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Normal Range of Motion of Lower Extremity Joints in Mongolian Subjects †

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Abstract: It is important to identify the normal range of motion (ROM) of the human joints for both biomechanical and clinical applications. For health care providers, including physicians and therapists, the restoration of normal ROM is a difficult task. The severity of impaired joint mobility or the postoperative rehabilitation process must be evaluated in comparison with a normal reference value. However, there are no studies that have reported the ROM of Mongolian subjects. In this study, we measured the hip, knee, and ankle joint angles using multiple wearable inertial sensors. Ten healthy young subjects participated. The three-dimensional (3D) motion data were collected while the subject were walking at normal speed. In our knowledge, this study is the first to analyze the normal ROM of Mongolian male subjects. The collected data can be used as reference values for evaluating the disability of the motion and performance in rehabilitation programs.

Keywords: normal range of motion; Mongolian; wearable sensors

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1. Introduction

Identification of the natural gait characteristics of people is important from both biomechanical and clinical perspectives [1]. Many diseases and injuries can impair joint mobility, which results in a decline in ROM or changes the gait characteristics. Furthermore, abnormal gait characteristics are associated with aging and an abnormal lifestyle. Joint motion varies with age and is generally more restricted in the older age group [2].

For health care providers, including physicians and therapists, the restoration of normal ROM is a difficult task. The severity of impaired joint mobility or postoperative rehabilitation process must be evaluated in comparison with normal gait patterns. These normal gait parameters have been investigated extensively in a variety of countries including the United States [3], Sweden [2], Korea [1], Japan [4], and China [5]. However, there are no comparison studies on ROM in Mongolia with other countries. Furthermore, video-based motion analysis systems cannot provide the details of joint motions during movements. The 3D joint angle measurement is an important requirement, notably in the orthopedic and rehabilitation fields [6].

Recent developments in sensor technology allow us to precisely measure human movements. Several studies have used the inertial measurement unit (IMU) sensor for analyzing the kinematics of the lower extremity during normal walking and other motions in a variety of countries [6–9]. In this study, we investigated the joint angles of the hip, knee, and ankle during walking using wearable IMU sensors.

2. Materials and Methods

2.1. Participant Information

Ten male subjects (age, 26.1 ± 7.8 years; height, 177 ± 7 cm; weight, 76.4 ± 17.6 kg), who had not had any musculoskeletal injuries within the past year, were recruited in this study. All subjects were recruited with informed consent from the Mongolian University of Science and Technology (MUST).

2.2. Experiment Procedure

Each subject performed three bouts of walking under supervision. Subjects were asked to perform their walking with normal speed to minimize the speed differences. Prior to the experiment, each participant was asked to perform several bouts of walking as a warm-up. The experiment was conducted in the indoor laboratory at MUST. The subjects were wearing IMU sensors, a training suit, and sports shoes. In total, six IMU sensors (Wearnotch, Notch Interface Inc., New York, NY, USA) were used to record the right lower extremity motion during normal walking. The sensors were attached to the chest, stomach, right thigh, shank, and foot using the straps. The IMU sensor includes 3-axis acceleration and 3-axis gyroscope with ±16 g and ±2000°/s, with a sampling rate of 100 Hz. The sensors' locations are described in Figure 1.

