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KINETOSTATIC ANALYSIS OF KNEE JOINT USING MBS SIMULATION

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ABSTRACT

The paper presents the kinetostatic analysis of the right and left knee joints using a multibody system that replicates the human body lower limbs. The model is developed in MSC Adams and it composed of 7 kinematic elements (pelvis, right and left femur, right and left tibia and right and left foot) interconnected through 6 spherical joints constrained to 1 degree of freedom each (DOF). To simulate the MBS system we have developed laws of motion for 6 major joints composing the human lower limbs structure (right and left hip, right and left knee and right and left ankle). The laws of motion were determined based on kinematic data generated by a depth camera. Thus, determining the MBS model kinematics we were able to conduct the kinetostatic analysis using the inverse dynamic analysis principles. The MBS system was simulated during bipedal cycle walk of 2 steps in 3 loading cases: normal weight (43.38 Kg), with an additional weight of 34.46% equivalent of 146.599 N and with an additional weight of 64.93% equivalent of 276.233 N. The kinetostatic analysis has provided the ground reaction forces variation with respect to time for left and right knee joints (LKJ, RKJ) in the 3 loading cases.

KEYWORDS: knee joint, MBS, kinetostatic analysis, human body

1. INTRODUCTION

Human boy gait is a voluntary and semi - automatic action executed without being perceived or how is performed. Due to the complexity of the human body locomotor system and because the human gait can be influenced by internal and external factors, human gait is considered an asymmetrical action that continuously adapts to situation.

The aim of this paper is to determine through a noninvasive method the ground reaction forces applied during normal gait and with overload for the right and left knee.

The knee is the largest and most complex joint of the human body. During all activities executed by the human body locomotor system this joint takes external and internal forces. As internal forces, we can mention propulsion forces or contact forces.

Accurate quantification of internal loads exerted by the movement of the human body may have clinical implications for models of motor control [5], for prostheses preclinical testing and as input for finite element models to estimate bone adaptation [1, 3].

Previous authors [7] conducted studies for determining contact forces and moments acting on the tibial component, measured in 5 subjects in vivo by an instrumented knee implant during various activities of daily living. The average force was calculated as percentage of body weight.

Knowledge of muscle and joint contact forces during gait is necessary to characterize muscle coordination and function as well as joint and soft-tissue loading [4]. Therefore, multibody system simulation is necessary in estimating muscle and joint contact forces, since direct measurement is not feasible under normal conditions.

Other authors [6] examined vertical ground reaction force and knee mechanics of twelve healthy dancers (six males, six females; age 18.9 ± 1.2 years, mass 59.2 ± 9.5 kg, height 1.68 ± 0.08 m, dance training 8.9 ± 5.1 years) while executing saut de chat. It was hypothesized that vertical ground reaction force during landing would exceed that of take-off, resulting in greater knee extensor moments and greater knee angular stiffness.

2. METHOD

The dynamic behavior of the muscular - skeletal human system can be simulated using multibody systems. These systems are composed of rigid parts and redundant actuators. Thus, for determining the kinetostatic of the right knee joint (RKJ) and left knee joint (LKJ) we developed an MBS system characterized by 1 DOF, 7 kinematic elements (pelvis, right and left femur, right and left tibia and right and left foot), 6 spherical joint constrained to 1 DOF (right and left hip, right and left knee and right and left ankle) and 1 translation joint for simulating the human gait (figure 1) [2].

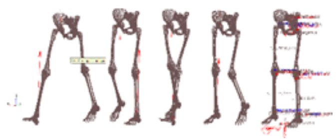

Fig. 1. *The MBS model while executing a fraction of the gait cycle [2]*

To simulate the MBS model we created a law of motion using data generated by a depth camera. The laws of motion were created for 3 cases as follows [2]:

- The first loading case - The subject has executed a gait cycle;
- The second loading case - The subject has executed a gait cycle with overload (34.46% of his body mass);
- The third loading case - The subject has executed a gait cycle with overload (64.93 %. of his body mass).

