Moment Analysis of Virtual Human Joint Based on JACK

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Abstract. The purpose of this study is to explore the torque size of the joints of the ankle, knee, and hip under the static posture of car driving when an external force is exerted to the low limb joint. Twenty five anthropometric parameters of ten participants were sampled. The personalized digital model of ten participants was set up with sampled anthropometric data in the senior digital modeling of JACK. By simulating the driving posture and using the static strength prediction module of JACK, external force was imposed on front foot to calculate moment of low limb joint when the degree of ankle joint and knee joint was changed. The results indicated that the moment of knee joint and ankle joint produced by external force gradually decrease with the increase of ankle joint angle and the rate of decrease was faster and faster. The moment of hip joint gradually decreased with the increase of ankle joint angle and the decrease amplitude was uniform and linear trend. The moment of ankle joint monotonously increase with the increase of knee joint angle and the increase rate was slower and slower. The moment of knee joint first decreased and then increased with the increase of knee joint angle and the moment of knee was minimum when the angle of knee joint is 110°. The moment of hip joint gradually increased and made a linear increase with the increase of knee joint angle. The results calculated by JACK were compared to the data measured by Primus RS system and their results were consistent. Conclusions can be made from the result: the drivers can properly increase their ankle joint angle or decrease their knee joint angle, so as to reduce the low limb joints torque produced by external force imposed on foot because of braking; it is suggested that 108° to 113°of knee joint angle is the best.

Keywords: Human digital model · Lower limb joint moment · Driving posture · Computer simulation

1 Introduction

Human body joints are important load-bearing parts of the force and moment under different working posture and movement. It is of great significance to study the stress state and the change trend of related limb joints under the particular position in order to

plan working posture reasonably, prevent joint damage, improve working comfort, and guide the design of artificial joints and so on. But it is difficult to measure the stress state of the joint parts directly because of the osculating coupling between limb joints musculoskeletal and other tissues. JACK which is currently acknowledged as the software of modeling and simulation of human body and ergonomic evaluation has a function of the strength prediction. People can easily calculate the force and torque in the digital body joint by with JACK [1]. Digital human model based on JACK software has been widely used in scientific research and optimized engineering design of many fields [2–5].

At present, with the rapid development of modern society, automobile driving gets wide attention. Understanding for driving force of the lower limb joints, especially in a particular driving position and joints angle will have great guiding significance for the analysis of driving fatigue and design of the comfortable driving position, etc.

Domestic and international Scholars have carried out extensive research work about the comfortableness of driving posture and appropriate joint angle. Rebiffe et al., established human biomechanics model to simulate the automobile driver's posture and position [6]. They calculated out of the comfortable joint angle theoretically. Ma et al. combining the characteristics of Chinese human body, quantitatively proposed the mean value and range of joint angle about comfortable driving posture, compared and analyzed the differences of comfortable driving angle between the body of Chinese and foreign body through a large number of vehicles driving tests [7]. Zhao et al. established a three-dimensional biomechanical model that can be used to calculate the force and torque of each limb joint which is based on the driving position of tank drivers [8]. However, in the context of present literature survey, the researches related to the main joint torque of lower limbs under the driving position are not enough. This requires further study to validate and supplement the result of the present research.

In this paper, by modeling individualized digital human based on JACK and using its static strength prediction module researchers got the moment of the ankle, knee and hip joints from the right lower limb of human body under static posture in the car driving. And they hope to get the change rule and trend of joint torque with the change of the angle and external force of the lower limb joints. The results will provide reference for the design of automotive cockpit and man-machine interface.

2   Modeling of Digital Human

Module of JACK that can accurately establish the digital human model contains 25 static measurements items. Ten participants who are fit and healthy adult males and the age is form 20 to 25 (mean 23) were selected in this study. Twenty five static anthropometric parameters of human body were measured. The results were shown in Table 1.

