Development of an Empirically based Dynamic Biomechanical Strength Model.

A. Pandya(1), J. Maida (2), A. Aldridge(1), S. Hasson(3),
B. Woolford(2)

(1) Lockheed Engineering and Sciences Company, Houston, Tx.

(2) NASA-JSC, Houston, Tx.

(3) Texas Womens Univesity, Houston, Tx.

Abstract:
Computer aided engineering (CAE) is commonly used in many aspects of aerospace engineering. Extensions and enhancements of these useful tools of analysis are now beginning to be applied to the complex area of human modeling. The overall goals of such systems include analyses of the performance capabilities of a given individual or population in a specific environment. This is a multifaceted problem. The issues of anthropometric representations, kinematic articulation of joints (reach), vision, and strength are just a few examples of the areas of complexity involved. The focus of this report is on the development of a dynamic strength model for humans.

Unlike earlier attempts at strength modeling, which were based on rotational spring and damper systems, our model is based on empirical data. The shoulder, elbow, and wrist joints are characterized in terms of maximum isolated torque, position and velocity in all rotational planes. This information is reduced by a least squares regression technique into a table of single variable second degree polynomial equations determining torque as a function of position and velocity. The isolated joint torque equations are then used to compute forces resulting from a composite motion-- which, in this case, is a ratchet wrench push and pull operation. What is presented here is a comparison of the computed or predicted results of the model with the actual measured values for the composite motion.

Introduction:

Computer aided engineering (CAE) analysis tools are being applied to a wide variety of applications from light and sound raytracing, heat transfer models to finite element analysis of structures. The techniques of CAE are now beginning to be applied to the issues involved in human modeling (strength, vision, and reach analysis). What is presented here is a dynamic human strength model.

A dynamic strength model could be used to assess and predict whether a person or population is capable of performing a physical task on the job. This is important in the case of space Extra Vehicular Activities (EVA) where crew members need to handle massive structures such as satellites and various space assembly components. In these situations, mission planners would benefit from a simulation model of all the forces, torques and accelerations that would be imposed by and imposed on the crew member.

Equipment design engineers could also benefit from a strength model. Design specifications can be enhanced if engineers could predict the forces and torques to be applied on or with a given piece of equipment. These applications include, for example, threshold torques needed to open hatches and doors and to operate tools needed for assembly or to determine maximum forces applied to ensure that the equipment will not be damaged. Equipment may be better designed if information on the strength of the user population were available.

Equipment placement designs and scenarios may also be enhanced. Questions like "What is the best configuration for this body restraint relative to this tool for maximum strength?" or "Where should this hand hold be placed for the most efficient strength utilization?" could be better answered by the systematic examination of many possibilities and scenarios with the goal of defining more comfortable and safer designs.

Lastly, a strength model is useful as a tool of study to achieve a greater understanding of how the musculoskeletal system functions, of how the torques and forces are propagated, and of what the system control mechanisms and parameters are. This knowledge may lead to, for instance, better designs of robotic and manipulator systems of the future.

Our objective is to develop and validate a human dynamic strength model using empirical data.

Method:

Data collection:

The data collection effort occured over an eight week period. There were fourteen subjects, eight males and six females, ranging in ages from 21 to 28 years. Each subject was tested isokinetically for isolated upper extremity motion (shoulder, elbow, wrist) at four velocities (60, 120, 180, 240 deg/sec) and then tested with a simulated ratchet wrench maneuver at two velocities (120, 240 deg/sec).

The general procedure for evaluating all the upper extremity joint movements was the same. Torque was measured by using a Lido multi-joint testing unit (Loredan Biomedical, Inc., Davis, CA. see figure 1). The subjects

were positioned so that the axis of the joint was directly in-line with the axis of the dynamometer goniometer. Dynamometer attachments were selected and placed in order to isolate the joint being measured. The subject was positioned on the instrument and maximally stabilized with the joint positioned at a specified initial condition. The subject was then instructed to give a maximum effort for each of five repetitions and informed to move the isolated joint through the entire range of motion. A three minute recovery period was taken before each change in velocity setting. The axes of motion measured were the shoulder flexion-extension, shoulder medial-lateral rotation, shoulder abduction- adduction, elbow flexion-extension, wrist flexion-extension, wrist radial-ulnar deviation, wrist supination-pronation. The setups for these motions are described in the Lido multi-joint testing manuals.

