EXPERIMENTAL STUDY

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Biomechanical effects of daily physical activities on the lower limb

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Objective: The aim of this study was to determine the joint torques on the lower extremity during the daily physical activity movements of sit-to-stand, crouch down-stand up, and stair climbing without using an external device.

Methods: The study subject was a healthy 26-year-old male without any physical problems. A link-segment model was prepared according to the subject's individual anthropometric characteristics and transferred to the MATLAB® program. Joint torques were calculated using SimMechanics™ software. Motions were recorded by one digital video camera as the subject performed the movements (sit-to-stand from 20 cm and 40 cm height, crouch down-stand up, and climbing 10 cm and 20 cm high step) and the joint's position data was obtained using a digitization process. In addition, the vertical ground reaction forces were measured using a force plate in order to test the accuracy of the link-segment model. Lower extremity joint torques were calculated.

Results: Maximum joint torques occurred in the knee joint. The knee and the ankle joints were the most loaded joint during the high step movement. The highest torques of the knee and ankle joint were 157.2 Nm and 146 Nm, respectively, during the movements. Knee joint torque and the ankle joint torque increased when the sitting height increased. The hip joint experienced the least amount of load during the movements.

Conclusion: The knee joint has enough strength against high torques during extension and flexion movement. Joint torques can be successfully calculated using a simulation process involving an inverse dynamics method without an external device mounted on the limbs. The obtained data can be used in the design of prosthetics and orthotics and for structural analysis of the bones.

Key words: Biomechanical analysis; inverse dynamic method; joint torque; lower limb; motion analysis; physical activity.

The identification of human movement is important for orthosis and prosthesis designs,[1,2] ergonomic studies,[3] sportive activities,[4,5] and humanoid mechanism.[6,7] As human movements result from the interaction of countless muscles, joints and nerves, movement in daily life occurs without conscious awareness. Relatively more strength is required to carry out some of these movements. The lower extremity and body muscles work in unison to execute the movements of sit-to-stand (STS), crouch down-stand up, and climbing up stairs.

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The joint-limb models that explain the mechanical structure of the human body simplify the formation that make up movement such as skeletal muscles, joints and bones[8] thereby easing dynamic analyses. The joint-limb model in our study was created using the MATLAB® Simulink and SimMechanics™ (The MathWorks Inc, Natick, MA, USA) libraries that have been reported to provide successful examination of non-complex human movements.[2,6] SimMechanics™ is a software in which the geometric and mass attributes of real dimension physical systems are modeled as block diagrams and dynamic solutions are carried out in accordance with the laws of Newton mechanics.

Various external devices placed on the limbs are most commonly used to determine the forces and moments that occur on the joints during movement.[9,10] However, these devices can limit movement and hinder accurate measurement.

The objective of this study was to create a joint-limb model for the kinematic and kinetic analyses of daily movements. To this end, a simulation model was developed and its effectiveness verified using data acquired from a live subject. An inverse dynamic method was used to analyze the model. This method indirectly determines forces and moments by making use of the kinematic and inertia attributes of moving objects.[11]

Materials and Methods

The volunteer study subject was a 26-year-old male with a mass of 70.2 kg and height of 174 cm and had no health problem that would hinder his ability to move. Information was given to the subject prior to the study and consent was given. The study was carried out at the Biomechanics Laboratory of School of Physical Education and Sports, Sakarya University.

Anthropometric properties of the subject were determined to carry out the kinematic and kinetic analyses using anthropometric models[12,13] and computer-aided design (CAD) software[14] (Table 1). The MATLAB®

