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Abstract

A comparative analysis was conducted on the mechanical properties of knee joint cartilage tissues (meniscus, femoral cartilage, tibial cartilage) between the unaffected side of stroke patients and the corresponding side of healthy individuals. A complete finite element model of the knee joint was developed based on MRI and CT data; kinematic and kinetic data during walking were synchronously collected from stroke patients and healthy populations using an 8-camera Qualisys motion capture system and a Kistler three-dimensional force platform; knee joint moments and joint reaction forces were calculated using a musculoskeletal model in OpenSim and served as inputs for the finite element model to compute the stress conditions of knee cartilage tissues (meniscus, femoral cartilage, tibial cartilage) in both groups using finite element analysis software, with differences compared using independent samples t-test. The peak equivalent stress, maximum principal stress, and maximum shear stress of knee cartilage tissues (meniscus, femoral cartilage, tibial cartilage) on the unaffected side of stroke patients all showed significant differences compared to those on the corresponding side of healthy individuals (all P-values < 0.01). In gait analysis of stroke patients, the FE (finite element) model can calculate the mechanical properties of knee cartilage tissues, providing a new approach for obtaining biomechanical data of stroke patients and an effective method for helping stroke patients prevent cartilage injury. The "healthy" limb of stroke patients is no longer considered truly healthy and should be considered together with the affected limb when formulating rehabilitation treatment plans.

Full Text

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Analysis of Mechanical Properties of Knee Joint Cartilage in Stroke Patients

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Abstract: This study comparatively analyzes the mechanical properties of knee-joint cartilage tissues (meniscus, femoral cartilage, and tibial cartilage) on the healthy side of stroke patients and on the corresponding side in healthy individuals. A complete finite-element model of the knee joint was established based on MRI and CT. Kinematic and kinetic data during walking in stroke patients and healthy individuals were synchronously collected using an 8-camera Qualisys motion capture system and a Kistler three-dimensional force platform. Knee-joint moments and joint reaction forces were calculated using the musculoskeletal model in OpenSim; the joint moments and joint reaction forces were used as inputs to the finite-element model. Finite-element analysis software was then used to calculate the stress conditions of knee-joint cartilage tissues (meniscus, femoral cartilage, and tibial cartilage) in the two groups. Differences were compared using independent-samples T tests. The equivalent stress peak values, maximum principal stress, and maximum shear stress of the knee-joint cartilage tissues (meniscus, femoral cartilage, and tibial cartilage) on the healthy side of stroke patients were all significantly different from those of the corresponding knee-joint cartilage tissues in healthy individuals (P values all < 0.01). In gait analysis of stroke patients, the FE (finite element) model can be used to calculate the mechanical properties of knee-joint cartilage tissues, providing a new approach for obtaining biomechanical data from stroke patients and an effective method to help prevent cartilage injury in stroke patients. The "healthy" limb of stroke patients should no longer be regarded as truly healthy; it should be considered together with the affected limb when rehabilitation treatment plans are formulated.

Keywords: stroke; finite-element model; meniscus; femoral cartilage; tibial cartilage

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Mechanical characterization of knee cartilage in stroke patients

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Abstract: This paper makes a comparative analysis of mechanical properties of the cartilage tissues (meniscus, femoral cartilage and tibial cartilage) of knee joints of the healthy side of stroke patients and the corresponding side of the knee joints of the healthy population. A complete finite element model of the knee joint was established based on MRI and CT; kinematic and kinetic data of walking in stroke patients and healthy people were synchronously collected by an 8-shot Qualisys motion capture system and a Kistler 3D force platform. Knee joint moments and joint reaction forces were computed by a musculoskeletal model