The aim of this study is to determine the ground reaction force applied on the RKJ and LKJ during normal gait and gait with overload. Thus, the created model was simulated over 2 normal steps. The gait cycle was divided as following [2]:

- Start simulation phase: from orthostatic position (sub – phase 1) the model prepress to pass to support phase;
- Support phase: The first sub – phase (sub – phase 2) of the support phase is initial contact. In this sub – phase the RKJ passes from flexion state to full extension and the LKJ is in a slight supination [8]. When the model reaches the sub – phase 3 it enters in a state of initial support or double support. This sub-phase is characterized by the highest instantaneous speed of the gait cycle. The sub – phase 4 is called support [9], followed by completion support (sub – phase 5) and by balance initiation (sub – phase 6);
- Balance phase;
- Stop simulation: in this phase the MBS model reaches again the orthostatic position.

3. KNEE JOINT KINEMATIC ANALYSIS

The knee joint kinematic analysis was conducted based on laws of motion generated using a depth camera. Although the subject tried to execute the gait cycle sub – phases symmetrically, the resulted data are without patterns.

Angular velocity variation for the RKJ in all three cases has a maximum value of 19.99 degrees/s when the right kinematic chain is in the sub – step of initial contact (figure 2, 3, 4). Time variation of average angular velocity has a slight increase in the second loading phase and a slight decrease in the third loading phase. The first case is characterized of an average value of 2.66 degrees/s, in the second case of 2.84 degrees/s and in the third of 2.78 degrees/s [2].

LKJ’s angular velocity variation with respect to time has a maximum value of 15 degrees/s in all three studies (figure 2, 3, 4). This amplitude was reached towards the end of the sub – phase called support completion. The average angular velocity shows a different variation trend. The data from the second case shows a decrease from 1.45 degrees/s to 1.39 degrees /s followed by an increase over the initial value, to 1.54 degrees/s [2].

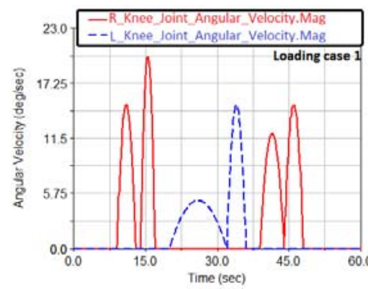

Fig. 2. *RKJ and LKJ angular velocity with respect to time (first loading case) [2]*

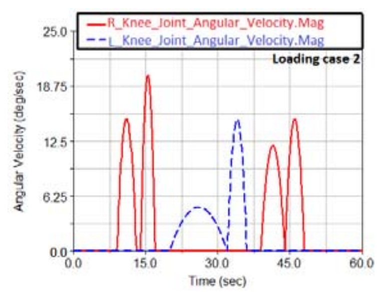

Fig. 3. *RKJ and LKJ angular velocity with respect to time (second loading case) [2]*

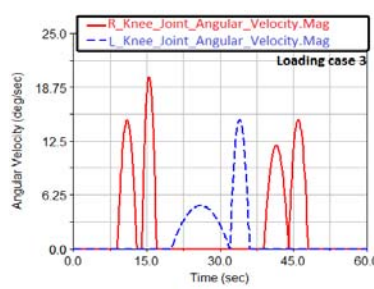

Fig. 4. *RKJ and LKJ angular velocity with respect to time (third loading case) [2]*

Time variation of angular acceleration for the RKJ (figure 5, 6, 7) reaches its amplitude when the MBS model passes from sub – phase 1 to sub – phase 2 [2].

In the first loading case, the angular acceleration has a maximum value of 25.87 degrees/s^2, followed by an increase to 30.79 degrees/s^2 in the second loading case. In the third case, the angular velocity increases with 111% relative to the second one, reaching a value of 65.27 degrees/s^2. It can be observed that the average value of the angular acceleration decreases from 2.07 degrees/s^2 to 1.95 degrees/s^2, followed by an increase to 2.06 degrees/s^2 [2].