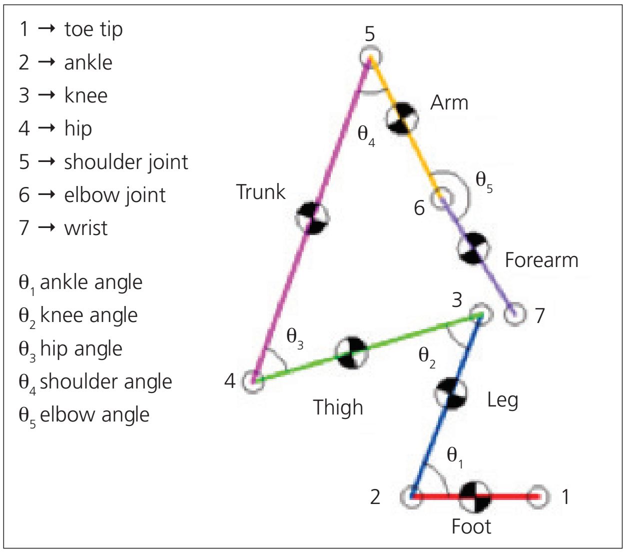

Fig. 1. The link-segment model and the joint angles in the sagittal plane. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

reference axis was taken into account when calculating the moment of inertia.[15]

The human body was represented by a joint-limb model with an open chain mechanical structure consisting of six solid limbs; foot, leg, thigh, trunk, arm and forearm (Fig. 1). Since the limbs move in unison during the examined movements, the joint-limb model was created by taking the half as reference with respect to the sagittal plane. Weights of the head and neck sections were added to the body. However, since these limbs are not displaced significantly during the examined movements, they were not physically included in the model.

The joint-limb model and anthropometric properties of the subject were transferred to the MATLAB®[16] environment using SimMechanics™ software for dynamic analysis. The limbs were accepted as solid objects in the model, which was prepared as two-dimensional in the sagittal plane.[2,8] Joints with many degrees of freedom and a polycentric structure were modeled as having only

Table 1. Anthropometric characteristics of the subject body parts.

Part	Part length (cm)	Mass (kg)	Moment of inertia (g·cm²)			The centre of mass from the proximal side (cm)
			I_{xx}	I_{yy}	I_{zz}	
Foot	24.33	0.993	$7 \cdot 10^3$	$30 \cdot 10^3$	$33 \cdot 10^3$	12.16
Leg	37.53	3.185	$329 \cdot 10^3$	$29 \cdot 10^3$	$391 \cdot 10^3$	16.25
Thigh	45.82	6.850	$1157 \cdot 10^3$	$224 \cdot 10^3$	$1137 \cdot 10^3$	19.84
Trunk	66.44	23.53	$19744 \cdot 10^3$	$9325 \cdot 10^3$	$12736 \cdot 10^3$	32.88
Arm	30.52	1.965	$132 \cdot 10^3$	$22 \cdot 10^3$	$133 \cdot 10^3$	13.3
Forearm	26.3	1.123	$64.5 \cdot 10^3$	$8.8 \cdot 10^3$	$66.9 \cdot 10^3$	11.31

