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Concept Verification of a Remote Automatic Scoring System for Evaluating Knee Function after Total Knee Arthroplasty

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Abstract

The Knee Society Score (KSS) is the most commonly used scale for evaluating postoperative pain and physical function after total knee arthroplasty (TKA). However, this scale requires clinic visiting, which is not quite convenient. Our concept verification study demonstrated a remote automatic system for evaluating knee function after TKA using the KSS. The remote scoring system consists of two modules for data acquisition, an application for patients, a cloud server, and an application for doctors. The kinematic data are collected by the data acquisition modules and transmitted to the patient application via Bluetooth. The data acquisition module contains a motion sensor, a microcontroller unit, a power supply, and a Bluetooth module. The motion sensor consists of an accelerometer, a gyroscope, and a geomagnetic sensor, all of which are three-axis instruments. Using the nine-axis data, the three-dimensional (3D) angles are calculated according to the theory of attitude and heading reference system. The KSS score is calculated using a scoring algorithm in the patient application and transmitted to the doctor application through the cloud server. The knee function of 10 patients treated with unilateral TKA was evaluated by both a doctor and the remote scoring system. The consistency in KSS between the doctor and the system was analyzed using the paired *t*-test. The remote scoring system successfully recorded knee function data and transmitted the scores from the patient application to the doctor application through the cloud server. There was no significant difference in the KSS scores evaluated by the doctor and that by the system ($p = 0.326$). This remote automatic scoring system provides a reliable and convenient method for evaluating knee function after TKA at home.

Keywords
- knee society score
- total knee arthroplasty
- remote automatic scoring system

Total knee arthroplasty (TKA) is the final treatment for end-stage knee osteoarthritis with severe pain and knee damage.[1,2] Evaluating pain and physical function play an important role in the diagnosis of osteoarthritis and the assessment of TKA treatment efficacy.[1,3,4] Clinical scoring methods, such as the Knee Society Score (KSS) and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), are widely used for these evaluations.[3,5–7] The KSS exhibited greater responsiveness and reliable convergent validity than the WOMAC.[8] It consists of two parts, the joint score and the functional score.[9] The joint score assesses pain, stability, and mobility of the knee. The functional score assesses walking distance and climbing staircase. The KSS can accurately assess the overall function and morphology of the knee.[10] However, this method requires clinic visiting, which is inconvenient for patients due to the long-term postoperative limb function recovery. In addition, the KSS is based on doctor's observation rather than objective measurement, which may introduce bias and errors.[11]

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Remote monitoring of human function is an emerging technology and can be used to assess organs or systems in a real-time and on-demand fashion. This technology integrates wireless sensors, mobile internet, cloud computing, and internet of things. In 2001, Gandsas et al for the first time obtained telemedicine data without restrictions of time or distance, including blood pressure, pulse, respiratory frequency, tidal volume, blood oxygen saturation, and electrocardiogram.[12] Markert et al developed a total implant telemetry system for cardiovascular, electrophysiological, and body temperature measurement.[13] Chou et al proposed an arrhythmia-detecting smart wheelchair that provides real-time electrocardiography monitoring for patients with heart disease and reduced mobility.[14] Christakos et al designed a human body area network for brain disease analysis based on wireless sensors and mobile communication.[15] Kanai et al developed a home telemetry system for real-time monitoring and evaluation of physical performance of older adults using conventional video communication.[16] In the field of knee function monitoring, Juen et al evaluated gait in a free state using acceleration sensors and a GaitTrack software in smartphones.[17]

The previous knee function analysis systems lack the ability of remote measurement and wireless data transfer. The patients must personally visit the clinics to be evaluated for knee functions. To address this issue, we have designed a remote automatic system for evaluating knee function using the KSS. The patients can use this device to self-evaluate the knee function at home. The results are automatically sent to the surgeons who are at the hospital. The present concept verification study aimed to test the accuracy and reliability of this remote scoring system in patients treated with TKA.

Materials and Methods

Configuration of the Remote System

The remote scoring system consists of two modules for data acquisition (accelerometer, gyroscope, and magnetometer), an application for patients, a cloud server, and an application for doctors (►Fig. 1). The kinematic data are collected by the data acquisition modules and transmitted to the patient application via Bluetooth. The KSS score is calculated using a scoring algorithm in the patient application and transmitted to the doctor application through the cloud server.