The angular acceleration variation with respect to time for the LKJ (figure 5, 6, 7) reaches its amplitude during the sub – phase called support completion. Therefore, the maximum recorded value for the first case is 23.34 degrees/s2, for the second it is 24.02 grade/s2 and 30.79 grade/s2 for the third. The average values show a slight increase from 0.65 degrees/s2 to 0.73 degrees/s2 in the second case and to 0.74 degrees/s2 in the third one [2].

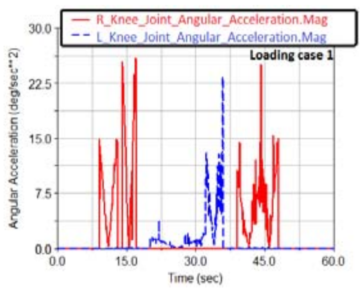

Fig. 5. *RKJ and LKJ angular acceleration with respect to time (first loading case) [2]*

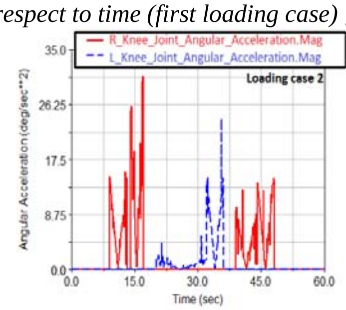

Fig. 6. *RKJ and LKJ angular acceleration with respect to time (second loading case) [2]*

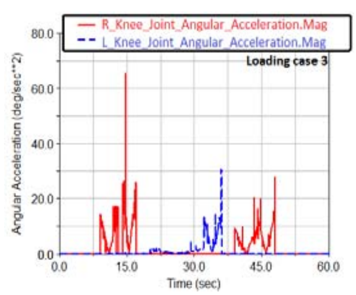

Fig. 7. *RKJ and LKJ angular acceleration with respect to time (third loading case) [2]*

4. KINETOSTATIC ANALYSIS OF THE KNEE JOINT

Using a multibody simulation software and applying the inverse dynamic method, we determine the ground reaction forces variation with respect to time. The results are essential for estimating the stress applied in the human lower limb kinematic chain joints. Therefore, it can reveal differences between loading cases corresponding to normal gait and with overload.

During the gait cycle, the ground reaction force reaches its amplitude at the end of sub – phase 2 of the first studied case (figure 8). The amplitude of the ground reaction force for the RKJ was 691 N, while the mean value of 122.83 N [2].

During the second loading case, the ground reaction force reaches an amplitude of 1336.4 N while during the third one the value of 1575.2 N. The average recorded value during the second loading case was 192.7 N and for the third one there was an increase of 28.16% (figure 9, 10) [2].

The LKJ has recorded during the first loading case a ground reaction force of 959 N (figure 8). This amplitude was reached during the sub – phase of starting balance. The average value of this force was approximate of 193.20 N [2].

The second and the third loading cases have recorded a ground reaction equal to 1063N and 1559.15 N respectively. The average value was equal to 304.37 N during the second loading case and 399.54 N during the third loading case. This increase is of approximately of 31.26% (figure 9, 10) [2].

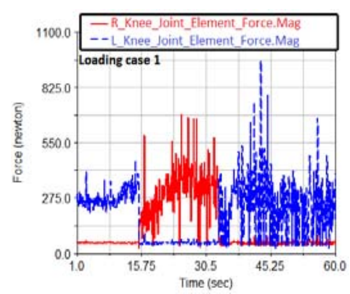

Fig. 8. *Ground reaction force with respect to time recorded in RKJ and LKJ (first loading case) [2]*