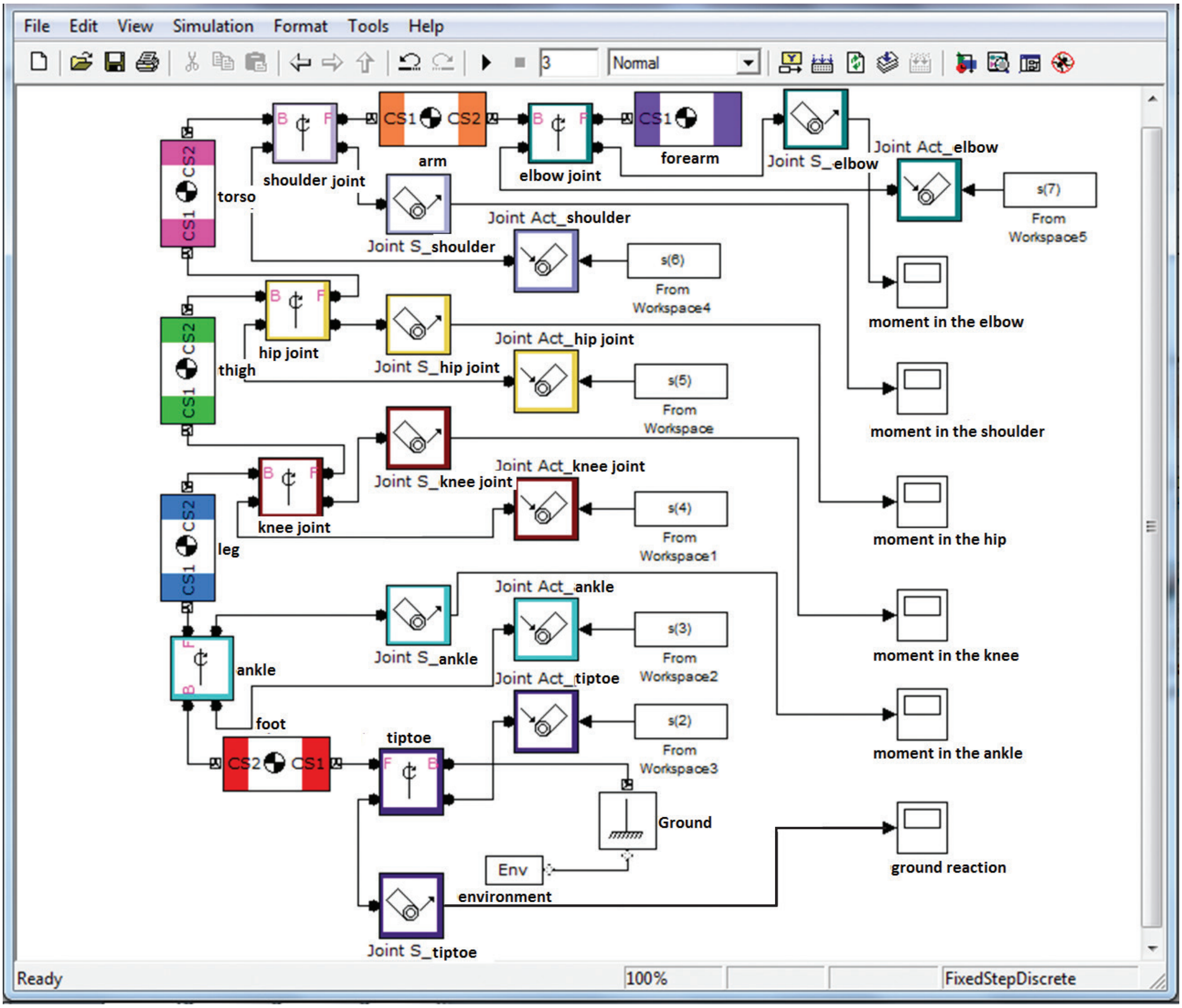

Fig. 2. SimMechanics™ block diagram of the link-segment model. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

one degree of freedom with the ability for extension-flexion movements in the sagittal axis.[8] Figure 2 shows the block diagrams of the SimMechanics™ model for dynamic analysis.

Reflecting markers were placed at the starting and ending points of the limbs, defined as the anatomic extremities that can be felt from the skin; the tip of the toe, the point where the fibula forms a joint with the talus, the top of the femur lateral condyle, the anterior superior iliac spine, the upper tip of the humerus, the elbow joint, and the ulnar styloid process. The subject was monitored using a single, digital video camera (50 frames per second, resolution of 720x576 pixels). Position data were acquired in the MATLAB® environment using image processing techniques. Images were selected, the number of coordinates were specified and sensitivity to light intensity was adjusted. The software perceives the position of the markers in the moving image and determines their coordinate values on each image frame before determining the image locations in order to establish their corresponding data points. Acquired coordinate values were saved on a file and could be reused. A low-pass digital filter was applied to the data in order to eliminate noise.[17] In addition, vertical ground reaction forces occurring during the movements were measured using a force platform (Quattro Jump; Kistler Group, Winterthur, Switzerland) with a data acquisition rate of 500 Hz.[8] Figure 3 shows the representative image of the movement analysis process prepared in the CAD software.

