A NEW METHOD TO DETERMINE THE BIOMECHANICAL PROPERTIES OF HUMAN AND DUMMY JOINTS

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ABSTRACT

A new method has been developed to determine the essential biomechanical responses of human and dummy joints. Moment-angle characteristics are measured for a quasistatic input about a fixed or moving center of rotation. In the test, the joint angle is increased and the resulting moment, forces, and linear and rotational displacements are measured.

The moment-angle characteristics for a joint are assessed separately for flexion and extension, and the orientation of rotation can be in the medial, lateral or vertical axes. The method is used to determine joint characteristics (kinematics and biomechanics) for human foot-ankle joints within the natural and injury range of motion. Preliminary results of human ankle-subtalar are given for failure in inversion/eversion. Moment-angle responses for the Hybrid III neck and ankle are also presented.

The center of rotation was determined from the displacement of the reaction plate supporting the bottom aspect of the joint. For example, the center of rotation of the foot-ankle is confirmed as the center of the spherical joint in the Hybrid III dummy leg. More complicated joints have a moving center of rotation with joint rotation, as for the ankle-subtalar joints in inversion/eversion.

The moment-angle relation for the Hybrid III neck and ankle were determined using the input torque and the reaction moment and loads. These data are sufficient to estimate the accuracy of the method. The analysis showed that the reaction moment and load could reproduce the input torque to within 5% ($p < 0.05$). The Hybrid III neck was first tested in flexion and extension to 28°, and in lateral rotation to ± 13°. The input torque ranged up to - 17 Nm in extension, 40 Nm in flexion, - 25 Nm in right lateral and 25 Nm in left lateral rotation. The Hybrid III ankle was tested to - 35° in dorsiflexion, 45° in plantarflexion, and - 25° in inversion and eversion. There is no joint moment in the natural range of motion, - 30° in dorsiflexion, 40° in plantarflexion, - 20° in inversion and 20° in eversion. Beyond the natural range of motion, the moment increases rapidly.

The repeatability of the method was assessed by testing the Hybrid III ankle 5 times to 35° in plantarflexion and - 25° in dorsiflexion. The results are repeatable within 1% variability. The new method provides information on joint responses and kinematics, including the center of rotation for a quasistatic loading condition. The data is useful for future dummy development and mathematical modeling.

THERE HAS BEEN a long-standing need to accurately measure moment-angle relationships of joints and linkages. Measurement of the joint mechanics during the natural motion sequence can be complicated by a moving center of rotation. For example, Miller *et al.* (1980) developed a method to determine the moment-angle characteristics of joints; but, it is not able to apply a sufficient torque to study human joints with moving center of rotation beyond the natural range of motion and during injury. The accurate measurement of the human joint biomechanical characteristics is the first step in developing and validating more humanlike dummies and mathematical models. Using an apparatus built by General Motors operating under the basic principles of a quasi-static seat device (General Motors, 1994), a method has been developed to investigate the mechanical properties of joints in quasistatic conditions. The method measures the load-displacement characteristics of specimen joints in their natural range of motion and/or to failure. The method determines joint characteristics (kinematics and biomechanics) for human foot-ankle joints.

The experimental set-up consists of monitoring the linear and rotational displacements of joints as a quasi-statical linear increase in joint rotation is applied to one end of a specimen, and measuring the resultant forces and moments at the other end. From experimental data, the center of rotation and moment-angle characteristics of joints can be assessed for flexion and extension in the medial, lateral and coronal axes. The data are determined in the normal range of motion of the joint and/or to failure. The results obtained with the method can be used to better understand injury tolerance of any joint(s).

In this study, results for the Hybrid III neck, Hybrid III ankle and human foot-ankles are presented. The Hybrid III neck was tested in flexion/extension and in lateral rotation while the Hybrid III ankle was tested in dorsiflexion/plantarflexion and in inversion/eversion, and 16 foot-ankles tested to failure in inversion/eversion. Validation of the method was assessed by comparing results with known information (Deng, 1989) and determining equilibrium of responses based on redundant changes of data for each test. The repeatability of the method was assessed by testing the Hybrid III ankle 5 times.

MATERIAL AND METHOD

SPECIMEN PREPARATION: To assess the mechanical properties of a specimen, the two ends of the specimen are linked to an apparatus (Fig. 1). The bottom end of the specimen is secured within a fixation cup, and the top end is secured to a second fixation device.