Because the database of human body size of JACK does not match the participants and there are internal functions to restrict coupling among some body size data of advanced digital human modeling modules in JACK, the body size data measured above cannot be completely input to JACK. When creating a personalized virtual human,7 parameters need to be set—the height, the distance between hip and knee, the

Table 1. The results of 25 static anthropometric parameters (cm)

Parameters	Results	Parameters	Results
Stature	174.5 ± 6.6	Hand length	17.6 ± 1.1
Abdominal depth	19.8 ± 2.0	Head width	15.7 ± 0.6
External ankle height	7.1 ± 0.7	Head height	24.2 ± 1.2
Shoulder height	144.3 ± 6.0	Head length	18.9 ± 0.4
Upper extremity length	75.8 ± 3.7	Hip breadth	33.2 ± 1.7
Shoulder peak width	32.7 ± 1.8	Papillary distance	7.7 ± 0.4
Maximum shoulder breadth	44.6 ± 2.4	Shoulder-elbow length	3.6 ± 1.5
Hip-knee length	55.8 ± 1.9	Shoulder height sitting	63.9 ± 2.8
Elbow height sitting	27.7 ± 1.9	Eye height sitting	84.4 ± 2.2
Forearm-fingertip length	45.1 ± 2.6	Sitting height	95.1 ± 2.7
Foot breadth	9.3 ± 0.6	Knee height sitting	52.4 ± 2.3
Foot length	25.1 ± 1.3	Thigh depth sitting	14.2 ± 0.7
Hand width	8.1 ± 0.4		

knee height in sitting, the height of lateral malleolus, the foot length, the foot width and the thighs thick in sitting. The rest of the body size was calculated by the functions of JACK. In the digital modeling senior module of JACK, the personalized digital human model corresponded to 10 participants were established, as shown in Fig. 1.
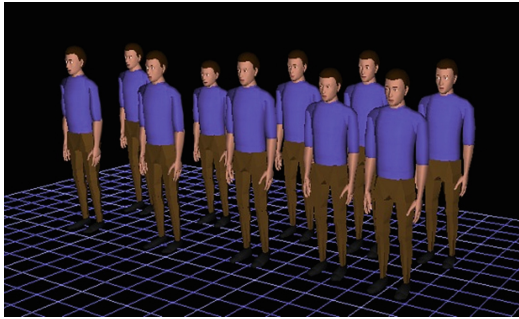
Fig. 1. Ten digital human models

Based on the results of Ma [7] the angel range of ankle, knee and hip joint of the right lower limb with driving position in this study was determined as, the ankle 90° ~110°, the knee 100° ~140°, the hip joint 95° ~115°. An external force is applied to the front end of the foot to simulate force of the foot when braking. Moreover the force is set in the plane of the right lower limb. The driving position of digital human in JACK was shown in Fig. 2.
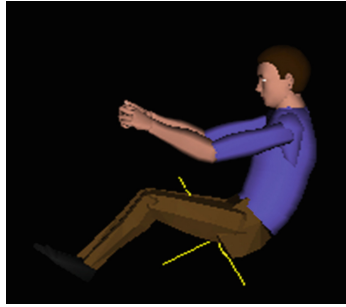
Fig. 2. Driving posture of digital human

3   The Influence on the Joint Torque by Changing Joint Angle

The method of controlling variables was used in this study which means to observe the changes of each joint torque by fixing the joint angle of two joints and changing the joint angle of the third joints. It included two cases as follows.

1. Fixed the hip joint angle to 100°and the knee joint angle to 120°. The ankle joint angles were changed form 90° to 110° which are set in step of 5°, that is 90°, 95°, 100°, 105°, 110°. Meanwhile, at each position, the force F was sequentially set to 10 N, 20 N and 30 N. Joint torque of ankle, knee and hip joint were recorded respectively.
2. Fixed the hip joint angle to 100°and the ankle joint angle to 100°. The knee joint angles were changed form 100° to 140° which are set in step of 10°, that is 100°, 110°, 120°, 130°, 140°. Meanwhile, at each position, the force F was sequentially set to 10 N, 20 N and 30 N. Joint torque of ankle, knee and hip joint were recorded respectively.

3.1   The Joint Torques Change of the Right Lower Limb with Ankle Joint Angle

In the module of JACK of advanced digital human modeling, the personalized digital human that correspond to the 10 participants was set up with anthropometric data of this study. Each digital human was adjusted for driving position. Using static strength prediction module and external force was applied at the location of the forefoot of the digital human. External force was located in the plane of the right lower limb, the direction of which has a 45° angle with horizontal direction of the earth coordinate system pointing in the direction of digital human (Fig. 3). Each joint under specific static force was calculated.