Sitting down and standing up movements were performed using a stool with no armrest and back support at a normal speed from heights of 20 cm and 40 cm.[18]

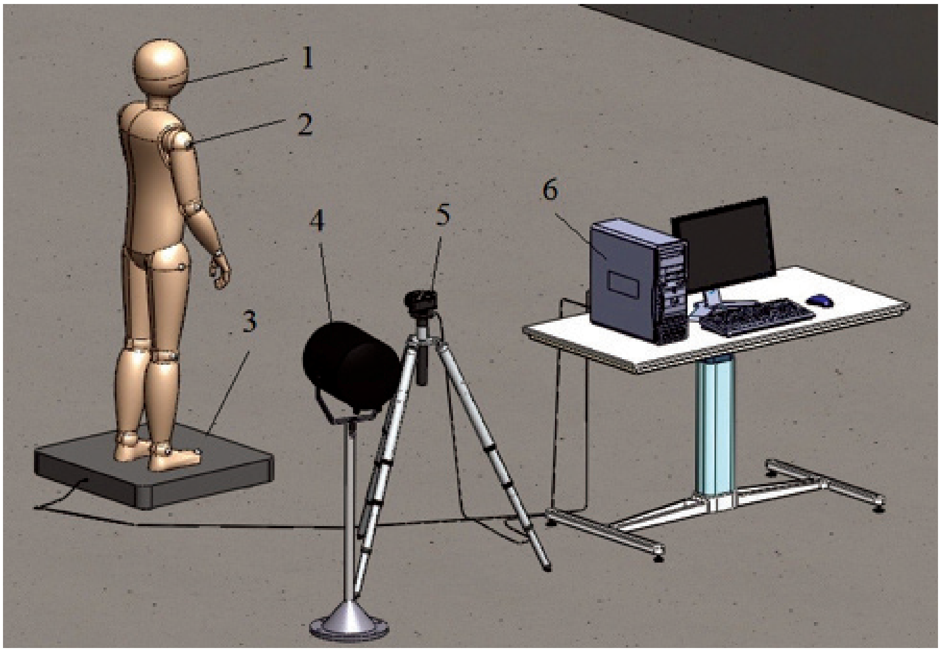

Fig. 3. CAD presentation of the analysis process. 1: The subject; 2: Markers; 3: Force platform; 4: Light; 5: Digital video camera; 6: Computer. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

The crouch down and stand up movement were carried out with the body in a straight position standing on two feet by crouching down and returning to the same initial position. The step climbing movements were performed by stepping on high steps of 10 cm and 20 cm using the dominant foot. The angular displacement data of the joints acquired via movement analysis were used in the execution of the inverse dynamic model created in the SimMechanics™ software.

Moment changes in the ankle, knee and hip joints were analyzed and the vertical ground reaction forces measured using the force platform were compared with the vertical ground reaction forces calculated via the MATLAB® software in order to test the accuracy of the established model.

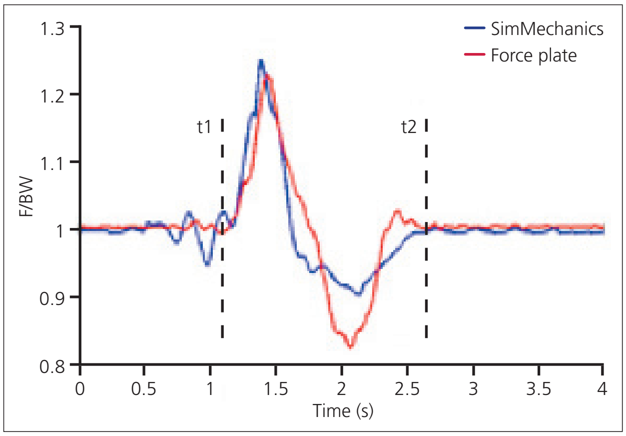

Fig. 4. Comparison of the vertical ground reaction forces during sit-to-stand from 40 cm height. t1: Time of the hip leaving from the chair; t2: Time of standing; F: Force; BW: Total body weight. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

Results

Ground reaction forces were in accordance with the measured ground reaction forces. Figure 4 shows the comparison of the vertical ground reaction forces during standing up from a height of 40 cm. Maximum vertical ground reaction force corresponded to approximately 1.25 times the body weight. The reaction force decreased to below body weight after a certain section of the movement was completed due to the reverse acceleration that occurs in the joints in order to bring the accelerating body to a static position at the end of the movement. The maximum value of the ground reaction force calcu-

Table 2. The highest joint torques.