For the multi-joint test, a ratchet wrench maneuver, the subject was stabilized with velcro straps at the waist and across the chest. The subject gripped a simulated ratchet device at a height of 90% of the linear distance measured from the subjects greater trochanter to the acromio-clavicular joint. The range of motion for the ratchet bar was between 45 and 50 degrees. To minimize the motion of the upper extremity, the subject extended the elbow and shoulder fully forward without bending at the waist. This test was also a maximum torque effort of five repetitions with a three minute recovery period before each change in the velocity settings (120, 240 deg/sec).

The anthropometric data which was collected included height, weight, age, sex, skinfold measures and dimensional assessment. The anthropometric data format is documented in NASA's Man Systems Integration Standards (MSIS) document (NASA-STD-3000) [6]. The standard was also used to provide the joint limit information. Joint limits for the model were applied statistically as this information was not collected in our study.

Figure 1 Loredane Inc., Lido multi joint testing system.

Data reduction:

The data was collected using the Loredan software, "Lido Active 3.3", executing on an IBM PC. For all cases, the data set consisted of torque and angle pairs. The data was uploaded to a graphics workstation (Silicon Graphics), formatted into an ASCII file, noise filtered, reformatted to aid the polynomial coefficient calculation and reduced to a table of coefficients of second degree polynomials. The polynomials coefficients were computed using a least squares regression method. The polynomial represents the torque as a function of angle. For each joint, the complete model input format consisted of the name of the joint, the axis of rotation, the direction of rotation, the number of polynomials and the list of the calculated torque polynomial coefficients for each velocity (one polynomial per velocity). The modeling program builds its internal lookup tables from this data organization (see Figure 2) .

elbow

```
y
extension
4
60.000000      6.281160  0.069170   0.003640
120.000000     3.587850  0.293850  -0.000580
180.000000    -1.247410  0.618840  -0.006430
240.000000   -11.244930  0.972970  -0.01040
y
flexion
4
60.000000     16.040550  0.304760  -0.000910
120.000000    15.216640  0.239190   0.000350
180.000000    16.851919  0.162090   0.000010
240.000000     8.983800  0.513420  -0.005050
```

Figure 2- Example input file for strength model derived from collected data for elbow for one subject.

In addition, the anthropometric data collected for each of the subjects is processed by the modeling program into a geometric human model. The specific anthropometry is necessary in order to properly convert the torques to forces for a particular individual. The human model is then made into a fully articulated human representation with proper segmentation of the body parts and statistically determined joint limits.

Environment setup:

Each individual was created in the graphics environment using that individual's anthropometric data. The initial conditions of the ratcheting operation were set to match, as closely as possible, the actual conditions. This was a critical step for validation. The main parameters of the initial conditions included the initial and final joint angles for the ratcheting motion, the distance of the hip from the rotation point of the ratchet axis and the height of the end-effector on the ratchet. Using the graphics environment, all these initial conditions were set for each individual prior to the execution of the computer simulation of the ratchet operation (figure 4).

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Torque vector calculation.

Each joint of the upper extremity was associated with a table of polynomial coefficients describing its dynamic torque production potential [9] (figure 2). In the modeling process, the tables were loaded into computer memory for use by a table lookup module. When a joint motion occured in our test case, the axis of motion, the direction of motion, angle of motion and speed of motion were mapped to the appropriate polynomial and a torque value returned.

Since each axis of rotation for a particular joint is perpendicular to each other axis for that joint, the square root of the sum of the squares was used to determine the available torque for each joint involved in that motion.

$$Ts = sqrt(tx \cdot tx + ty \cdot ty + tz \cdot tz)$$

where

Ts = total torque for shoulder
tx = torque for x axis
ty = torque for y axis
tz = torque for z axis

The torque values at the other joints were similarly calculated.

For each joint, the lever arm to the point of application of the force, in this case the palm, was determined. This is the Euclidean distance from the location of the center of rotation of that joint to the end-effector location. The torque values for each of the joints were converted into forces at the end-effector by dividing out the respective lever arm lengths (Ls, Le, Lw).