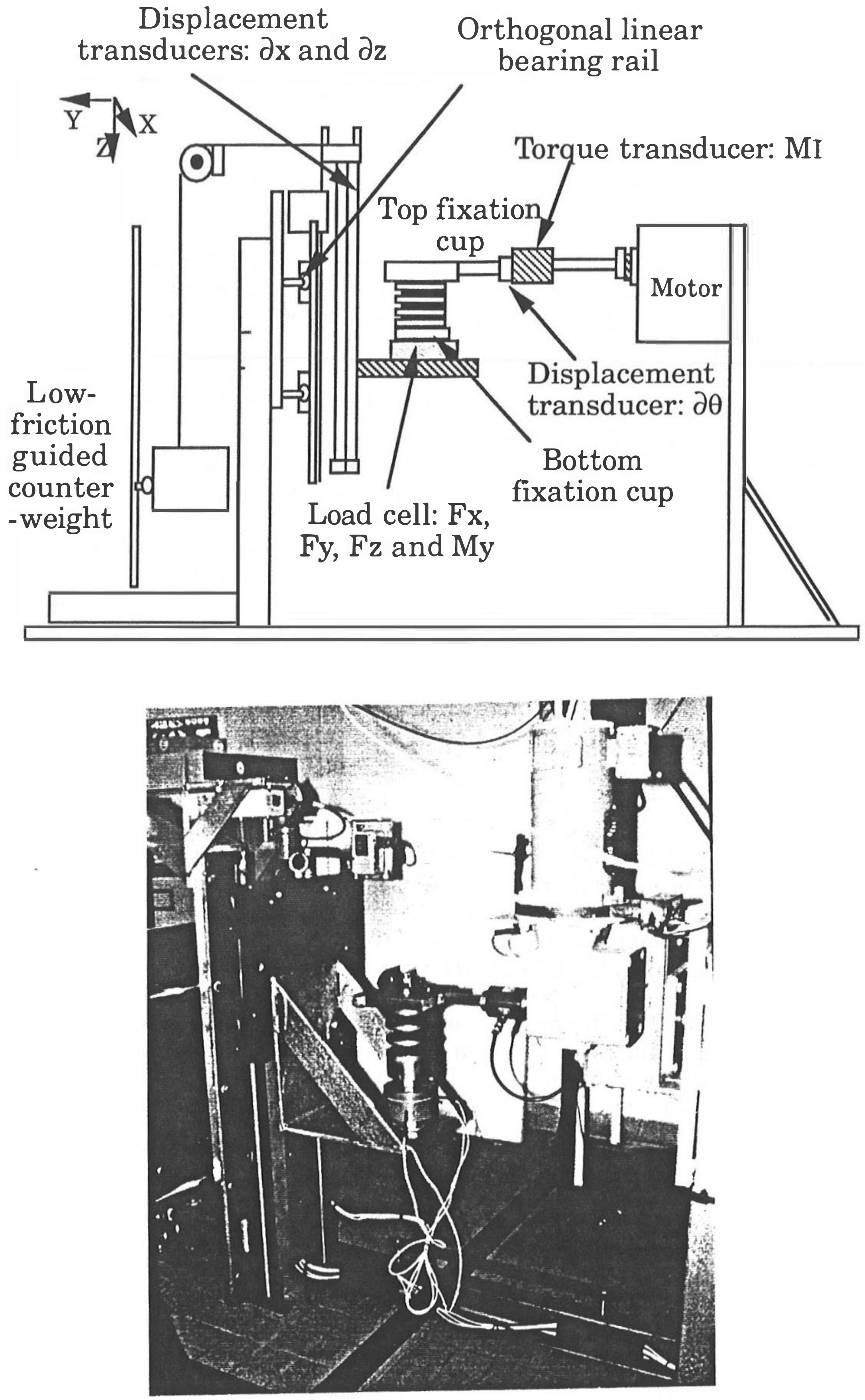

Figure 1. Test set-up with the apparatus and fixation devices for the Hybrid III neck.

EXPERIMENTAL SET-UP: Figure 1 shows the set-up used to determine the properties of the Hybrid III neck. The cup at the bottom of the neck is screwed into a load cell, and secured to a flat plate. The flat plate is connected to a guide rail where the moving mass is counterbalanced by an equal mass, reducing the additional load produced by the set-up. Orthogonal low friction rails are used to provide controlled, free motion of the joint in the X and Z direction. The degree of frictional forces were ± 15 N is the X-axis and ± 19 N in the Z-axis.

The top of the neck was loaded with an electric torque motor (BALDOR DC Motor) through a fixation device. The velocity of the input torque was constant at 6.1°/sec. The speed of the motor was controlled electronically.

Measurements were made on (1) the rotational displacement of the input torque shaft, θ; (2) input torque, M_I; (3) the resultant forces in the load cell, F_x, F_y and F_z; (4) the resultant moment in the load cell, M_y; and (5) the linear displacement X and Z plane, along the medial and coronal axis respectively. In this study, electronic data was amplified (8 Channel Universal Amplifier 8MV1, module V, Johne + Reilhofer). The amplifier was connected to a personal computer via an interface board. The data was recorded at 100 Hz sampling frequency with a computer software, (LABVIEW, National Instruments).

INSTRUMENTATION: Three orthogonal forces (F_x, F_y and F_z) and one moment (M_y) acting at the fixed end of the specimen were recorded with a 4 channel load cell (RS Technologies, model 066204-00202). Two linear potentiometers (Celesco, PT101) were used to record the displacement of the specimen base in X and Z directions with an accuracy of 0.1% and a resolution of 0.03 mm. The rotation of the fixed fixation cup was calculated from the rotational displacement of the motor shaft. A linear potentiometer (TME, PV 75 A, model 040-5057) was wrapped 3 times around the motor shaft to measure the rotational displacement. The input torque was measured with a strain gage socket torque sensor (RS Technologies, model 071075-00301).

ANALYSIS: The purpose of this study was to measure the moment-angle characteristics of any joint(s) at its (their) natural (and possibly moving) center of rotation. The moment-angle characteristics can, however, be determined at any other point with the results obtained from the experiment.

Center of Rotation (CR) - To assess the center of rotation (CR), the trajectory of the bottom end of the specimen must first be determined. The trajectory of the bottom end corresponds to the plot of the medial versus coronal linear displacements, ∂z vs ∂x. As smoothing was needed, mathematical curve fits were used on the linear displacements as a function of joint rotation (delta x(θ) and delta z(θ)). Minor disturbances in the displacement were related to friction in the linear bearing and the need to overcome up to 20 N resistance.