The data acquisition module contains a motion sensor, a microcontroller unit, a power supply, and a Bluetooth module (►Fig. 2). The motion sensor consists of an accelerometer, a gyroscope, and a geomagnetic sensor, all of which are three-axis instruments. Using the nine-axis data, the three-dimensional (3D) angles are calculated according to the theory of attitude and heading reference system.[18,19] The microcontroller unit (CC2640) runs program written in the C + + language using the Arduino IDE 1.8.2 (www.arduino.cc). The Bluetooth module adopts the 4.0 protocol with features of low power consumption and long transmission distance. Each frame of data are composed of 1 byte of initiating character, 6 bytes of angle, 6 bytes of acceleration, and 1 byte of checksum. The data are obtained and send to the patient application at 20-Hz frequency via Bluetooth.

The application for patients was designed in the Android Studio. The programming language is Java and the software development kit is Android 5.0 (Google, Mountain View, CA). The main function of the patient application is receiving the kinematics data and calculating the KSS scores. Then the KSS scores and patient information are saved and sent to the cloud server.

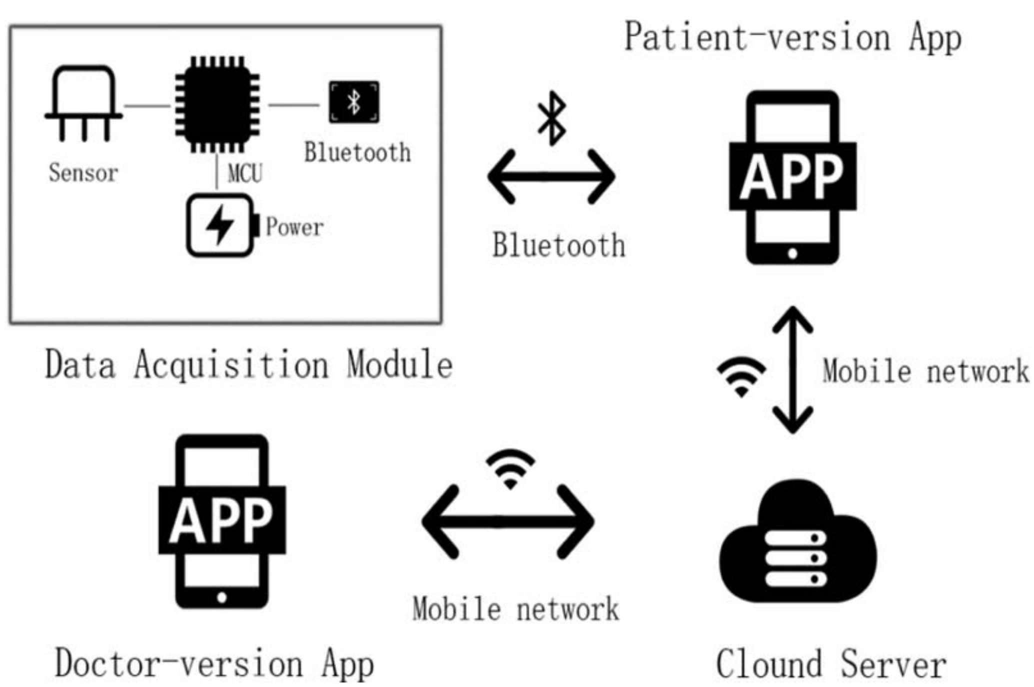

Fig. 1 Diagram of the remote automatic system. MCU, microcontroller unit.

Fig. 2 The data acquisition modules.

Fig. 3 Measurement of the knee joint angles using two data acquisition modules.

The cloud server was developed in the Alibaba Cloud, which provides reliable serverless cloud services and various cloud server capabilities. Two database tables were created for storing the data, one for the patient information and one for the KSS scores, respectively.

The application for doctors was designed in the same way as the patient application. Its main function is querying the KSS scores and patient information from the cloud server. Doctors can also evaluate patient condition and provide suggestions to them via the cloud server according to the KSS scores.

Scoring Algorithm

Two data acquisition modules were fixed on the thigh and the pretibial area, respectively, for measuring the 3D angles of the knee. The KSS score was calculated according to Insall et al.[9] Pain was scored by the patients. Stability score was measured by the doctors and were usually invariable. Scores of total range of flexion, flexion contracture, extension lag, and alignment (varus and valgus) were calculated using the scoring algorithm in the patient application. The scoring algorithm was based on the 3D angles formed by the thigh and the pretibial area.