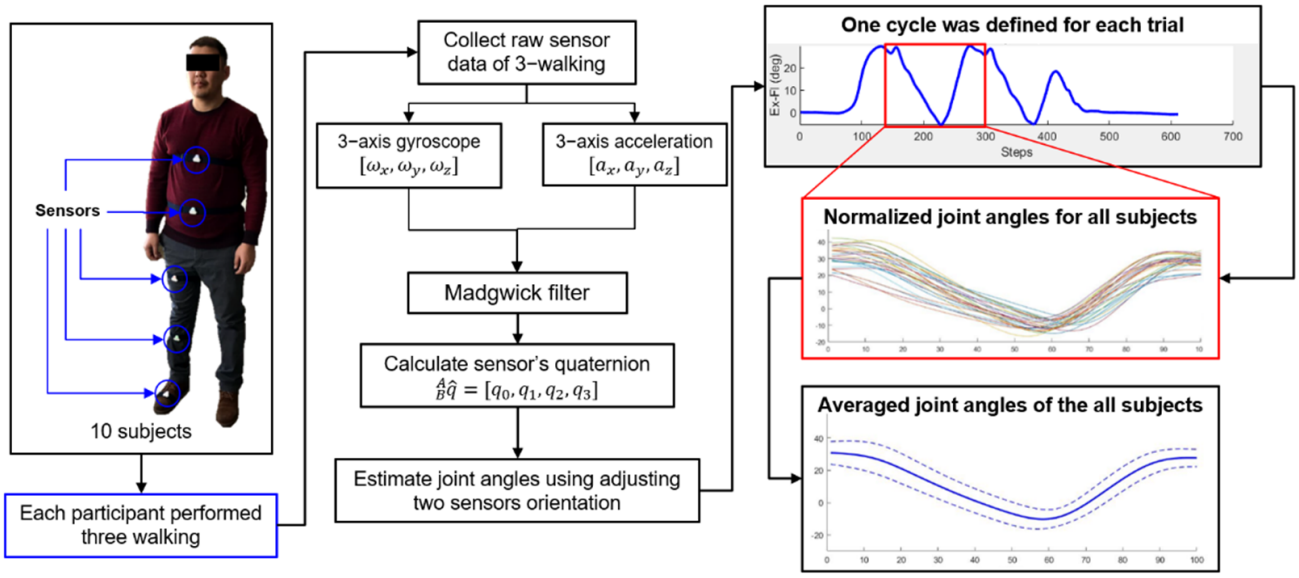

Figure 1. The experiment protocol and data processing.

2.3. Data Processing

At the beginning of the walking, subjects did a steady pose as a calibration. After sensor calibration, each participant performed normal walking. The sensor's raw data was sent to the server computer and processed using Matlab® R2015a (The Mathworks Inc., Natick, MA, USA) [10]. After data processing, the quaternions of the six sensors were estimated using the 3-axis acceleration and 3-axis gyroscope data based on the Madgwick filter algorithm [11]. Then, the joint angles were estimated based on the orientation difference between the adjusting two sensors. The joint angles were represented as the Euler angles of the distal segment reference frame relative to the proximal segment reference frame using the sensor's orientation [12]. The accuracy of the wearable sensor was compared against the conventional marker-based system in our previous study. The estimated error between the wearable sensors and marker-based system was approximately 5.8% [10]. The 3D rotations of the joints in sagittal, transverse, and coronal planes were expressed as extension-flexion (Ex-Fl), internal-external (Int-Ext) rotation, and adduction-abduction (Add-Abd), respectively (Figure 2). After calculating the 3D joint angles, the cycle of one

bout of walking was defined and normalized. From the start to the end of the cycle was from a right heel strike to the next right heel strike.

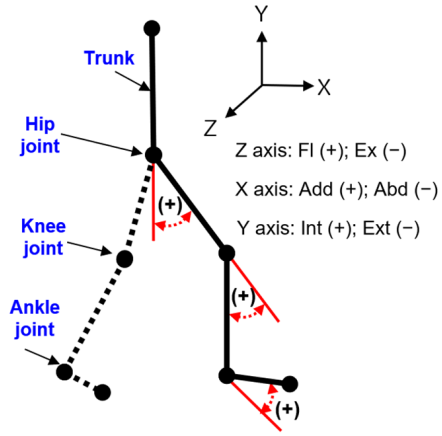

Figure 2. Joint angle definition for hip, knee, and ankle joints.

3. Results

3.1. Joint Angles of Hip, Knee, and Ankle Joint

The hip, knee, and ankle joint angles during walking are shown in Figure 3. The maximum extension-flexion angles of the hip and knee were 30.8 ± 3.5° and 55.2 ± 3.4°, respectively. In the ankle joint, the dorsiflexion-plantar flexion angle was 13.5 ± 6.0°. The maximum adduction-abduction angles of the hip, knee, and ankle joints were 5.3 ± 4.8°, 16.6 ± 10.2°, and 10.3 ± 5.8°, respectively. The maximum internal-external rotation angles of the hip, knee, and ankle joints were 5.5 ± 4.5°, 7.3 ± 10.2°, and 6.3 ± 3.8°, respectively (Figure 3).