The linear displacement curve, delta z(θ) vs delta x(θ), represents the smooth trajectory of the bottom end of the specimen. As the rotation is known at each point along the trajectory, (delta x(θ); delta z(θ)), equations of lines were formed as a function of X and Z:

$$(Z\text{-delta } z) = m^*(X\text{-delta } x) \quad (1)$$

where m is the slope equal to the inverse tangent of the angle, $(\tan\theta)^{-1}$.

The CR for motion between two angles was estimated by the intersection between two consecutive lines. The center of rotation (X_{cr}, Z_{cr}) was calculated at each Δ interval using the following equations:

$$X_{cr}(\theta) = [(Z_{cr}(\theta)\text{- delta } z(\theta)) / m(\theta)] + \text{delta } x(\theta) \quad (2)$$

$$Z_{cr}(\theta) = [m(\theta+\Delta)^*\text{delta } z(\theta) - m(\theta)^*\text{delta } z(\theta+\Delta) + m(\theta+\Delta)*m(q)*(\text{delta } x(\theta+\Delta)\text{-delta } x(\theta))] / (m(\theta+\Delta)\text{- } m(\theta)) \quad (3)$$

<u>Moment-Angle</u> - The moment at any point in the specimen, can be estimated using the following equilibrium equations:

$$\Sigma M = \Sigma M_1 + r_{3\text{-}1} X \, \Sigma F_1 \quad (4a)$$
$$\Sigma M = \Sigma M_2 + r_{3\text{-}2} X \, \Sigma F_2 \quad (4b)$$

where the moment and force are the vectors with x, y and z components, and 1 represents the torque transducer (M_I), 2 the load cell, 3 an arbitrary point, and r is the distance between two points. Because of equilibrium, F_1 equals F_2. In the equations, $r_{3\text{-}1}$ is the distance between the torque transducer and a given point, and $r_{3\text{-}2}$ is the distance between the load cell and the point. The accuracy of the results was estimated by comparing the moments at a given point, calculated using equations 4a and 4b.

VALIDATION OF THE SET-UP AND ANALYSIS: The validity of the method was assessed. First, the center of rotation of the Hybrid III ankle was determined and compared with its known center of rotation. Secondly, the Hybrid III neck was tested to 28° in both extension and flexion, simulating the experiment by Deng (1989). The moment-angle characteristics were compared. The neck used in the experiment consists of five circular disks connected by rubber material and a cable in the center. The neck was compressed with a 1.3 Nm pre-load moment on the inner cable.

The validity of the set-up was also determined by comparing the two moments at the input torque shaft, one estimated with equation 4a and the other with 4b. In this case, $r_{3\text{-}1}$ is the distance between the input torque shaft and the input torque transducer, equal to 0 mm in all axis directions and at any rotational displacement, and $r_{3\text{-}2}$ is the distance between the input torque shaft and the load cell, initially at 0 mm in the medial and horizontal axis, and at 186 mm in the coronal axis. $r_{3\text{-}2}$ varies as a function of joint rotation.

The moment at the input torque shaft is directly measured and can be independently computed:

Flexion:

$M_I(\theta) = M_1$ (4a)

$M_I(\theta) = M_I(\theta)\ M_y(\theta) + F_x(\theta)*(0.186\text{-delta } z(\theta))\text{-}Fz(\theta)*(0\text{+delta } x(\theta)$ (4b)

Extension:

$M_I(\theta) = M_1$ (4a)

$M_I(\theta) = M_y(\theta) + F_x(\theta)*(0.186\text{-delta } z(\theta))\text{-}Fz(\theta)*(0\text{-delta } x(\theta))$ (4b)

REPEATABILITY: The repeatability of the equipment was assessed using the Hybrid III foot. The Hybrid III foot has been tested 5 times in 35° plantarflexion and - 25° dorsiflexion. An average of displacement characteristics of the foot was calculated with standard deviation.

RESULTS

CENTER OF ROTATION: The CR was determined in the Hybrid III ankle. It corresponds to the center of the dummy spherical joint (Fig. 2). The CR was at an average 62 mm vertical distance from the input torque shaft in the saggital plane and 61 mm in the lateral plane respectively (Table 1). The center of rotation was also determined in the Hybrid III neck. Figure 3 shows the CR of the dummy in flexion/extension and in lateral motion. The CR was at an average 57-58 mm from the input torque shaft (Table 1).