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in OpenSim, and the joint moments and reaction forces were used as inputs to the finite element model. The stresses on the knee cartilage tissues (meniscus, femoral cartilage and tibial cartilage) of the two groups were calculated by the finite element analysis software, and the differences were compared by the independent samples t-test. The peak equivalent force, maximum principal stress, and maximum shear stress of the cartilage tissues (meniscus, femoral cartilage and tibial cartilage) of knee joints on the healthy side of the stroke patients were significantly different from those on the corresponding side of the healthy population (all P values less than 0.01). The FE model can calculate the mechanical properties of knee cartilage tissues in gait analysis of stroke patients, providing a new way to obtain biomechanical data from stroke patients and an effective way to help prevent cartilage damage in stroke patients. The "healthy" limb of a stroke patient is no longer considered to be truly healthy and should be considered in conjunction with the affected limb in the development of a rehabilitation program.

Key words: stroke; finite element model; meniscus; femoral cartilage; tibial cartilage

Approximately 70% of stroke patients develop hemiplegia, among whom 40%-60% present with knee hyperextension[^1]. Long-term knee hyperextension changes the mechanical trend of the lower limbs and disrupts the load-bearing response of the knee joint, reducing standing stability and causing the body to lean forward. Related studies have also found that the knee-joint moment on the unaffected side of stroke patients is greater than that in healthy controls; these changes lead to uneven stress distribution in the knee joint. Walking in this manner for a long time can cause knee-joint pain and cartilage injury, and lead to cumulative injury and degenerative changes of knee-joint cartilage[^2-3]. Other tissues around the knee joint, such as the meniscus, may also undergo pathological changes[^4]. At present, there is still no effective drug therapy for cartilage injury or for repairing cartilage defects[^5]. If irreversible damage to articular cartilage can be detected by medical imaging before it occurs and appropriate treatment is adopted, normal knee-joint function can be maintained and disability avoided. Therefore, it is important to detect early pathological changes in cartilage.

[[unclear: author name]][^6] used a zero-TE double-echo imaging sequence to analyze knee-joint cartilage in stroke patients. The study found that, compared with the unaffected side, the free-water content ratio of cartilage in the anterior horn (1.16 vs. 1.06) and posterior horn (1.13 vs. 1.25) of the lateral meniscus on the affected side showed significant differences. Knee flexion in stroke patients can cause changes in the water content of knee-joint cartilage, and the changes in knee-joint cartilage become more obvious as the degree of knee flexion increases. However, this method has certain limitations: it can only reveal the imaging condition of knee-joint cartilage in stroke patients, and cannot obtain the mechanical parameters of cartilage. Therefore, in order to better understand the characteristics of stress distribution in knee-joint cartilage, many biomechanical studies have been based on cadaveric specimens. Although studies based on cadaveric specimens have certain advantages, there are certain limitations for in-depth research[^7-12]. With advances in digital medicine and computational software, finite element analysis (FEA) can better address the pain points of cadaveric and in vivo research in biomechanical analysis[^13]. Researchers can study the mechanical response of tissues in a noninvasive manner and simulate human mechanical testing at relatively low cost and risk[^14]. In addition, researchers can repeatedly study the established finite element model, and make the research results more intuitive through visual analysis[^15-16].

Based on magnetic resonance and CT images, this study established a complete knee-joint finite element model. Kinematic and kinetic data from stroke patients and healthy people during walking were collected synchronously using an eight-camera Qualisys motion-capture system and a Kistler three-dimensional force platform. Knee-joint moments were calculated through the musculoskeletal model in OpenSim. The joint moments were then used as inputs to the finite element model, and finite element analysis software was used to calculate the stress conditions of the meniscus, femoral cartilage, and tibial cartilage in the two groups.