Fs = Ts / Ls
Fe = Te / Le
Fw = Tw / Lw

The force values were then applied to the respective direction vectors of rotation and vectorially added to produce the total end-effector force Ft. Ft represents the total force at the end-effector from the contributions of all joints in the chain. Ft is also perpendicular to the lever arm. The direction of Ft was calculated by taking the cross product of the current lever arm with the previous lever arm and then crossing the resultant with the current lever arm. This calculation was performed at each iteration for each joint.

For the test case the force vector <Ft> needed to be resolved to a torque value at the ratchet axis. This was done by first projecting the force vector <Ft> onto the normalized direction vector of rotation <Rt> for the ratchet bar yielding a vector <Fproj> in the direction of rotation of the ratchet bar with a magnitude representing the force applied in that direction. This force was then multiplied by the lever arm length (Lr) of the ratchet, the distance from the point of rotation to the point of application, yielding a torque value (Tr). This torque value and the current angle of rotation of the ratchet bar were written to a file. In addition, the force vector <Ft> and the force vector <Fproj> were graphically displayed. (see figure 3)
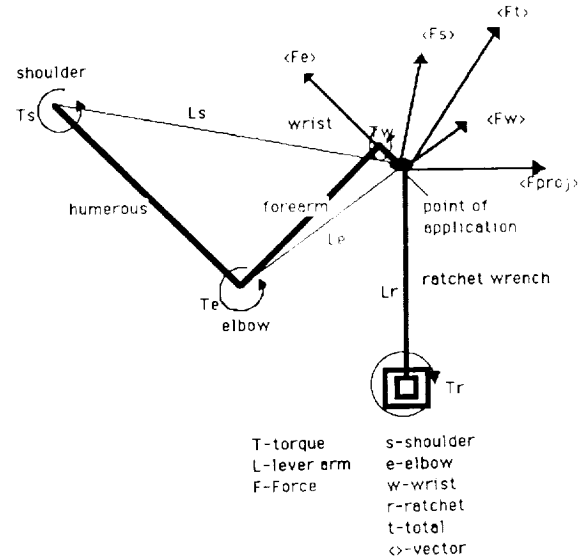

Figure 3- Diagram illustrating the force vector propagation.

Modeling the motion (Inverse kinematics):

To model the reaching characteristic of the arm while operating the ratchet bar, an inverse kinematics algorithm was needed to solve the joint angles of the arm [2,7] . Also, the human model with its corresponding anthropometry needed to be accessible to the force modeling software in order to integrate the torque functions with the motion of the arm. A software package named JACK [1], developed at the University of Pennsylvania, was used as a platform for our strength model. Although many enhancements and modifications were required, the underlying inverse kinematics and anthropomerics implementation permitted us to model the required motion.

The simulation of the ratchet bar motion consisted of the following sequence of events.

1) The parameters of the motion (start angle, end angle, steps to take, and the velocity of the ratchet) were input.

2) Time sequence information was computed which satisfied all the conditions of the ratchet's motion.

3) The location of the joint chain forming the arm and the location of the point of application on the ratchet bar were graphically selected.

4) Using the joint chain information, the torque functions for each component of the arm were loaded into the force model for use during the iterations of the ratchet operations.

5) The ratchet was moved to its initial or next position and the inverse kinematic module invoked to grasp the point of application on the ratchet with the specified end-effector (palm) in the joint chain.

6) The state of all the components of the arm, the joint angles of the arm and the state of the ratchet were extracted and input to the force model where the torque prediction was computed and written to an output file.

7) Steps 4 and 5 were repeated until five iterations of pushing and pulling were performed (See figure 4) .
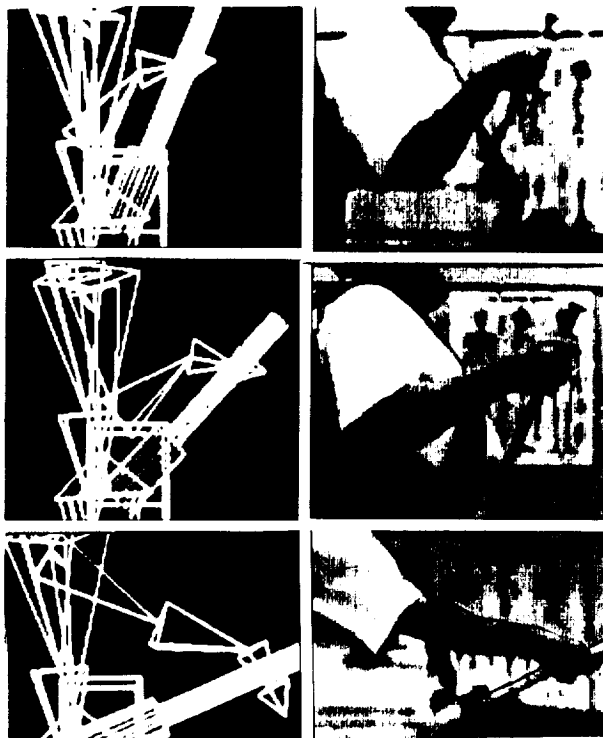
Figure 4 Comparison of actual vs. modeled ratchet wrench motion.