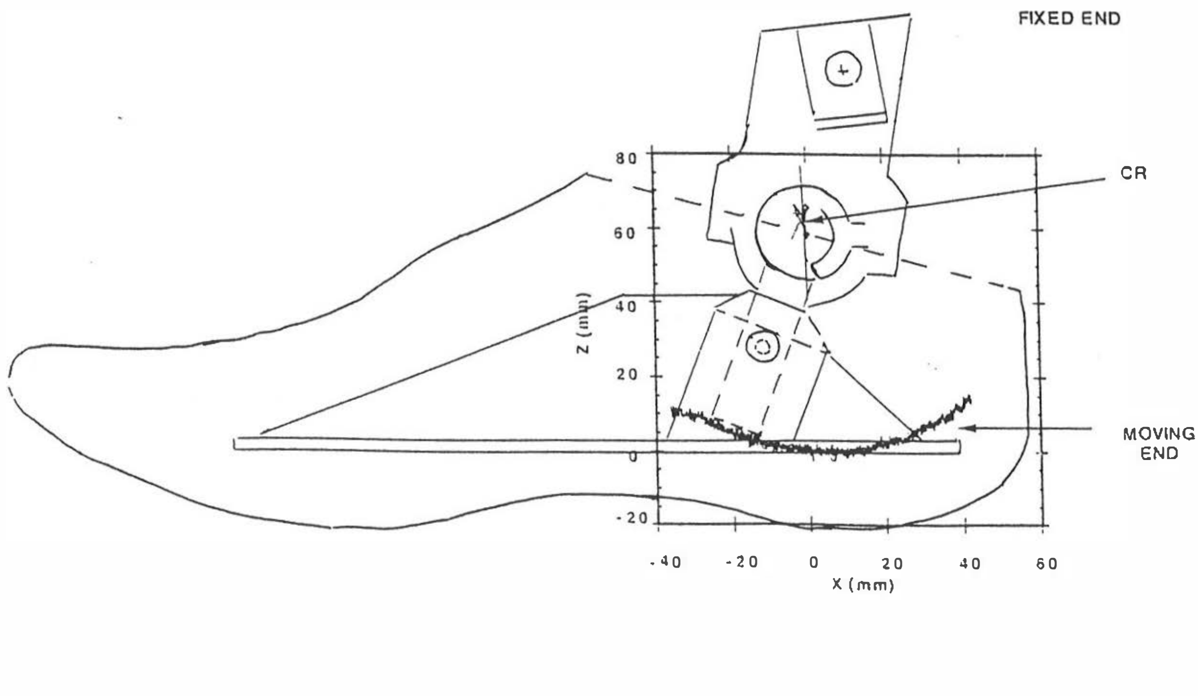

Figure 2. Kinematics and center of rotation of the Hybrid III ankle

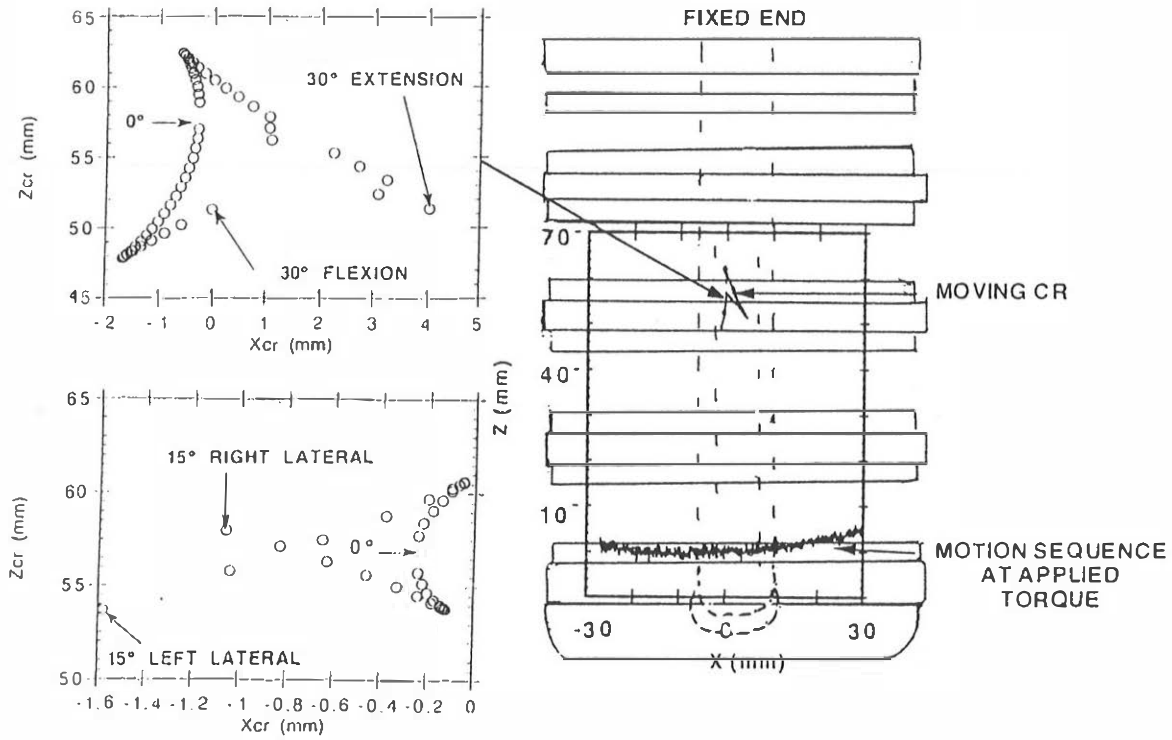

Figure 3. Kinematics and center of rotation of the Hybrid III neck

Table 1. Distance between the input torque shaft and the center of rotation

	Saggital plane	Lateral Plane
Hybrid III ankle	(0; 62) mm	(0; 61) mm
Hybrid III neck	(0; 58) mm	(0; 57) mm
Human ankle-subtalar joints	-	(2; 50) mm

Figure 4 shows the average CR of human foot-ankles in inversion/eversion. It varies with the rotational displacement, $\partial\theta$. However, since the calculated moments at a fixed and at the moving CR were similar, the center of rotation was assumed to be fixed in this study. The CR was at an average 2 mm and 50 mm in the lateral and vertical axis respectively from the input torque shaft (X_{cr} = 2; Z_{cr} = 50 in Table 1), corresponding to the location of the subtalar joint.