The digital human was adjusted for driving posture. The hip joint angle was adjusted to 100°, and the knee angle to 120°. The ankle joint angle was changed gradually in steps of 5° between the 90° to 110° which is sequentially set to 90°, 95°, 100°, 105°, 110°. Meanwhile, at each position, the force F was sequentially set to 10 N, 20 N and 30 N, and joint torque of ankle, knee and hip joint was recorded respectively.
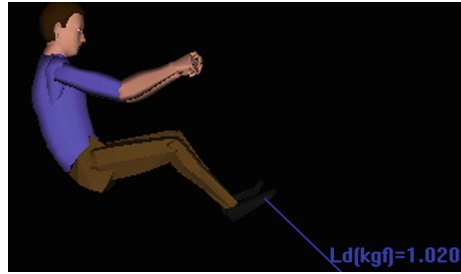
Fig. 3. Force on foot

Table 2. Joint torque of ankle, knee and hip with 10 N of external force (N·m)

Ankle joint angle	Ankle joint torque	Knee joint torque	Hip joint torque
90°	1.404 ± 0.211	1.050 ± 0.168	4.194 ± 0.671
95°	1.326 ± 0.199	0.972 ± 0.146	4.116 ± 0.645
100°	1.237 ± 0.186	0.884 ± 0.124	4.028 ± 0.604
105°	1.140 ± 0.182	0.787 ± 0.129	3.930 ± 0.589
110°	1.033 ± 0.144	0.681 ± 0.114	3.823 ± 0.573

Table 3. Joint torque of ankle, knee and hip with 20 N of external force (N·m)

Ankle joint angle	Ankle joint torque	Knee joint torque	Hip joint torque
90°	2.808 ± 0.422	2.101 ± 0.336	8.388 ± 1.342
95°	2.651 ± 0.398	1.945 ± 0.292	8.232 ± 1.290
100°	2.475 ± 0.372	1.769 ± 0.248	8.055 ± 1.208
105°	2.280 ± 0.364	1.574 ± 0.258	7.860 ± 1.178
110°	2.067 ± 0.288	1.361 ± 0.228	7.647 ± 1.146

The analysis was made with static strength prediction module of JACK when external force is 10 N, 20 N, 30 N. The mean and standard deviation for each joint torques of the right lower limb were shown in Tables 2, 3 and 4. It could be seen from the results of the table that the torque on the ankle generated by the external force show a declined trend and the rate of torque reduction becomes higher when the angle of the ankle joint increase gradually. This was because when the angle of the ankle joint is larger, the increase of angle of the ankle joint make the force arm in the center of the ankle joint determined by external force reduce in larger amplitude. Thus the reduce rate of the torque was bigger. The change trend of the torque generated by external force at the knee joints is the same at the ankle. The joint torque at the hip joint decreased gradually along with the increase of the angle of the ankle joint, and reduced uniformly in a linear decrease trend basically.

Table 4. Joint torque of ankle, knee and hip with 30 N of external force (N·m)

Ankle joint angle	Ankle joint torque	Knee joint torque	Hip joint torque
90°	4.212 ± 0.633	3.151 ± 0.504	12.582 ± 2.013
95°	3.977 ± 0.597	2.917 ± 0.438	12.347 ± 1.935
100°	3.712 ± 0.558	2.653 ± 0.372	12.083 ± 1.812
105°	3.419 ± 0.546	2.360 ± 0.387	11.790 ± 1.767
110°	3.100 ± 0.432	2.042 ± 0.342	11.471 ± 1.719

Table 5. Joint torque of ankle, knee and hip with 10 N of external force (N·m)

Knee joint angle	Ankle joint torque	Knee joint torque	Hip joint torque
100°	0.798 ± 0.119	0.818 ± 0.123	2.327 ± 0.326
110°	1.033 ± 0.155	0.054 ± 0.008	3.178 ± 0.411
120°	1.237 ± 0.185	0.884 ± 0.131	4.028 ± 0.564
130°	1.404 ± 0.210	1.707 ± 0.256	4.851 ± 0.679
140°	1.528 ± 0.230	2.478 ± 0.371	5.621 ± 0.784

3.2 The Joint Torques Change of the Right Lower Limb with Knee Joint Angle

The digital human was adjusted for driving posture. The angle of hip joint and the ankle joint was fixed to 100°. The knee joint angle changed from 100° to 140° in steps of 10° which was 100°, 110°, 120°, 130°, 140°. Meanwhile, at each angle position, the force F was sequentially set to 10 N, 20 N and 30 N. The mean and standard deviation for each joint torques of the right lower limb were shown in Tables 5, 6 and 7.