In order to validate the reaching motion calculated by the inverse kinematics algorithm, a real time magnetic tracking system was devised for input into the algorithm. The tracking system consisted of a Polhemus isotrack magnetic tracker connected to a Silicon Graphics Workstation. The magnetic tracker was linked to the end-effector of the man model representation. As the tracker was moved in space by a person, it fed the position and orientation information of the person's end-effector to the inverse kinematics algorithm. This information was then used to simulate the motion of the person's arm in the
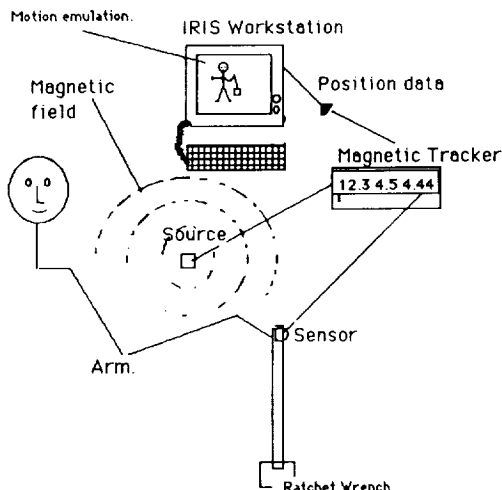
computer model. The tracker of the Polhemus device was attached to a bar which could be rotated the same way the ratchet bar was rotated. Comparison by visual inspection of the actual motion of a person's arm performing a ratcheting operation with the graphically emulated motion computed by the inverse kinematics algorithm showed a strong correspondence. (see figure 5)

Analysis of data:

All the subjects were run in the graphics environment with initial conditions and orientations closely matched to the actual runs. (See Figure 4) The ratcheting was modeled at the same velocities as the measured data (120, 240 deg/sec). Output from the model were files of torque vs. angle pairs in the same range of angle values as the measured ones. For both the model output data as well as the measured ratcheting data, the average torque produced and the total work done per iteration was computed. This data was the basis of the validation of the model. Statistical analysis was done in two forms, pairwise T tests and regression analysis[8,9]. Software was written to do these tests in an automated way without user intervention.

For the T test, the measured vs. model files of the averages and total work done over all subjects were read and a difference vector is created. This difference vector is the basis of the T test comparison. Our hypothesis is that there is no difference between the means and the work between the model and the measured values. That is, assume

ud (difference) = u(model) - u (measured)
(where u is the average and the work done for each subject).

Ho : ud = 0   (u (model) = u (measured)).
H1 : ud <> 0   (u (model) <>u (measured)).

Hence the decision rule is reject Ho if
T(computed from the data) < The critical value 2.46 (alpha = .01).

The regression test was simply a way to gage the correlation between the actual and measured values. We plotted the model average vs the measured average for all subjects and did a linear regression on that data set. The same analysis was done on model vs measured work.

In addition to the above analysis, plots of actual vs measured raw torque values were also produced.