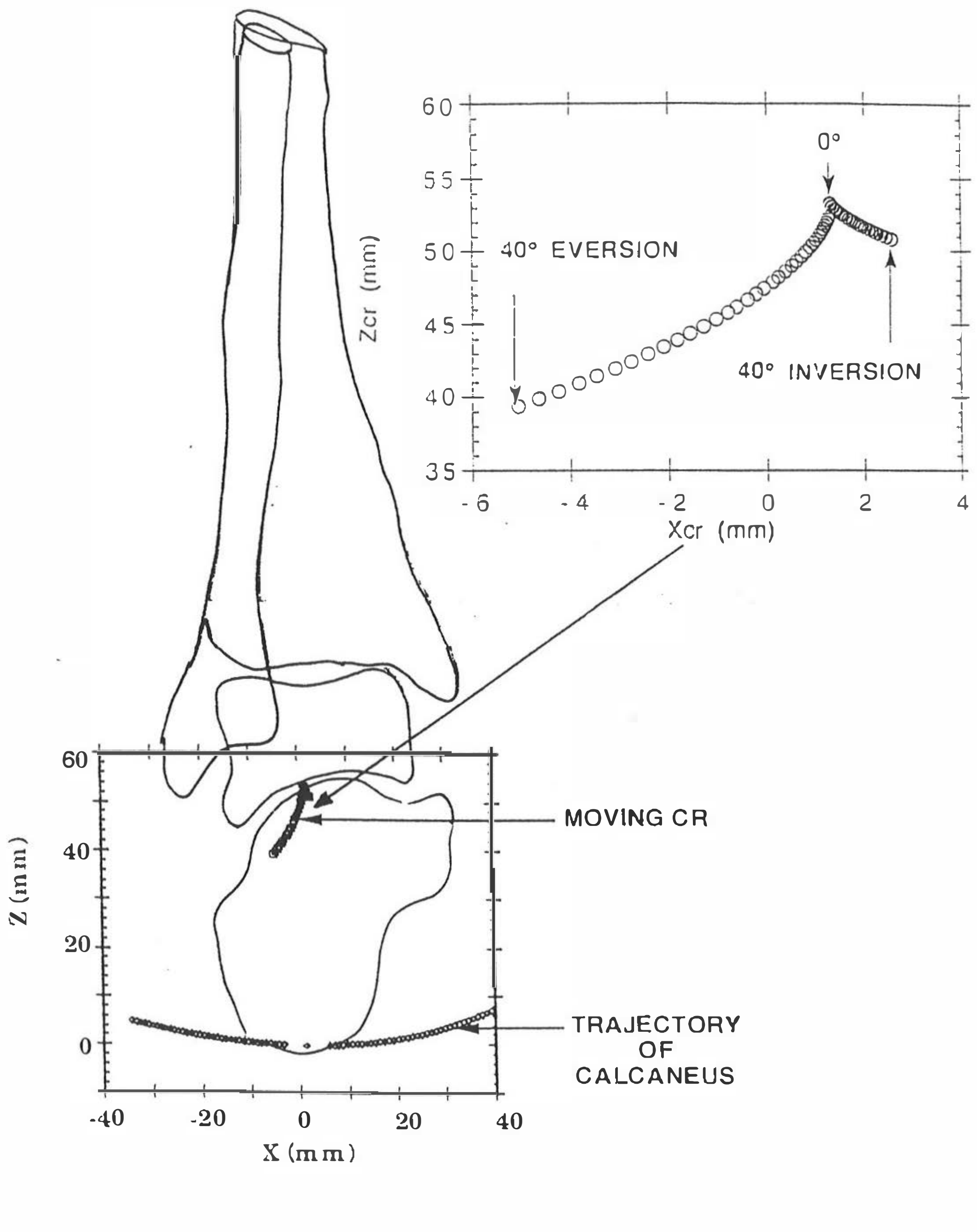

Figure 4. Kinematics and center of rotation of the ankle-subtalar joints in inversion/eversion.

MOMENT-ANGLE: The moment-angle of the Hybrid III ankle was determined at the fixed center of rotation in dorsiflexion/plantarflexion and in inversion/eversion. As seen in Figure 5, the range of motion of the Hybrid III foot is 0 to - 33° and 0 to 43° in dorsiflexion and plantarflexion respectively. The range of motion is lower in lateral plane, from 0 to ± 24° in both inversion and eversion. Beyond the maxima, the moment rapidly increases at 20 Nm/degree in dorsiflexion and 12 Nm/degree in plantarflexion.