1 Research Subjects and Methods

1.1 Research Subjects and Data Collection

1) Kinematic and kinetic data

Figure 1 illustrates the workflow of this study. A total of 15 stroke patients treated at the Tianjin Rehabilitation and Recuperation Center of the Joint Logistics Support Force of the Chinese People's Liberation Army (the affected side was the right side in all cases), and 15 healthy participants from the Shichunli community, were included in the experimental data collection (basic information on the participants is shown in Table 1). All participants involved in this study had obtained approval from the Ethics Committee of Tianjin University of Sport (TJUS2023-029). Inclusion criteria for stroke participants: Brunnstrom stage IV; more than 6 months after stroke; no cognitive impairment and ability to understand the experimental procedure; ability to walk independently for 20 m; no other major diseases; and ability to sign the participant informed-consent form[^16]. Inclusion criteria for healthy participants: no cardiovascular-system diseases and no lower-limb injury within the past six months.

Paste scheme: lower limb punctation
(CAST_Marker_Set_Lower_Boby)

Capture static poses

Capture dynamic poses

.trc file

.mot file

Generic musculoskeletal model

OpenSim: IK, ID, SO operations

(IK, ID, SO)

Stroke patient gait-process simulation

(output knee-joint moment and joint force)

Joint moment and joint force

Subject-specific finite element model

Subject MRI

Meniscus stress

Femoral cartilage stress

Tibial cartilage stress

Figure 1 Flow chart of this study

Test protocol. Before testing, the subjects were informed of the purpose, methods, and precautions of the experiment and signed an informed-consent form. Testing was conducted at Tianjin University of Sport. Kinematic and kinetic data were collected synchronously using an 8-camera Qualisys motion-capture system (sampling frequency: 300 Hz), with the marker placement scheme set to the lower-limb marker set (CAST_Marker_Set_Lower_Body), and a Kistler three-dimensional force platform (GRF, 1 000 Hz, two force plates).

As can be seen from Table 1, in this study there were no significant differences between the stroke patients and the healthy population in age, body mass, height, or BMI.

Table 1 Basic information of the subjects

Tab. 1 Basic information of the subjects

Item	Age/years	Body mass/kg	Height/cm	BMI
Stroke patients	61.5 ± 3.5	68.2 ± 2.4	167.2 ± 3.4	24.4 ± 2.1
Healthy population	61.2 ± 3.4	68.5 ± 2.0	166.9 ± 2.9	24.6 ± 1.8
P value	>0.05	>0.05	>0.05	>0.05

2) CT and MRI data

A Light Speed VCT (GE, USA) and MRI Signa 3.0 T (GE, USA) were used (specific CT and MRI scanning parameters are shown in Table 2) to collect left-knee-joint data from two subjects. One subject was from the stroke patient group (61.3 years old, 68.5 kg, 1.67 m, affected side on the right); the other was from the healthy group (61.4 years old, 68.5 kg, 1.67 m). Standardized finite element models of the knee joint were established from the collected CT and MRI data. These two individuals were selected because all of their physical indicators were closest to the mean values within their respective groups and, except for age, their height and body mass were the same. The MRI scanning parameters are shown in Table 2. The CT scan slice thickness was 0.5 mm, the interslice spacing was 0.5 mm, the number of CT rows was 320, the collimator width was 0.5, the image size was 512 × 512, and the image format was DICOM.

Table 2 MRI specific scanning parameters

Tab. 2 MRI specific scanning parameters

MRI	T2 TSE	3DT1 TSE	DWI EPI
TR/ms	3 500	5.18	4 900
TE/ms	95	2.56	119
Flip angle/(°)	170	10	–
Slice thickness/mm	4	2.5	5.5
NSA	1	1	3
Time	1 min 33 s	19 min	1 min 05 s

Finite element model of the knee joint with boundary loads

Figure 1: Finite element model of the knee joint with boundary loads

1.2 Data processing

First, Qualisys (2020) software was used to export the kinematic and kinetic data as files in C3D format. Second, the built-in MATLAB interface file c3dExport.m in OpenSim was used in MATLAB (R2021a) software to convert the C3D files into files in .trc (marker data) and .mot (GRF data) formats. Third, in OpenSim 4.3 software, the model Gait2354_Simbody was used for scaling, inverse kinematics, inverse dynamics, and static optimization, and the kinematic and kinetic data during walking in stroke patients and the healthy population were calculated, as follows: lower-limb joint angles, joint moments, and joint reaction force (JRF). The kinematic and kinetic data were filtered in MATLAB R2021a using a fourth-order Butterworth low-pass filter, with a cutoff frequency of 6 Hz [17-18].