Validation of the Remote Scoring System

A total of 10 patients (one male and nine females) with end-stage knee osteoarthritis treated with unilateral TKA (five left side and five right side) were enrolled in our study. The age, weight, height, and body mass index are 61.6 ± 7.2 years, 69.2 ± 9.3 kg, 159.8 ± 5.0 cm, and 27.1 ± 3.7 kg/m^2, respectively. All patients presented with pain of the knee and Kellgren and Lawrence scale grades III to IV. The exclusion criteria were a history of lower limb or back surgery and neurological or orthopedic disorders. All patients were performed TKA in our hospital and all patients have provided written informed consent.

Two data acquisition modules were fixed on the thigh and the pretibial area of the patients, respectively (►**Fig. 3**). The patients were asked to perform specific actions in the KSS and evaluated by the automatic scoring system and an experienced clinician independently at times of before the surgery, immediately after the surgery, and postoperative 4 days. The clinician scored the alignment (varus and valgus) using the medical record and other angles using a medical protractor. The system measured the angles using the data acquisition modules. Scores of total range of flexion, flexion contracture, extension lag, and alignment (varus and valgus) were calculated based on these angles according to the KSS. Pain and stability were scored using the same method by the clinician and the automatic scoring system.

To verify the accuracy of the data acquirement module, it was tested in a healthy volunteer. A data acquisition module was fixed on the pretibial area. The angle between the pretibial area and the ground was measured using the data acquisition module. The participant was asked to walk through a 10-m track, during which the angle was measured simultaneously by the data acquirement module and a 3D motion capture system. The root mean square error between these two angles was calculated to verify the accuracy of the sensors.

Statistical Analysis

All data were presented as means and standard deviations. The scores evaluated by the clinician was regarded as the gold standard. The consistency between the automatic scoring system and the clinician was analyzed using the paired *t*-test. All statistical analyses were performed using the SPSS 20.0 (SPSS, Chicago, IL). A $p < 0.05$ was considered statistically significant.

Results

Results of System Design

The patient application and the doctor application were installed separately in two Android phones for independent testing (►**Fig. 4**). The running environment was Android 5.0, and the mobile network was unobstructed. The patient