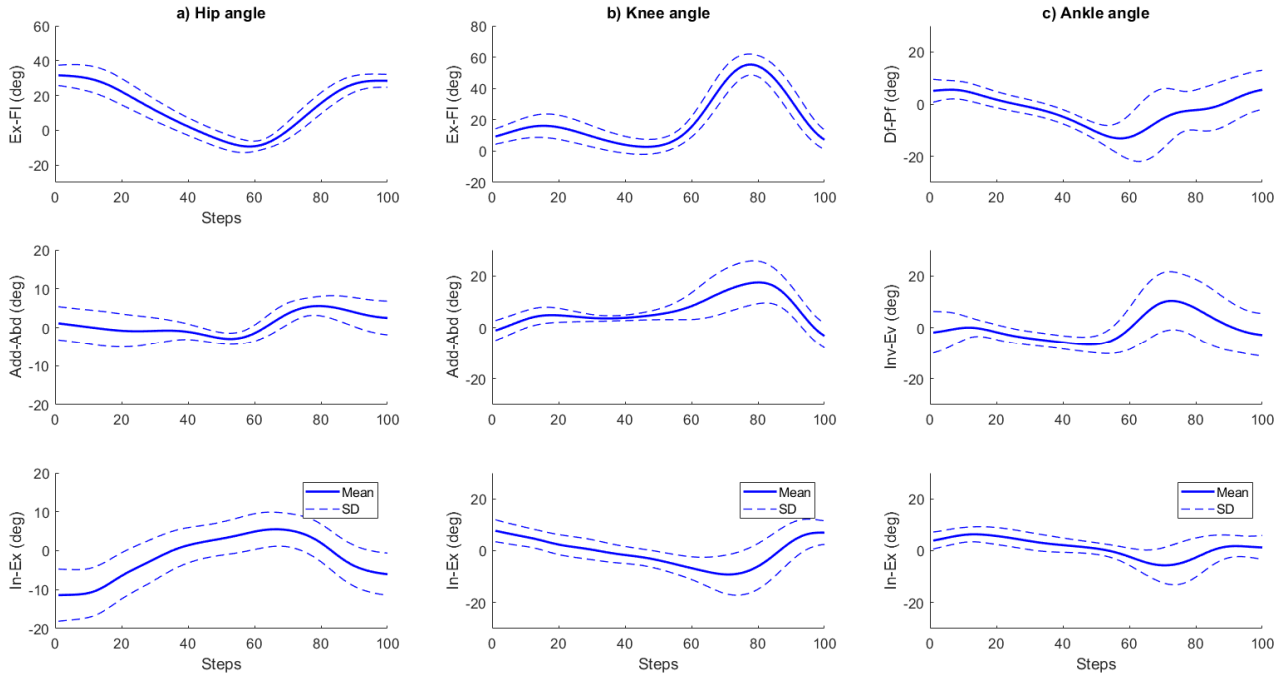

Figure 3. Joint angles of hip, knee, and ankle joint.

3.2. Comparison with Previous Studies

The maximum flexion angles of the hip, knee, and ankle joints were compared to the previous studies. The results are summarized in Table 1. The total joint angle data were similar to previous studies [1,5,13,14]. Of note, the hip and ankle flexion were similar to

that data from the Chinese population, while the knee flexion was similar to all data except the Chinese. This is due to the anthropometric similarities between Asian countries.

Table 1. Maximum flexion angle comparison with previous studies.

	Hip	Knee	Ankle
Our study	30.8 ± 5.5°	55.2 ± 3.4°	13.5 ± 6.0°
United States [13]	38.2 ± 3.1°	57.4 ± 5.0°	10.6 ± 3.9°
Korea [1]	24.2 ± 6.6°	58.9 ± 5.8°	10.8 ± 4.1°
China [5]	34.7 ± 3.0°	66.2 ± 4.8°	13.7 ± 4.3°
Italy [14]	43.4 ± 8.0°	55.6 ± 4.4°	19.7 ± 8.1°

Throughout flexion motions, the maximum difference of hip, knee, and ankle joints between the current and the previous studies was 12.6°, 11.0°, and 6.2°, respectively. The dissimilarity may be from the use of different motion capture systems. Our study utilized the wearable motion capture system, while other studies have used the conventional marker-based system. Of course, the difference occurred due to the gait characteristics of different nationalities.

4. Conclusions

In this study, we utilized a wearable IMU sensor for measuring the normal ROM of the lower extremity during walking for Mongolians. The wearable sensor technology can be applied to both indoor and outdoor environments without any restrictions. The raw sensor data was processed using the in-house developed algorithm based on the Mahony filter. To my knowledge, this study is the first to analyze the 3D normal ROM of the Mongolian subjects. But, the subjects were only male, and the number of participants was small. Therefore, future work will need to include a large number of subjects as well as different sexes and age groups. Future work will also focus on the gait characteristics of the nomadic peoples. This study provides fundamentals of the normal gait characteristics during walking, which can be reference values for evaluating the disability of the motion and performance in rehabilitation programs.

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Data Availability Statement: Not applicable.

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Conflicts of Interest: The authors declare no conflict of interest.

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