The results of tables showed that the ankle joint torque increased monotonously with the increase of the knee joint angle and the increase rate became slower and slower. It was obvious that the change of the knee joint angle has a big effect on the ankle joint torque within the scope of a comfortable driving position when the knee joint angle is small, And when the knee joint angle increased gradually, the effect on the additional torque generated by the external force on the ankle reduces with the knee joint angle change. However, in general, the increase of the knee joint angle caused the increase of the ankle joint torque.

With the gradual increase of knee joint angle, there was a variability characteristic that the knee joint torque increase after the first reduce. When the knee joint angle was 110°, the additional torque generated by the external force on the knee joint reached to the minimum. Since then, the knee joint torque increased along with the increase of joint angle. This was because when the knee joint angle is 110°, the knee joint center fall in the near of the action line of the external force, and the force arm to the center of the knee joint generated by the external force reached to the minimum, so reduced the balance of torque at the knee joints at the same external force. In the process of the knee joint angle gradual increase after reaching 110°, the distance between the center of the knee joint and the action line of the external force which is called the force arm increased gradually, so the torque took the trend of gradual increase.

Table 6. Joint torque of ankle, knee and hip with 20 N of external force (N·m)

Knee joint angle	Ankle joint torque	Knee joint torque	Hip joint torque
100°	1.596 ± 0.238	1.637 ± 0.246	4.655 ± 0.652
110°	2.067 ± 0.310	0.109 ± 0.016	6.356 ± 0.822
120°	2.475 ± 0.370	1.769 ± 0.262	8.055 ± 1.128
130°	2.808 ± 0.420	3.413 ± 0.512	9.701 ± 1.358
140°	3.055 ± 0.460	4.955 ± 0.742	1.243 ± 1.568

Table 7. Joint torque of ankle, knee and hip with30 N of external force (N·m)

Knee joint angle	Ankle joint torque	Knee joint torque	Hip joint torque
100°	2.394 ± 0.357	2.455 ± 0.369	6.983 ± 0.978
110°	3.100 ± 0.465	0.163 ± 0.024	9.534 ± 1.233
120°	3.712 ± 0.555	2.653 ± 0.393	12.083 ± 1.692
130°	4.212 ± 0.630	5.120 ± 0.768	14.552 ± 2.037
140°	4.583 ± 0.690	7.433 ± 1.113	16.864 ± 2.352

Along with gradual increase of the knee angle, the hip joint torque increased monotonically. Moreover, with the gradual increase of the knee joint angle, the torque of the external force in the hip joint increased steadily in an approximate linear growth trend.

4   Test and Analysis

In order to compare to the results of JACK, the data of static stress on the foot front-end of right lower limbs was collected from previous10 participants on Primus RS function simulation system with simulating driving posture. Because it was difficult to measure the torque of the knee and hip with the measurement system, only the data of the ankle was collected in this study.

In the test, the participants sat on the chair with his upper torso and waist fixed and the right lower limb was in a driving posture, while the right thigh, the right shank and the right foot in the same vertical plane, and feet were placed on the training tool. In order to simulate the force of the front end of foot, a force transducer was fixed in the front end of the test tool 701. The front of participants' feet put on a sensor and exerted the force of 30 N. After the readings of force sensor were stabilized, click "start" button on the Primus RS interface. The system measured the torque transferred from the practice center of Primus RS which is approximately regarded as the torque of the ankle of the participants. In the test, the participants maintained the angle of the hip joint to 100°and the knee joint to 120°. Moreover they adjusted the angle of the ankle joint to 90°, 95°, 100°, 105°, 110° in turn. Test scenario was shown in Fig. 4. Table 8 was the experimental data.
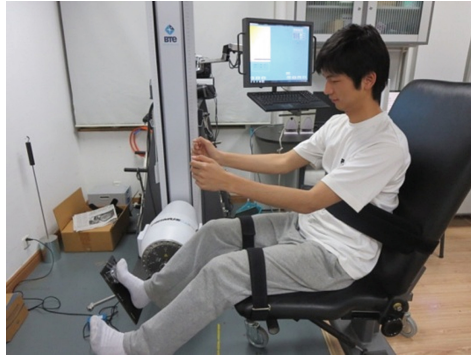
Fig. 4. Test scenarios