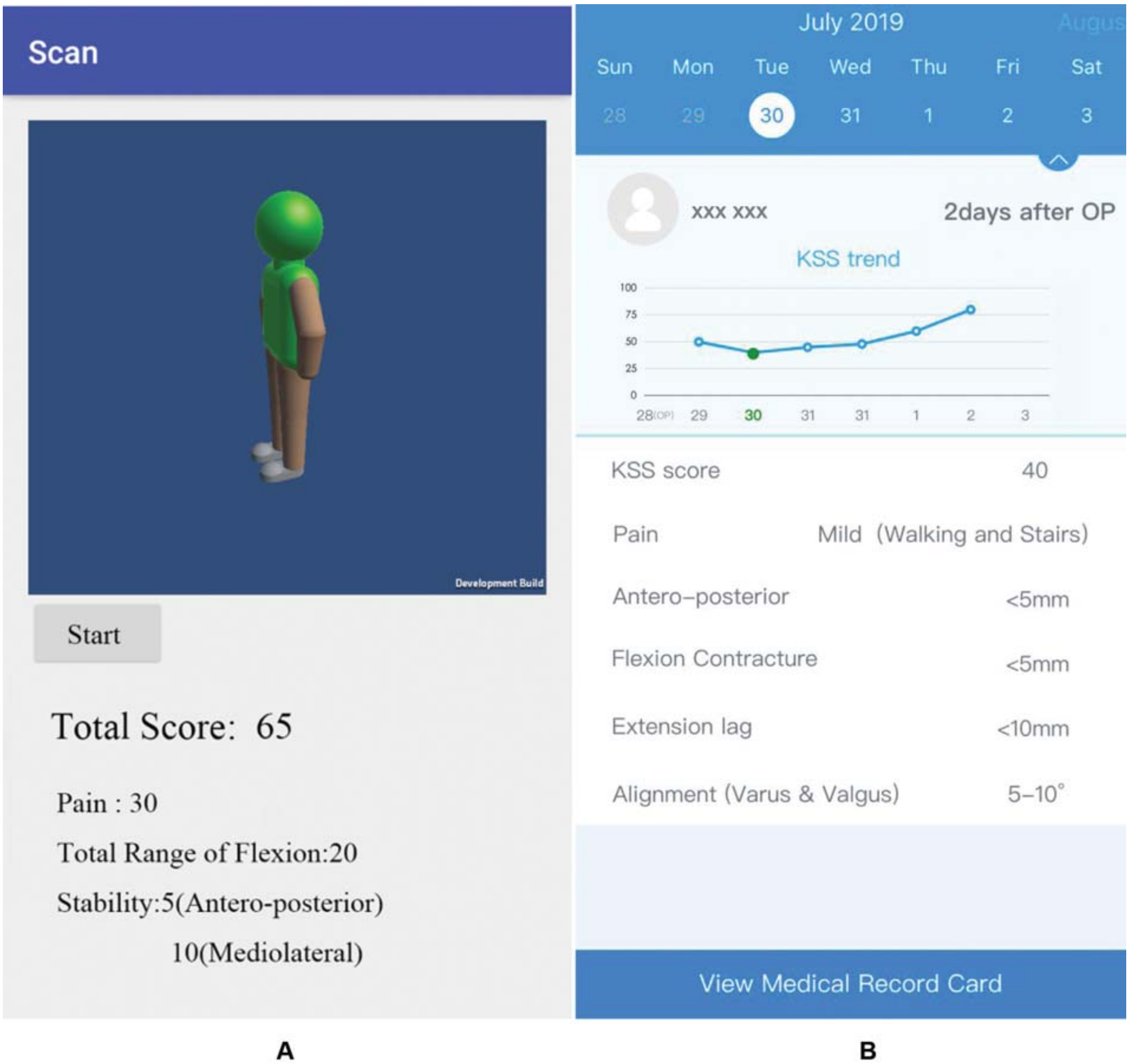

Fig. 4 (**A**) The application for patients; (**B**) the application for doctors.

application successfully calculated the KSS scores and sent the data to the cloud server. The doctor received the notification through the doctor application.

The angles between the pretibial area and the ground were independently obtained using the data acquisition module and the 3D motion capture system during four complete gait cycles (►**Fig. 5**). The root mean square error of the two series of angles was 2.3 degrees, suggesting stable and reliable performance of the data acquisition module.

Results of Score Algorithm

The scores of pain were evaluated by the patients and were 30.0 ± 9.1, 29.0 ± 9.7, and 32.0 ± 7.5 before the surgery, immediately after the surgery, and at postoperative 4 days, respectively. The anteroposterior stability score and the mediolateral stability score were 10.0 ± 0.0 and 15.0 ± 0.0, respectively, which were the same before the surgery and immediately after the surgery. There was no significant different in the scores between the remote scoring system and the clinician, suggesting good consistency between them (►**Table 1**). The scores of flexion contracture, extension lag, and alignment improved immediately after the surgery. The scores of total range of flexion score decreased immediately after the surgery and increased gradually alone with time.

The total KSS scores evaluated by the system and the clinician both showed an increasing trend (►**Fig. 6**). The total KSS scores increased significantly immediately after the surgery ($p = 0.040$, 0.038). There was no significant difference from immediately to 4 days after the surgery ($p = 0.014$, 0.014).

Discussion

Our study demonstrated a remote automatic scoring system for evaluating knee function after TKA. The KSS scores evaluated by the remote scoring system showed good consistence with that evaluated by the clinician. The scoring system provides a low-cost and effective method for patients to evaluate knee function at home.