1.3 Material properties and constraint loads of the finite element model

1) Material properties

The elastic modulus of the femur was 13 600 MPa and the Poisson' s ratio was 0.3; the elastic modulus of the tibia was 16 200 MPa and the Poisson' s ratio was 0.3; the elastic modulus of the fibula was 15 200 MPa and the Poisson' s ratio was 0.3 [19]; the elastic modulus of femoral cartilage was 5 MPa and the Poisson' s ratio was 0.46; the elastic modulus of tibial cartilage was 5 MPa and the Poisson' s ratio was 0.46; the elastic modulus of the meniscus was 59 MPa and the Poisson' s ratio was 0.49; the elastic modulus of the ligament was 215.3 MPa and the Poisson' s ratio was 0.4 [20].

2) Constraint loads

The constraints and loading conditions of the complete knee joint were as follows: the anterior cruciate ligament (ACL), posterior cruciate ligament, medial collateral ligament, and lateral collateral ligament were completely fixed to the femur and tibia at their attachment points; the tibia and fibula were fixed relative to each other; the medial collateral ligament was in smooth contact with the femur and tibia; and the proximal and distal ends of the femur were completely fixed [21-22].

The load data were calculated in OpenSim through inverse dynamics (joint moments) and static optimization (JRF). The finite element model with complete boundary conditions is shown in Figure 2.

Figure 2 Finite element model of the knee joint with boundary loads

Fig. 2 Finite element model of the knee joint with boundary loads

1.4 Finite element model validation

Method 1: A 750 N longitudinal load was applied to the proximal end of the femur, and a 134 N anterior pushing force was applied posterior to the tibia; the equivalent stress, maximum shear stress, and maximum principal stress of the meniscus, femoral cartilage, and tibial cartilage were observed [21].

Method 2: A compressive force of 3.47 times body weight was applied to the distal end of the tibia (upward direction), and the peak equivalent stress of the tibial cartilage was observed [20,23].

Method 3: A compressive force of 4.24 times body weight was applied to the distal end of the tibia (upward direction), and the peak equivalent stress of the tibial cartilage was observed [20,23].

1.5 Data statistics

The obtained data are expressed as mean ± standard deviation. Joint moments were standardized using each subject' s own body mass [17-18]. Independent-samples t tests were performed for the equivalent stress, maximum principal stress, and maximum shear stress in the stroke patient group and healthy population group ($P < 0.05$).

2 Results

2.1 Model validation results

As can be seen from Table 3 and Fig. 3, when a 750 N axial load was applied to the femoral head and a 134 N anterior thrust was applied posterior to the tibia, the peak values of equivalent stress in the meniscus, femoral cartilage, and tibial cartilage in the FE model of the stroke patients were 19.03, 2.09, and 2.30 MPa, respectively; the maximum shear stresses were 10.90, 1.11, and 1.30 MPa, respectively; and the maximum first principal stresses were 14.14, 2.02, and 1.76 MPa, respectively.

(a) Stroke patients

Meniscus equivalent stress
Femoral cartilage equivalent stress
Tibial cartilage equivalent stress

Meniscus maximum shear stress
Femoral cartilage maximum shear stress
Tibial cartilage maximum shear stress

Meniscus maximum first principal stress
Femoral cartilage maximum first principal stress
Tibial cartilage maximum first principal stress

(b) Healthy population

Meniscus equivalent stress
Femoral cartilage equivalent stress
Tibial cartilage equivalent stress

Meniscus maximum shear stress
Femoral cartilage maximum shear stress
Tibial cartilage maximum shear stress

Meniscus maximum first principal stress
Femoral cartilage maximum first principal stress
Tibial cartilage maximum first principal stress

Fig. 3 Method 1 model validation results (unit: MPa)

The peak equivalent stresses of the meniscus, femoral cartilage, and tibial cartilage in the healthy-population FE model were 19.10, 2.08, and 2.40 MPa, respectively; the maximum shear stresses were 10.94, 1.11, and 1.35 MPa, respectively; and the maximum principal stresses were 14.21, 2.01, and 1.83 MPa, respectively.