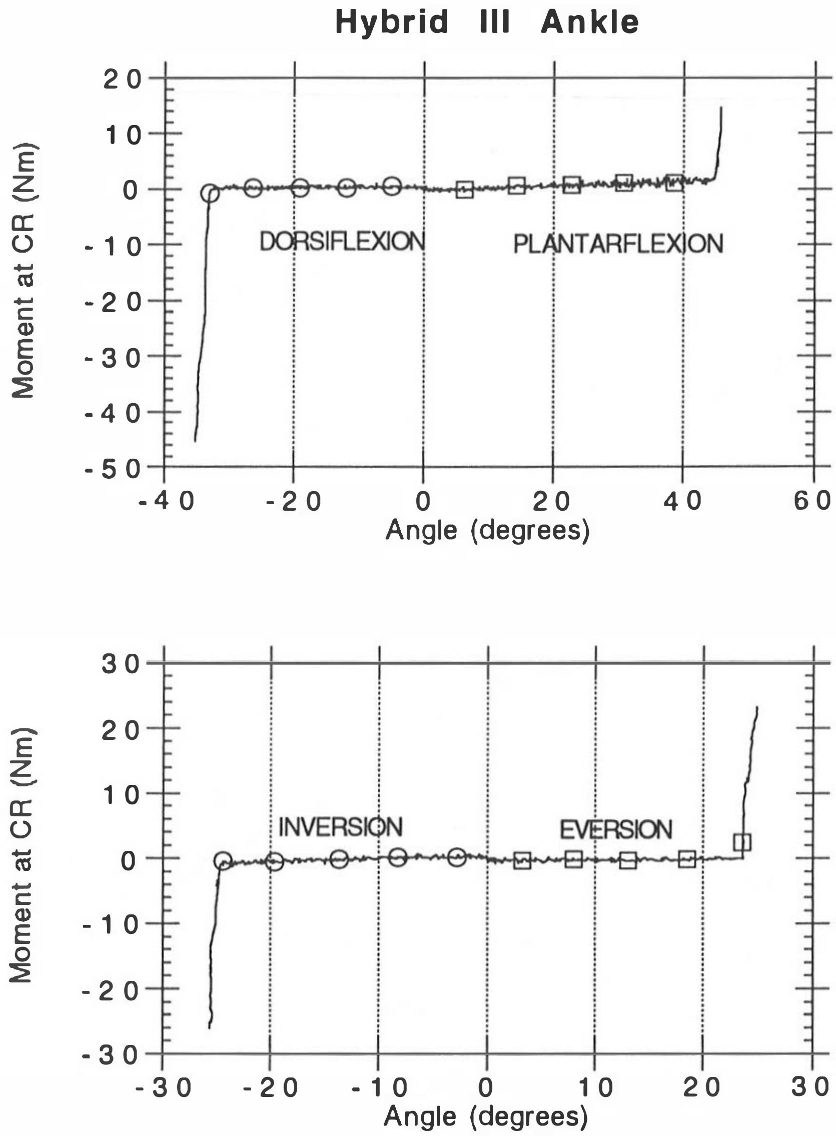

Figure 5. Moment-angle characteristics of the Hybrid III ankle in dorsiflexion/plantarflexion and inversion/eversion.

Figure 6 shows moment-angle characteristics of the Hybrid III neck. The data was determined at a fixed center of rotation (Table 1). The neck was tested to ± 28° in flexion/extension, and to ± 13° in inversion/eversion. The moment reaches 40 Nm in flexion and -17 Nm in extension. The moment reaches ± 25 Nm at 13° lateral motion.

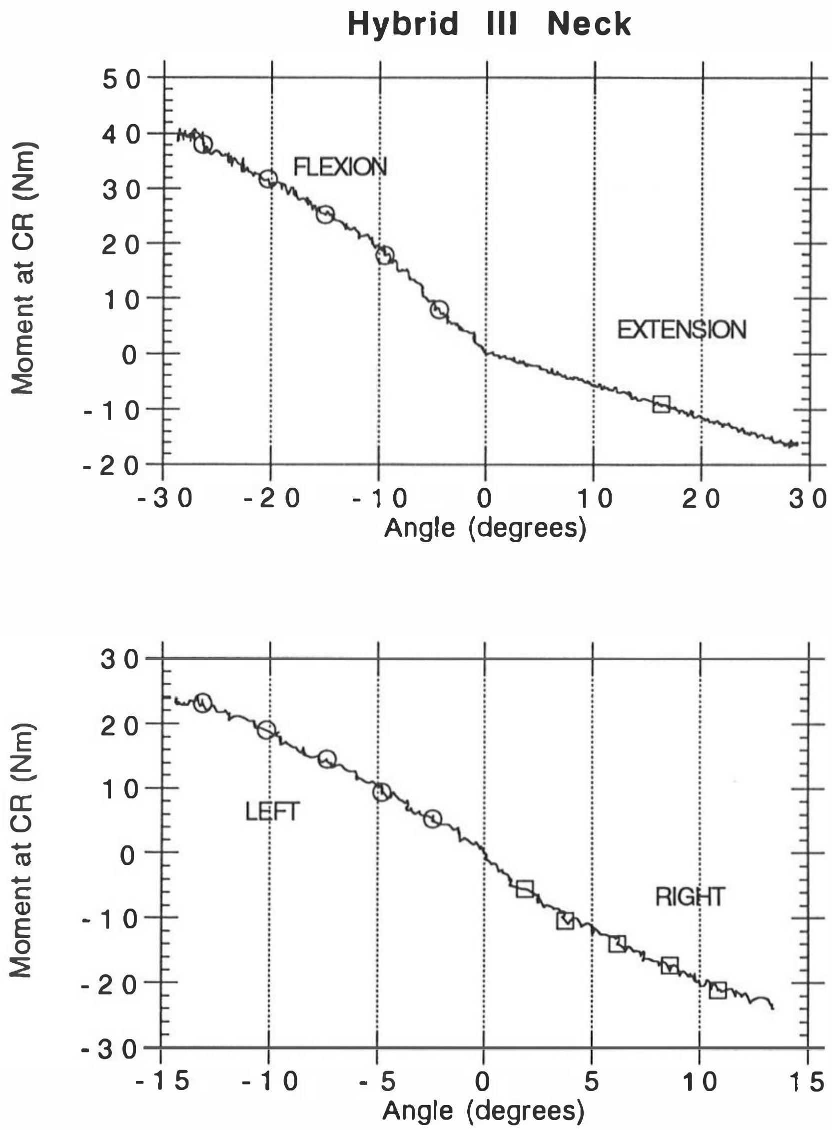

Figure 6. Moment-angle characteristics of the Hybrid III neck in flexion/extension and right/left lateral motion.