Table 8. Joint torque measured by Primus RS system (N·m)

Joint angel	90°	95°	100°	105°	110°
Joint torque	8.3 ± 0.4	7.7 ± 0.5	6.8 ± 0.3	5.6 ± 0.3	4.2 ± 0.5

It could be seen from Table 8 that with the gradual increase of the angle of the ankle joint, the torque of the ankle joint decreased in a faster and faster reducing rate. The change trend of the data was consistent with the results of JACK. Therefore, during driving drivers could increase properly the angle of the ankle joint to reduce the moment generated by the external force imposed on the foot at each joints of the lower limb when braking. But in the process of test, by asking participants' comfort degree, it was found that the participants feel uncomfortable in different degree when the ankle's angle was close to the upper limit of threshold, So, although the torque on the lower limb joint is smaller with the greater of ankle's angle, it make drivers feel uncomfortable. Because when the joint's angle was larger, the difficulty of muscular contraction force increased so that it is more difficult for participants to maintain position. Therefore, as to the angle of the ankle under the driving position, it was not the bigger the better. The ankle angles should be increased moderately. At the same time, by reducing the knee joint angle, the torque can be reduced generated by the force which is imposed from the brake pedal to the foot on the ankle and hip of the lower limb. But the torque of the knee joint came to minimum at the 108°of the knee joint's angle. In addition when the knee joint angle was a little bit small or large, the drivers will feel uncomfortable because their position was constrained by cabin space. Thus it was advisable that the knee joint angle is between108° and 113°.

There were significant differences between the data in Table 8 and in JACK ($p < 0.05$). When the participants were measured with Primus RS system, the front foot of the subjects is forced. Although the stress could be controlled by the force transducer, it was difficult to accurately control the direction of the force, thus the error that cannot be ignored was produced. The measurement results of Primus RS system was not the real moment of the ankle. However, when the center of the ankle joint of the

participants was aimed at the center of the equipment tool head axis, the moment conduct by external pedal tools into the internal equipment was considered approximately as the moment of the ankle of the participants. Because the foot had the characteristic of human tissue biomechanics, muscle contraction produced complex stress environment to the tissue around the ankle, so the measurements of Primus RS contained part influence factors of biomechanics. Therefore, the Primus RS system measurement method could obtain the experimental results that are relatively close to the actual stress, but the measurement location was limited. The ankle moment could only be measured approximately. It was difficult to obtain the torque of the knee and hip, and the adjustment of the subjects' posture and the external environment settings would produce errors that cannot be ignored.

JACK digital human modeling method is based on anthropometric parameters to establish a digital human model. The balance torques of the joints was obtained by internal biomechanical calculation functions of static prediction module of JACK. The main error sources of this method are that the size of JACK digital human model doesn't exactly match with the size of the real people. Because the JACK prediction module of the static strength calculation is based on the size of the digital human, the joint torque of the personalized digital human calculated by JACK is not exactly the ankle joint torque. However JACK has the powerful function in modeling and simulation of digital human, it can easily adjust the digital human position and set its stress environment, conveniently obtain the stress of the joints.

5   Conclusion

In this study, based on JACK and simulation of car driving, personalized digital human models were set up, the stress of the right lower limb joints was analyzed, and data obtained from JACK and Primus RS system was compared. Through calculation and analysis, this research can draw the following conclusion:

(1) Within the scope of the comfortable driving posture, when the knee joint angle and the hip angle are fixed, the moment of the ankle, the knee joint and the hip joint will gradually decrease with the increase of the ankle joint angle. Therefore, the moment of lower limb joints that imposed on the foot in the brakes by external force can be reduced by properly increase the ankle joint angle when drivers are driving. (2) Within the scope of the comfortable driving posture, when the ankle joint angle and the hip angle are fixed, the moment of the ankle joint and the hip joint will gradually increase with the increase of the hip joint angle. Therefore, in consideration of the driving space of the car and the factors of stress on lower limbs, in driving it is advisable that the driver's knee joint angle should keep from 108° to 113°. (3) Digital human modeling method by JACK which can conveniently obtain the stress of the joints, is a reliable and efficient method.

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