As can be seen from Table 3, the peak equivalent stresses and maximum shear stresses of the meniscus, femoral cartilage, and tibial cartilage in the model established in this study are basically consistent with those in the model of Yang Junliang et al.

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As can be seen from Table 3 and Fig. 4, when a pressure of 3.47 times body weight was applied to the distal tibia (upward direction), the peak equivalent stresses of the tibial cartilage in stroke patients and the healthy population were 2.30 and 2.20 MPa, respectively; when a pressure of 4.24 times body weight was applied to the distal tibia (upward direction), the peak equivalent stresses of the tibial cartilage in stroke patients and the healthy population were 2.60 and 2.65 MPa, respectively. These values are basically consistent with the equivalent-stress values of tibial cartilage reported in the literature

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Table 3 FE model validation results for stroke patients and the healthy population (unit: MPa)

Tab. 3 Results of FE model validation in the stroke patients and the healthy population (unit: MPa)

Method	Knee-joint part	Stress	Stroke patients	Healthy population	Literature data
Method I	Meniscus	Peak equivalent stress	19.03	19.10	18.86 21
		Maximum principal stress	14.14	14.21	–
		Maximum shear stress	10.90	10.94	10.67 21
	Femoral cartilage	Peak equivalent stress	2.09	2.08	1.91 21
		Maximum principal stress	2.02	2.01	–
		Maximum shear stress	1.11	1.11	1.10 21
	Tibial cartilage	Peak equivalent stress	2.30	2.40	2.40 21
		Maximum principal stress	1.76	1.83	–
		Maximum shear stress	1.30	1.35	1.38 21
Method II	Tibial cartilage	Peak equivalent stress	2.30	2.20	2.39 20, 2.19 23
Method III	Tibial cartilage	Peak equivalent stress	2.60	2.65	2.81 20, 2.60 23

Note: "–" indicates that this indicator was not reported in the cited literature.

(a) Method II—equivalent stress of tibial cartilage

Fig. 5

Figure 2: Fig. 5

(b) Method III–equivalent stress of tibial cartilage

Fig. 4 Model validation results for methods II and III (unit: MPa)

2.2 Results for joint moment and JRF

As can be seen from Fig. 5, during walking, the trends of the JRF and joint-moment curves on the healthy side of stroke patients are basically consistent with those on the corresponding side of the normal population. However, because the affected-side muscles of stroke patients are weak and the center of gravity shifts toward the healthy side, compensatory force generation occurs on the healthy side, producing larger JRFs and joint moments.

Fig. 5 Mean JRF and joint moment curves of the healthy side of the stroke patients and the corresponding side of the healthy population

2.3 Stress Results

As can be seen from Table 4 and Fig. 6, during walking in the stroke patients, the peak equivalent stresses of the healthy-side meniscus, femoral cartilage, and tibial cartilage were (13.5 ± 0.45), (2.04 ± 0.05), and (3.10 ± 0.25) MPa, respectively; the maximum principal stresses were (12.1 ± 0.41), (1.98 ± 0.06), and (2.37 ± 0.21) MPa, respectively; and the maximum shear stresses were (7.71 ± 0.25), (1.09 ± 0.04), and (1.75 ± 0.22) MPa, respectively. During walking in healthy individuals, the peak equivalent stresses of the left-side meniscus, femoral cartilage, and tibial cartilage were (10.1 ± 0.15), (1.78 ± 0.06), and (2.50 ± 0.24) MPa, respectively; the maximum stresses were (5.64 ± 0.22), (1.29 ± 0.11), and (1.53 ± 0.22) MPa, respectively; and the maximum shear stresses were (5.69 ± 0.18), (0.71 ± 0.03), and (1.13 ± 0.16) MPa, respectively.