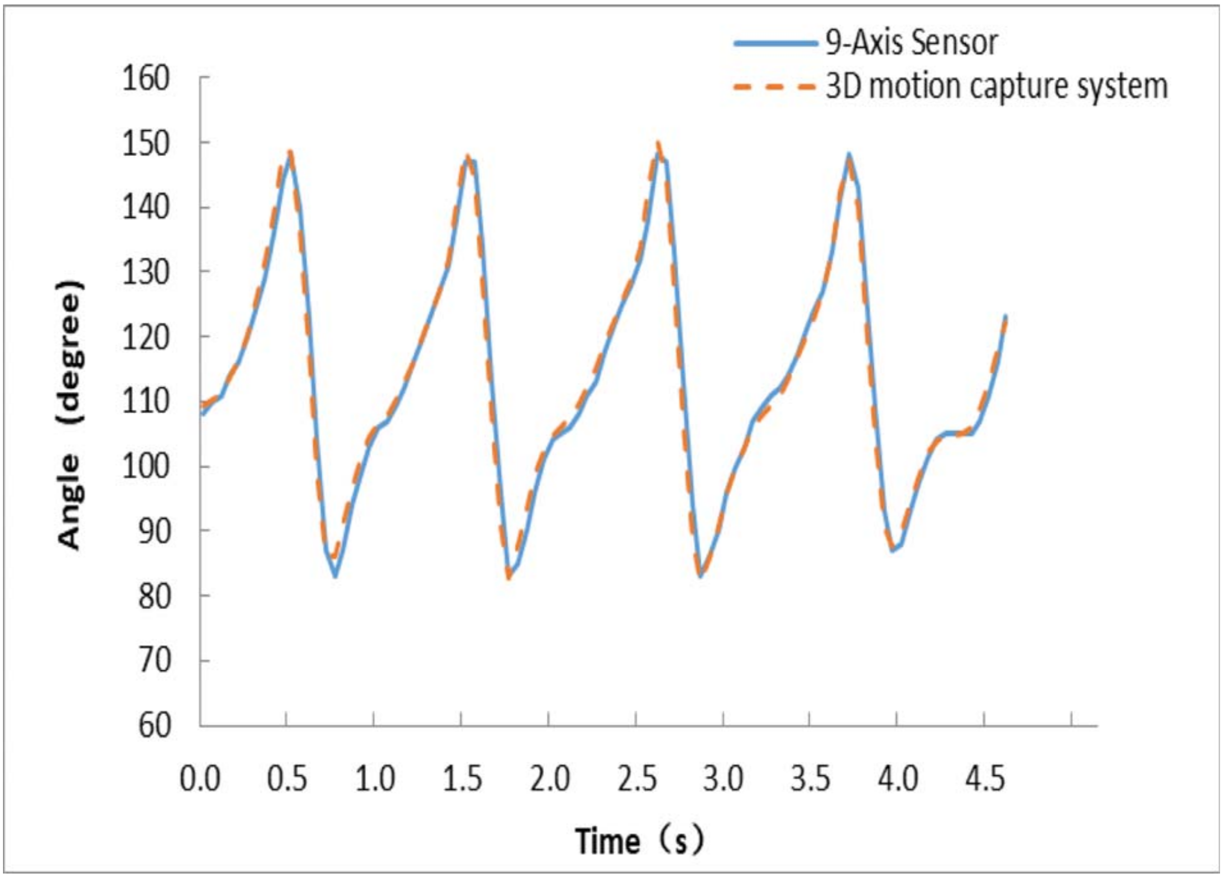

Fig. 5 Angles between the pretibial area and the ground during 4 complete gait cycles. 3D, three-dimensional.

Table 1 KSS scores evaluated by the system and the clinician: total range of flexion

		Total range of flexion	Flexion contracture	Extension lag	Alignment	Total score
Before the surgery	System score	23.4 ± 1.8	−0.4 ± 0.8	−0.5 ± 1.6	−16.0 ± 8.4	61.5 ± 15.6
	Clinician score	23.3 ± 1.9	−0.4 ± 0.8	−0.5 ± 1.6	−16.0 ± 8.4	61.4 ± 15.7
	p	0.343	–	–	–	0.343
Immediately after the surgery	System score	19.3 ± 4.1	0.0 ± 0.0	0.0 ± 0.0	−2.0 ± 6.3	71.2 ± 10.0
	Clinician score	19.2 ± 4.0	0.0 ± 0.0	0.0 ± 0.0	−2.0 ± 6.3	71.2 ± 10.0
	p	0.343	–	–	–	–
Postoperative 4 days	System score	20.7 ± 2.8	0.0 ± 0.0	0.0 ± 0.0	−2.0 ± 6.3	75.7 ± 8.4
	Clinician score	20.7 ± 2.8	0.0 ± 0.0	0.0 ± 0.0	−2.0 ± 6.3	75.7 ± 8.4
	p	0.343	–	–	–	–

Abbreviation: KSS, Knee Society Score.