	The highest joint torque (N·m)		
Movements	**Ankle**	**Knee**	**Hip**
STS from 20 cm	97.8	111.4	-68.2
STS from 40 cm	133.6	139.4	-50.1
Crouch down-stand up	-83.1	97.8	-81.3
Climbing stairs (10 cm)	144.7	139.6	-42
Climbing stairs (20 cm)	146	157.2	-29

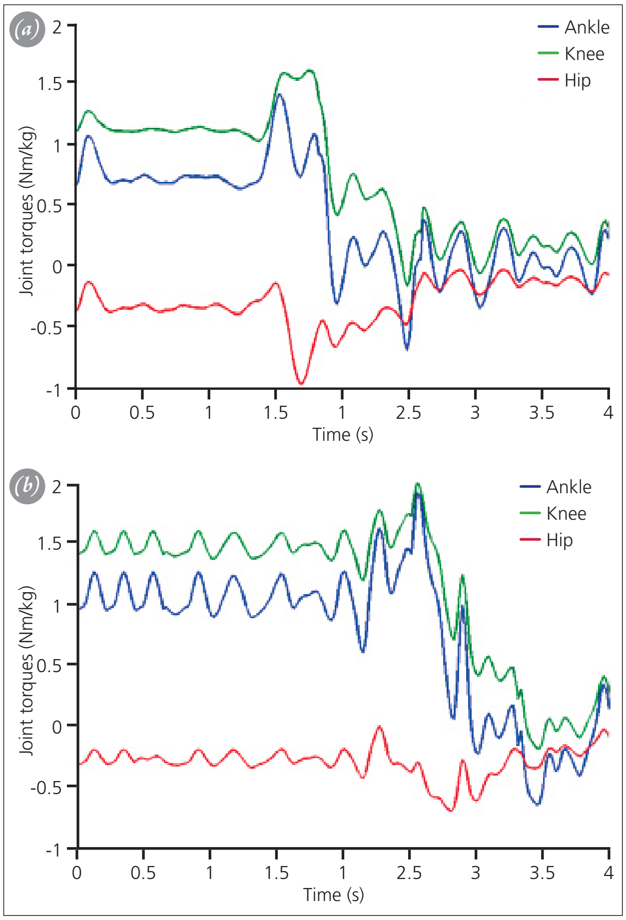

Fig. 5. Joint torques of the sit-to-stand. **(a)** 20 cm sitting height, **(b)** 40 cm sitting height. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

lated via simulation and the value measured via the force platform were very similar. The largest error of 7% in the calculation of the maximum ground reaction force occurred for the standing up movement from 20 cm.

Figure 5 shows the joint moments in the lower extremity joints during the sitting and standing up movements from various heights calculated as a result of the simulation.

Figure 6 shows the joint moments during the crouch down and stand up movements.

Figure 7 shows the joint moments measured during the movement of climbing up a stair from different heights.

Table 2 shows the largest joint moments during the examined movements.

Discussion

In this study examining daily physical activity movements via joint moments, the highest stress was found to

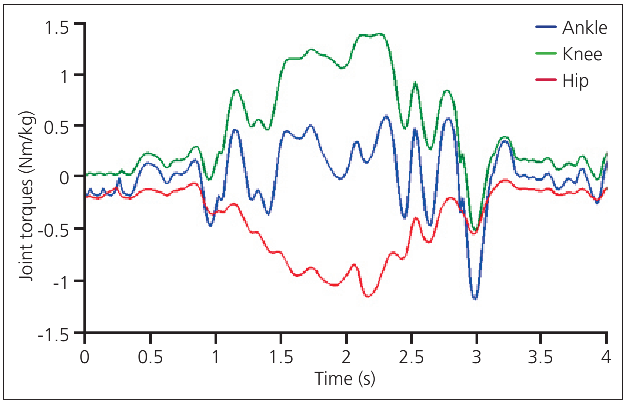

Fig. 6. Joint torque of the crouch down-stand up movement. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