Independent-samples T tests comparing the peak equivalent stress, maximum principal stress, and maximum shear stress of the meniscus, femoral cartilage, and tibial cartilage between the stroke patients and the healthy population showed that the peak equivalent stress, maximum principal stress, and maximum shear stress of the meniscus, femoral cartilage, and tibial cartilage in the stroke patients were all significantly different from those in the healthy population (P values all less than 0.01).

Table 4 Stress results in different parts of the knee joint in the stroke patients and the healthy population (unit: MPa)

Fig. 6 Stress cloud of stroke patients and healthy population (unit: MPa)

Figure 3: Fig. 6 Stress cloud of stroke patients and healthy population (unit: MPa)

Knee joint region	Stress	Stroke patients	Healthy population	P value
Meniscus	Peak equivalent stress	13.5 ± 0.45	10.1 ± 0.15	< 0.01
	Maximum principal stress	12.1 ± 0.41	9.07 ± 0.21	< 0.01
	Maximum shear stress	7.71 ± 0.25	5.78 ± 0.12	< 0.01
Femoral cartilage	Peak equivalent stress	2.04 ± 0.05	1.78 ± 0.06	< 0.01
	Maximum principal stress	1.98 ± 0.06	1.72 ± 0.05	< 0.01
	Maximum shear stress	1.09 ± 0.04	0.94 ± 0.03	< 0.01
Tibial cartilage	Peak equivalent stress	3.10 ± 0.25	2.50 ± 0.24	< 0.01
	Maximum principal stress	2.37 ± 0.21	1.91 ± 0.22	< 0.01
	Maximum shear stress	1.75 ± 0.22	1.41 ± 0.16	< 0.01

Panel labels in Fig. 6

- **(a) Stroke patients**
  - **Meniscus**
    - Equivalent stress
    - Maximum principal stress
    - Maximum shear stress
  - **Femoral cartilage**
    - Equivalent stress
    - Maximum principal stress

    - Maximum shear stress
  - **Tibial cartilage**
    - Equivalent stress
    - Maximum principal stress
    - Maximum shear stress
- **(b) Healthy population**
  - **Meniscus**
    - Equivalent stress
    - Maximum principal stress
    - Maximum shear stress
  - **Femoral cartilage**
    - Equivalent stress
    - Maximum principal stress
    - Maximum shear stress
  - **Tibial cartilage**
    - Equivalent stress
    - Maximum principal stress
    - Maximum shear stress

Fig. 6 Stress cloud of stroke patients and healthy population (unit: MPa)

3 Discussion

The purpose of this study was to compare and analyze, by means of knee-joint FE models, the mechanical properties of the knee-joint meniscus, femoral cartilage, and tibial cartilage during walking in stroke patients and healthy people. Many studies have found that there is marked asymmetry between the affected and unaffected sides in stroke patients. The walking speed of hemiplegic limbs is relatively slow, and their functional impairment leads to shortened stance duration, prolonged swing duration, reduced ground-reflex response, and insufficient propulsion force during standing[^24-26]. To adapt to this compensatory functional impairment, patients need to rely on the unaffected side to maintain balance and forward propulsion, resulting in biomechanical changes on the unaffected side and presenting an unstable state[^27]. Patients are more inclined to bear weight on the unaffected side, leading to an asymmetric hemiplegic gait[^28]. Relevant studies[^6] compared the affected and unaffected sides of stroke patients with healthy individuals'