The KSS has been widely used in preoperative and postoperative evaluation of knee function. It has been shown that the KSS scores can reflect the damage in artificial joint materials in 10 to 12 years after TKA. This provides a basis for improving artificial joint materials and surgical methods and reducing complications.[20] Sustained evaluation of knee joint function is useful for monitoring the long-term recovery after TKA. However, the KSS is inconvenient for patients. Remote human function monitoring technology has opened an opportunity to overcome the limitations of KSS.

Our study used a cloud server for remote monitoring. The kinematics data were acquired and the KSS scores were calculated by the application for patients. The KSS scores and patient information were saved and sent to the cloud server. The doctors can query the KSS scores and patient information from the cloud server. The doctors can also evaluate patient condition and provide suggestions to them according to the KSS scores via the cloud server. To get more reliable results, we calculated accurate and real-time 3D knee angles using the data acquisition modules in

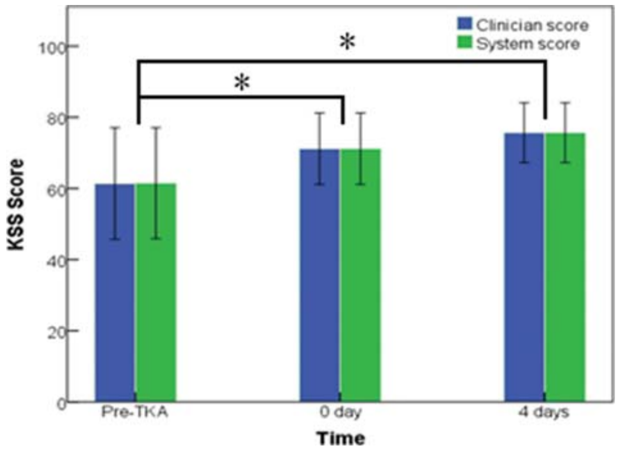

Fig. 6 Total KSS scores before the surgery, immediately after the surgery, and at postoperative 4 days. * $p < 0.05$; KSS, Knee Society Score; TKA, total knee arthroplasty.

our study. The knee angles measured by the remote automatic scoring system showed good consistence with that measured by the 3D motion capture system. In addition, the system scores also showed good consistence with the clinician scores. These results suggested that our scoring algorithm was convenient and reliable.

In our study, the KSS scores were evaluated during a short time after TKA. The scores of flexion contracture, extension lag, and alignment were improved immediately after TKA. The scores of total range of flexion decreased immediately after TKA and increased gradually alone with time. The total KSS scores increased after TKA. These results were consistent with the previous studies. Our findings suggested that the KSS can be used as a bases for the design of TKA and prediction of disease prognosis.

Our remote automatic scoring system provides a way to conveniently and effectively monitor the long-term rehabilitation of patients after TKA. The real-time and long-term KSS scoring after TKA can help the doctors to estimate the patient recovery and adjust the training program timely. The KSS scores measured after TKA is also useful for improving the surgical procedure of TKA. The accurate 3D knee angles obtained in our study may be used to improve the KSS to a more sensitive scoring system. In addition, our system can be used as a monitoring platform. By expanding the types of sensors, more physiological parameters and motion data can be obtained by the remote scoring system. It may provide in-depth and full-scale evaluation of rehabilitation of patients after TKA.

Limitations

Our study has limitations. First, the remote scoring system demands higher abilities for patients. Most patients treated with TKA will benefit from this remote scoring system if it is used in clinic. Second, the short-term effect of this remote scoring system was not evaluated in our study. Our future investigation will try to acquire a longer term rehabilitation information after TKA.

Conclusion

A remote automatic knee function scoring system was successfully established and fulfilled the intended features. The KSS scores obtained by this remote scoring system showed good consistency that evaluated by the clinicians. The system may provide a reliable and convenient method for clinicians to remotely evaluate knee function of the patients at home.

Note

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Ethical Approval

This study was approved by the Ethics Committee of Beijing Jishuitan Hospital, Beijing, China. All participants gave written informed consent.

Authors' Contributions

H.Z. and Y.Z. contributed to the conception and design of the study; H.Z. and Y.Z. collected and analyzed data; H.Z. and Y.Z. wrote the manuscript; all authors reviewed and approved the final version of the manuscript.

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Conflict of Interest

None declared.

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