | Minimum value | Maximum value | Average value | Standard deviation |
|---------------|------------------------|---------------|---------------|---------------|--------------------|
| injury group  | standing triple jump, m| 3.9           | 7.56          | 5.94          | 0.6675             |
|               | 100-m running, s       | 12.45         | 18.93         | 15.95         | 1.3258             |
|               | 2000-m running, min    | 7.81          | 13.41         | 10.76         | 1.6845             |
|               | one-minute rope skipping (time) | 36          | 242          | 134.52        | 39.772             |
| healthy group | standing triple jump, m| 4.3           | 8.15          | 6.25          | 0.6919             |
|               | 100-m running, s       | 11.37         | 16.42         | 13.59         | 1.1567             |
|               | 2000-m running, min    | 6.62          | 10.24         | 8.16          | 1.0532             |
|               | one-minute rope skipping (time) | 43          | 264          | 147.24        | 37.455             |
The contact area of the tibiofemoral joint and dissipating load via meniscus is to bear the load and absorb shock through increasing range of the knee joints of the injured subjects was much smaller outward displacement of the knee joints; therefore the movement extroversion angles, antedisplacement, retrodisplacement and other parameters such as strength and coordination also speed endurance and explosive power had remarkable declines, decline of physical fitness. The long-term consequence of anterior cruciate ligament and meniscus injuries, Am. J. Sports Med., 2007, 35, (10), p. 1756

It hints that protection for the meniscus should be paid attention on the knee joints with a meniscus injury and normal knee joints. The results revealed that meniscus injury could result in the decline of the flexibility, speed, explosive power and strength. This study was supported by the Scientific Research Project of Education Department of Hunan (no. 15C1449). Conflict of interests: None declared.

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Table 3 Comparison of movement angles of the knee joints (°)

| Angles of the knee joints | Injury group | Healthy group |
|--------------------------|--------------|---------------|
| maximum introversion angle | 3.653 ± 0.437 | 3.162 ± 1.362 |
| maximum extroversion angle | 2.731 ± 0.987 | 2.321 ± 0.363 |
| maximum internal rotation angle | 5.121 ± 0.564 | 7.660 ± 0.528 |
| maximum external rotation angle | 5.347 ± 0.703 | 7.456 ± 0.486 |
| maximum flexion angle | 63.950 ± 5.471 | 62.719 ± 4.287 |
| minimum flexion angle | 9.927 ± 1.451 | 6.879 ± 1.083 |

Table 4 Comparison of femoral offset (mm)

| Femoral offset | Injury group | Healthy group |
|----------------|--------------|---------------|
| maximum antedisplacement | 0.66 ± 0.04 | 1.10 ± 0.107 |
| maximum retrodisplacement | 0.19 ± 0.08 | 0.30 ± 0.06 |
| maximum upward displacement | 1.61 ± 0.19 | 1.62 ± 0.10 |
| minimum upward displacement | 0.23 ± 0.24 | 0.26 ± 0.21 |
| maximum outward displacement | 1.07 ± 0.09 | 1.37 ± 0.16 |
| minimum outward displacement | 0.34 ± 0.06 | 0.32 ± 0.13 |

Table 5 Comparison of stressed area and pressure of the knee joints under different flexion angles

| Group | Average stressed area, cm² | Average pressure, N/cm² | Average stressed area, cm² | Average pressure, N/cm² |
|-------|-----------------------------|-------------------------|-----------------------------|-------------------------|
| Healthy group | 12.468 | 56.251 | 11.541 | 48.202 |
| Injury group | 10.990 | 63.722 | 9.782 | 71.733 |
| 0° | 8.485 | 85.513 | 7.322 | 95.652 |
| 30° | 6.415 | 109.189 | 5.691 | 122.987 |
| 60° | 5.443 | 128.669 | 4.770 | 147.268 |

larger than that of the healthy group ($p<0.05$). The smaller the average stressed area, the larger the pressure. The large pressure was not beneficial to load transfer of meniscus and even induce further wear, degeneration and tear of the meniscus in the long term.

4. Discussion and conclusion: The meniscus is a shock absorber which can keep the knee joints stable. The injury of the meniscus will lead to the degenerative changes of the knee joint and the decline of physical fitness. The test and analysis of physical fitness suggested that the physical fitness of the athletes such as speed endurance and explosive power had remarkable declines, and other parameters such as strength and coordination also declined, though, not obviously.

The experimental results suggested that there were notable differences between the injury and healthy groups in the introversion and extroversion angles, antedisplacement, retrodisplacement and outward displacement of the knee joints; therefore the movement range of the knee joints of the injured subjects was much smaller than that of the healthy subjects. It might be because that the thickened meniscus took up some space in the articular cavity, and moreover, meniscus injury induced pain. The main function of the meniscus is to bear the load and absorb shock through increasing the contact area of the tibiofemoral joint and dissipating load via conversion to hoop stress [16]. A meniscus injury can result in a significant decrease in the stressed area of the tibia and declined capability of bearing load. Therefore the pressure of the injury group was obviously larger than that of the healthy group under different flexion angles. The performance of the injured subjects in three tests was poor; which was because fatigue and pain brought about by the constant abrasion of the injured meniscus weakened the strength of the knee joints and speed.

In this study, the effects of meniscus injury on physical fitness were investigated through a physical fitness test, and moreover, motion measurement and biomechanical analysis were performed on the knee joints with a meniscus injury and normal knee joints. The results revealed that meniscus injury should be paid attention to in daily fitness exercises.

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