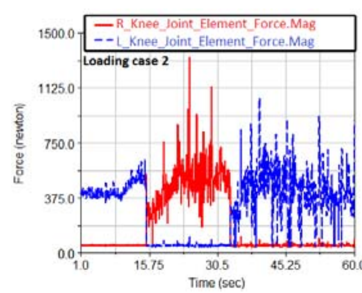

Fig. 9. *Ground reaction force with respect to time recorded in RKJ and LKJ (second loading case) [2]*

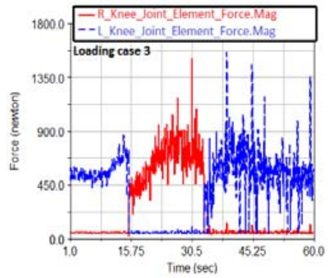

Fig. 10. *Ground reaction force with respect to time recorded in RKJ and LKJ (third loading case) [2]*

5. CONCLUSIONS

The multibody models that replicate the anatomical structures can provide critical information about the mechanical work performed by the human body locomotor system.

The resulted data can be integrated into the various levels of muscular-skeletal systems, being an ideal framework for identifying and estimating the limitations that cause malfunctions. Therefore, data that cannot be determined in vivo are obtained.

To study the dynamics of the human locomotor system we created a multibody model which we imposed real laws of motion, provided by a Kinect sensor. The created model is composed of 7 kinematic elements connected through spherical joints constrained to 1 DOF each.

From the inverse dynamic analysis, it can be observed that the amplitude of the ground reaction force in respect of the time for the RKJ and LKJ evolves asymmetrically. Therefore, it can be observed that the amplitude of the ground reaction force recorded in the LKJ is increased relatively to the RKJ in the first loading case (figure 11). A variation between the recorded forces can also be observed in loading cases two and three. This time it can be observe that the more loaded joint is the RKJ (figure 11) [2].

Due to the additional applied force, in the second loading case it can be observed an increase of loading force with 93.37% within the right knee joint and with 10.84% for the LKJ (figure 11) [2].

The third loading case is characterized by a ground reaction force increased with 127.95% for the right knee joint and with 62.58% for the LKJ (figure 11) [2].

The average value of ground reaction forces recorded within the RKJ and LKJ presents an ascendant trend in all tree loading cases. It can be observed that the loading determined in the RKJ increases with 56.88% and with 101.07% in the second and third cases (figure 12) [2].

Regarding the average values of the ground reaction force variation with respect to time, it can be observed that for the LKJ, the amplitudes are also characterized by an ascendant trend. The average values increase with 57.54% in the second loading case and with 31.26% in the third (figure 12) [2].

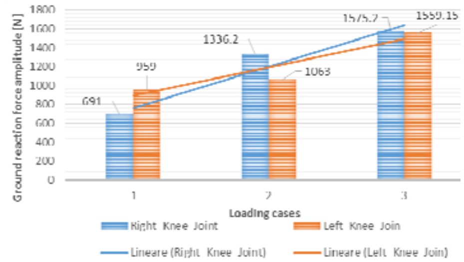

Fig. 11. *Ground reaction force amplitudes in all 3 cases for the RKJ and LKJ [2]*

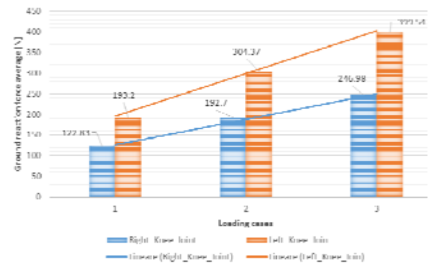

Fig. 12. *Average ground reaction force amplitudes in all 3 cases for the RKJ and LKJ [2]*

Therefore, the created multibody system can be considered an important tool in studies as kinetostatic analysis, analyzing the human locomotor system. Using laws of motion created from the depth images provided by the Kinect sensor we determined the kinematic of the human body lower limb, more precisely of the right and left knee. Appling the inverse dynamics principle we determined the ground reaction force variation with respect to time.

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