Figure 7 represents the inversion/eversion moment-angle characteristics of the human ankle-subtalar joints, determined at a fixed center of rotation. The moment-angle is maximum at - 33 Nm and - 37° in inversion, and 45 Nm and 35° in eversion

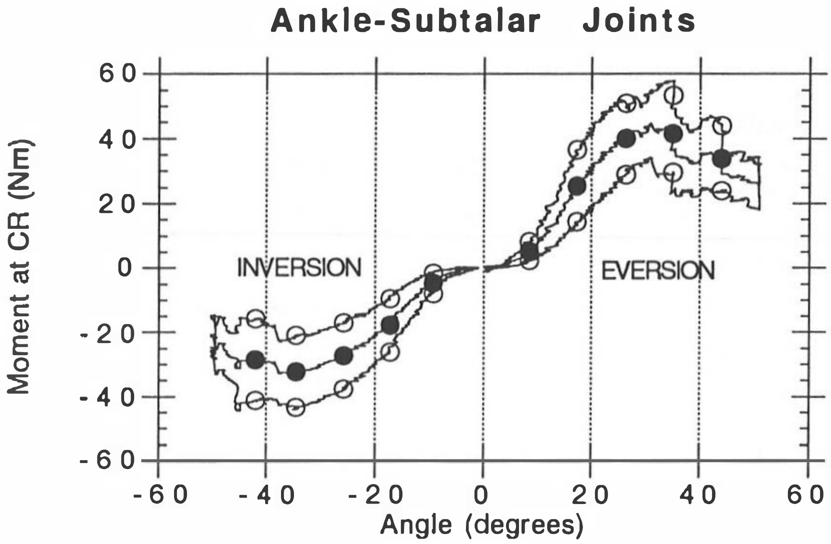

Figure 7. Average moment-angle characteristics at the center of rotation of the ankle-subtalar joints with ± one standard deviation.

VALIDITY: The moment-angle relationship of the neck was compared to Figure 6 of Deng (1989), and was similar ($p < 0.05$) . The flexion/extension input torque-angle characteristics of the Hybrid III neck are presented in Figure 8.

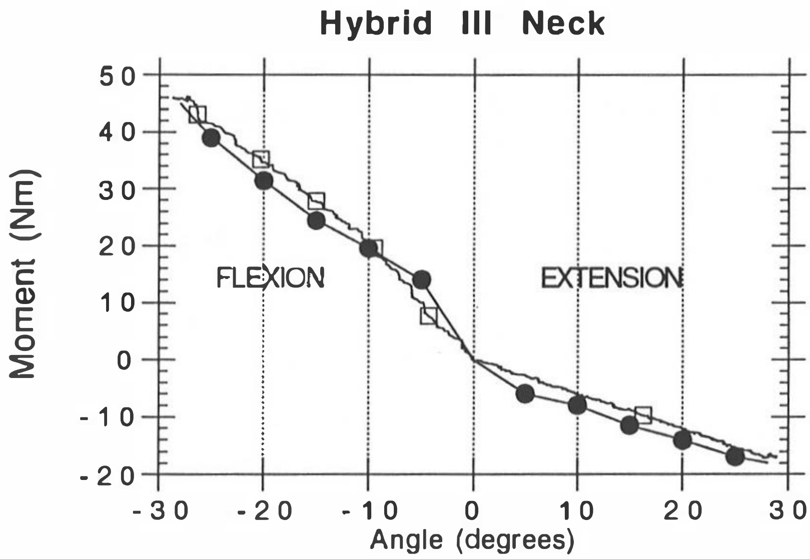

Figure 8. Comparison of the current test results (squares) and Deng's data (circles) for flexion/extension of the Hybrid III neck.

Figure 9 shows the input torque as a function of Hybrid III ankle and neck rotation. The input torque was determined from the input torque transducer and the load cell. The results were similar ($p<0.01$) in the Hybrid III leg. Results were also similar in the Hybrid III neck, up to 28° extension. In the flexion test, the torque was higher when measured with the torque transducer, 46 Nm at - 27°, than when calculated from load cell data, 41 Nm at - 27°. Overall, the method has an accuracy of more than 92%.