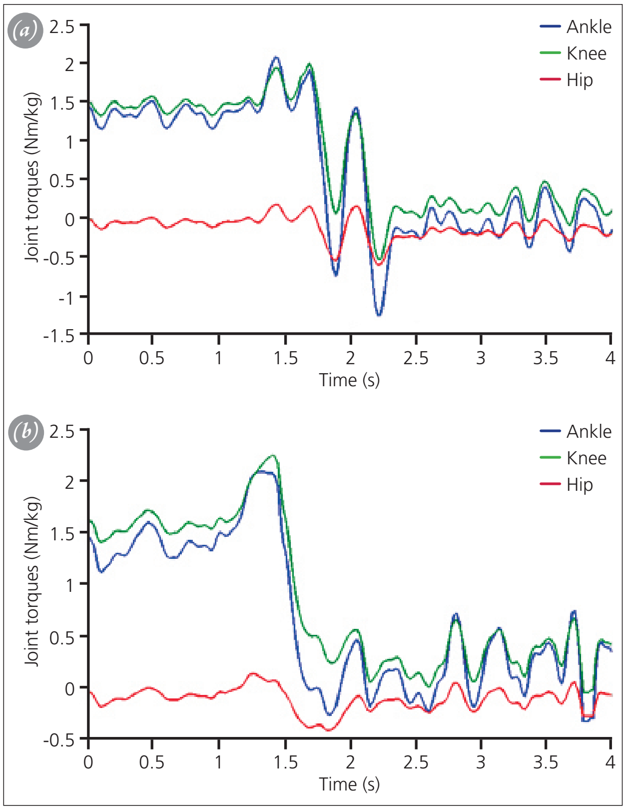

Fig. 7. Joint torques of the climbing stairs. **(a)** 10 cm stairs height, **(b)** 20 cm stairs height. [Color figure can be viewed in the online issue, which is available at www.aott.org.tr]

occur on the knee joint. Stair climbing placed the greatest stress on the knee joint and the moment on the joint increased as the height of the steps increased.

In a study evaluating sitting down and standing up movements, Mak et.al.[19] also determined that the highest joint moment occurs in the knee joint. The moment on the joint increases with increasing sitting height (from 20 cm to 40 cm), which results in the movement of the body center of gravity away from the knee and ankle joints. This in turn increases the resulting joint moment. However, as more time passes when standing up from a sitting height of 20 cm until standing erect (in comparison with a sitting height of 40 cm), more energy is spent when standing up from a height of 20 cm.

The lowest moments occur at the hip joint. The crouch down and stand up movement puts the greatest stress on the hip joint. Even though relatively smaller joint moments occur, the crouch down and stand up movement is the most tiring. When examining the graph taken of the crouch down and stand up movement, the longest change can be seen to occur during this movement, requiring that more energy be spent when completing this movement.

The most important limitation of this study was the examination of only one subject, as it should be taken into consideration that personal movements differ from person to person. Different results may be obtained when anthropometric differences are included as well. For example, the joint moment values given in Table 2 are closely related with the weight and other anthropometric properties of the subject. It is inevitable that different joint moments will be calculated for individuals with different anthropometric properties. A more comprehensive examination would be possible by increasing the number of samples.

In conclusion, joint moments can be calculated without the use of devices placed on the body which hinder movement through the use of software developed for the analysis of mechanical systems. The moment data obtained may be beneficial for the design of prosthesis or orthosis designs for the lower extremity. In addition, force and moment data can be used to define the loading conditions of the structural analysis for bones. Thanks to the flexible structure of SimMechanics™ tools, the model can be easily changed to carry out different analyses (for example determination of the energy spent during movements or the effects of weight increase on joint moments).

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Conflics of Interest: No conflicts declared.

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