Comparing the corresponding limbs of the two groups, it was found that the affected limbs and healthy limbs showed statistically significant differences at different cartilage sites. These differences were mainly manifested as decreased superficial free water and bound water contents and increased deep free water content, and these early- and middle-stage changes were consistent with the degenerative changes of articular cartilage. Meanwhile, Goldie et al.

suggested that, in stroke patients, the mechanical properties of cartilage tissue in the knee joint of the healthy limb also change compared with the corresponding limb in healthy people; however, they did not analyze the mechanical properties of knee cartilage tissue between the two groups. On this basis, the present study analyzed the mechanical properties of knee cartilage tissue in the two groups. The results showed that significant differences existed in the mechanical properties of the meniscus, femoral cartilage, and tibial cartilage of the knee joints between stroke patients and healthy individuals (P values were all less than 0.01). The peak von Mises stress, maximum principal stress, and maximum shear stress of the meniscus, femoral cartilage, and tibial cartilage in the healthy-side knee joint of stroke patients were all much greater than those of the corresponding knee-joint meniscus, femoral cartilage, and tibial cartilage in healthy individuals. This indicates that the mechanical mechanism and walking pattern of the patients' healthy side differ, so as to compensate for the function of the affected side, leading to varying degrees of injury. Therefore, changes occur in the healthy limb during compensation, which was also confirmed by the experimental results of this study (Figs. 5 and 6). There were significant differences between the healthy side of stroke patients and the corresponding side of healthy individuals in some knee-joint cartilages, indicating that the patients' so-called "healthy" limb had also changed to a certain extent and cannot be called truly healthy. Therefore, when formulating rehabilitation treatment plans, the "healthy" limb should be considered together with the affected limb[6,28]. Cartilage tissue has mechanical adaptability, and changes in the mechanical environment affect the structure and function of articular cartilage tissue[29]. Related studies have shown that normal mechanical stimulation is an important factor that promotes articular-cartilage formation and maintains the normal physiological behavior of cartilage cells[30]. Because the healthy side of stroke patients bears greater mechanical stimulation, a certain degree of injury occurs in the articular cartilage. This study found that the peak knee-joint moment and JRF (0.475 Nm/kg, 3.70 N/kg) on the healthy side of stroke patients were both greater than the peak knee-joint moment and JRF (0.351 Nm/kg, 2.50 N/kg) on the corresponding side in healthy individuals. Zhang Jingjing et al.[31] found that the maximum knee-joint moment on the healthy side of stroke patients was 0.51 ± 0.09 Nm/kg; Rane et al.[32]

found that, during walking in healthy individuals, the knee-joint JRF was 2.55 N/kg. These results are basically consistent with the peak knee-joint moment on the healthy side of stroke patients and the knee-joint JRF in healthy individuals in the present study, and they also verify, from another perspective, the effectiveness of the loading boundary conditions applied in the finite-element model of this study.

This study has certain limitations: the sample size was small; only CT and MRI data were collected from 2 subjects (1 stroke patient and 1 healthy individual), and kinematic and kinetic data were collected from 15 stroke patients and 15 healthy individuals; this study considered only walking and did not include stair ascent/descent or obstacle crossing; only the stresses of the meniscus, femoral cartilage, and tibial cartilage were analyzed, and their strains were not analyzed; this study only compared and analyzed the mechanical properties of the meniscus, femoral cartilage, and tibial cartilage in the two groups, and in the future the mechanical properties of the anterior cruciate ligament, posterior cruciate ligament, left collateral ligament, and right collateral ligament can be compared.

4 Conclusion

In gait analysis of stroke patients, the FE model can calculate the mechanical characteristics of knee-joint cartilage tissue, providing a new approach for obtaining biomechanical data in stroke patients and an effective method for helping stroke patients prevent cartilage injury. The "healthy" limb of stroke patients is no longer considered truly healthy; it should be considered together with the affected limb when rehabilitation treatment plans are formulated.

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Note: Figure translations are in progress. See original paper for figures.