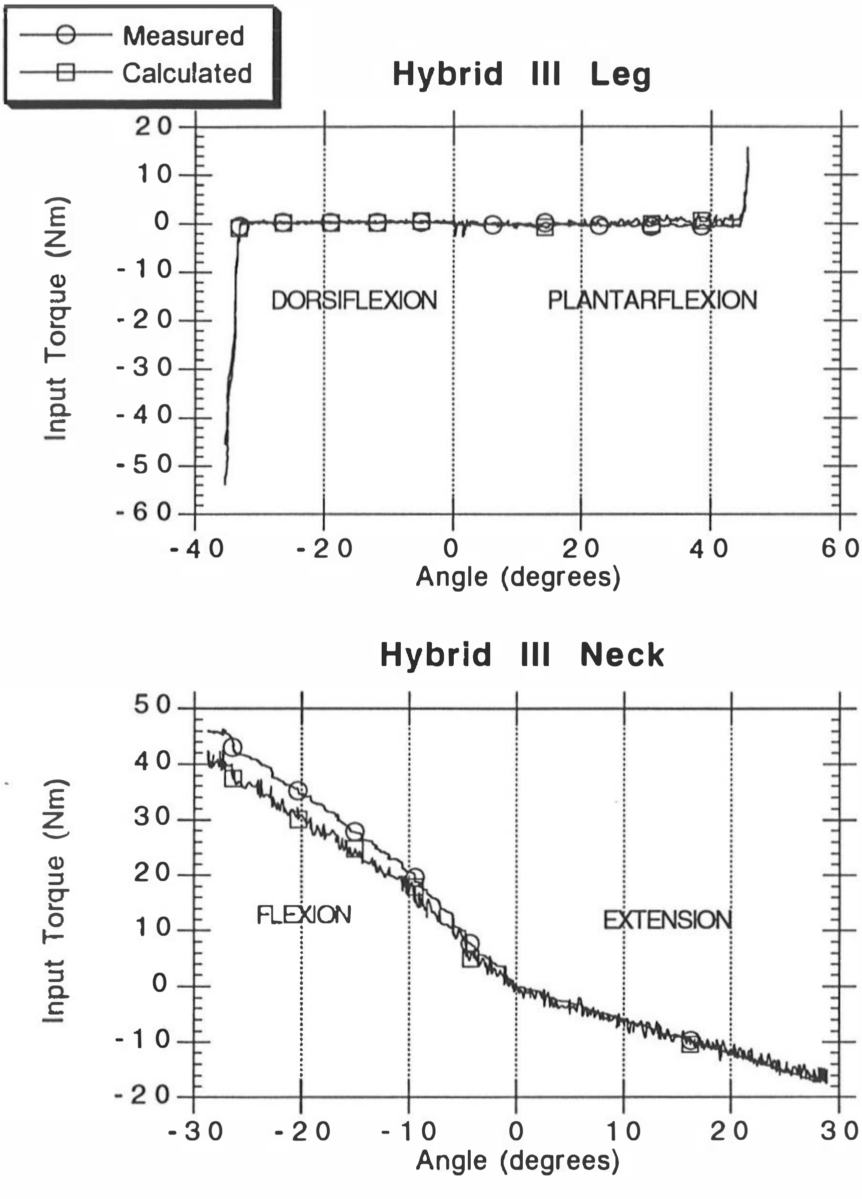

Figure 9. Comparison of the moment-angle characteristics at input torque shaft for the Hybrid III leg (upper) and neck (lower).

REPEATABILITY: The Hybrid III foot has been tested 5 times in 35° plantarflexion and - 25° dorsiflexion. The results of the lateral linear displacement-angle characteristics of the five tests are presented in Figure 10. The linear displacement varies from - 33 mm to 25 mm in all tests. The tests were reproducible with a 99% accuracy.

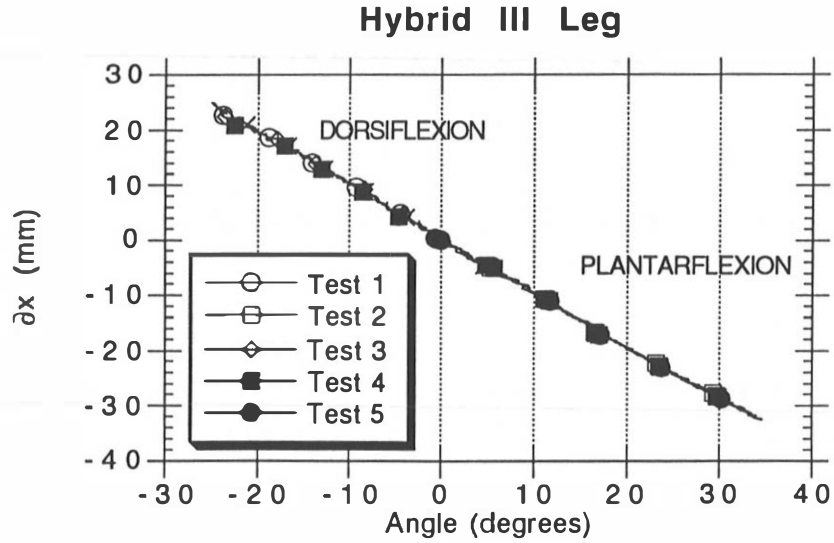

Figure 10. Linear displacement characteristics of the Hybrid III foot tested 5 times in 35° plantarflexion/ - 25° dorsiflexion.

DISCUSSION

A method was developed and validated to investigate the mechanical properties of joints. The method determines the moment-angle characteristics of dummy or human joints tested to failure in a quasi-static loading. In this study, the results of the Hybrid III ankle and neck, and 16 foot-ankles have been examined. The center of rotation of the Hybrid III ankle was determined and confirmed as the center of the dummy spherical joint. The moving center of rotation of the human ankle-subtalar joints is in the subtalar joint, adding to the fact that the subtalar joint influences the kinematics of the foot-ankle in inversion/eversion (Grant, 1952).

The Hybrid III neck was tested in flexion and extension, and the moment-angle characteristics of the neck were similar to literature data (Deng, 1989). The validity of the method was determined by comparing results of two transducers. The moment at a fixed point was determined using the torque transducer and the load cell, and the results were similar with a 92% accuracy. Testing was repeatable at an accuracy of 99%.

The mechanical properties of dummy or human joints can be investigated with accuracy using the best method described in this study. The moving center of rotation can also be determined. The data obtained with the method is useful for dummy development and mathematical modeling.

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