Results:

Figure 6 and 7 are regression plots of model vs measured averages (figure 6) and total work (figure 7). The correlation values (r = 0.854, and 0.842) indicate a strong relationship between measured and model values. This result indicates that the model can be used as a good predictor of the ratchet wrench torque produced when the model vs. measured values are compared for the entire subject pool in terms of the average torque produced and the total work done.
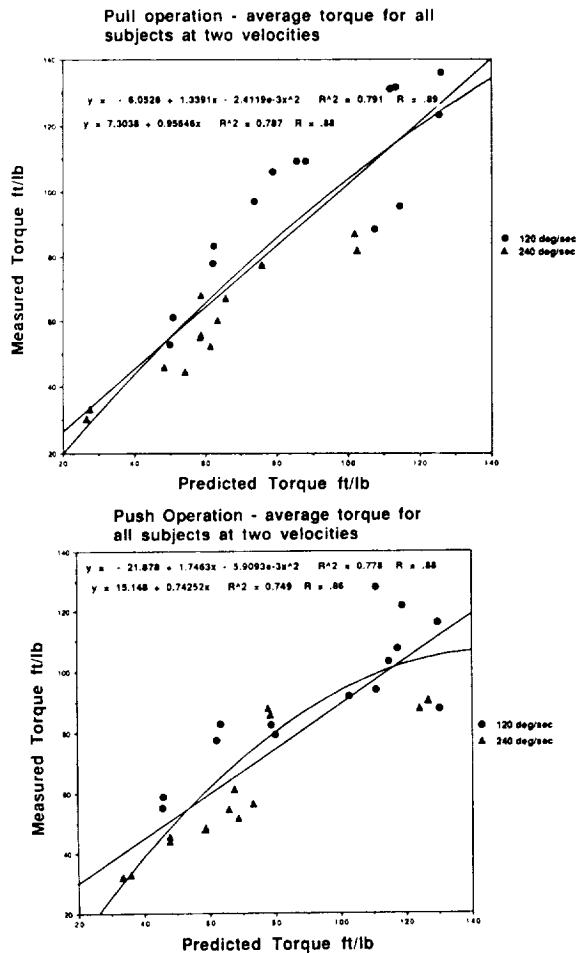

Figure 5. - Magnetic tracking setup.

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Pull operation - average torque for all subjects at two velocities

$y = -6.0526 + 1.3391x - 2.4119e-3x^2$ $R^2 = 0.791$ $R = .89$

$y = 7.3038 + 0.95646x$ $R^2 = 0.787$ $R = .88$

Measured Torque ft/lb

● 120 deg/sec
▲ 240 deg/sec

Predicted Torque ft/lb

Push Operation - average torque for all subjects at two velocities

$y = -21.878 + 1.7463x - 5.9093e-3x^2$ $R^2 = 0.778$ $R = .88$

$y = 15.148 + 0.74252x$ $R^2 = 0.749$ $R = .86$

Measured Torque ft/lb

● 120 deg/sec
▲ 240 deg/sec

Predicted Torque ft/lb

Figure 6 - Model vs measured average torque produced for the ratchet wrench motion.

Pull operation - predicted vs measured work for two velocities

$y = 709.39 + 0.83288x$ $R^2 = 0.711$ $R = .84$

$y = -1135.7 + 2.0522x - 1.8075e-4x^2$ $R^2 = 0.754$ $R = .87$

Measured work ft/lb

● 120 deg/sec
▲ 240 deg/sec

Predicted work ft/lb

Push Operation - predicted vs measured work for two velocities

$y = -70.292 + 1.2835x - 8.2792e-5x^2$ $R^2 = 0.742$ $R = .86$

$y = 941.76 + 0.66814x$ $R^2 = 0.730$ $R = .85$

Measured Work ft/lb

● 120 deg/sec
▲ 240 deg/sec

Predicted Work ft/lb

Figure 7 - Model vs measured work produced for the ratchet wrench motion.

In addition to a regression comparison of the average and work done over the range of the motion, a pairwise T test is also performed on that data. Figure 8 is a table indicating T statistic results. These result indicate that for the ratcheting motion the model predicted and measured torque values show no statistical difference across the subjects at a level of alpha equal to 0.01.

Ratchet	Push:	Pull
Average torque	T = 1.96	T = -1.52
Total work	T = 1.96	T = -1.42

At alpha = 0.01 Critical value for degrees of freedom equal to 27 (14 subjects at 2 velocities -1) is 2.47.

ud (difference) = u(model) - u (measured)
(where u is the average and the work).

Ho : ud = 0   (u (model) = u (measured)).
H1 : ud <> 0   (u (model) <>u (measured)).

Ho accepted because all T values calculated are within +/- 2.47, the critical value at alpha = 0.01.

Figure 8 - Pairwise T statistic results of average and total work across all subjects for all velocities.
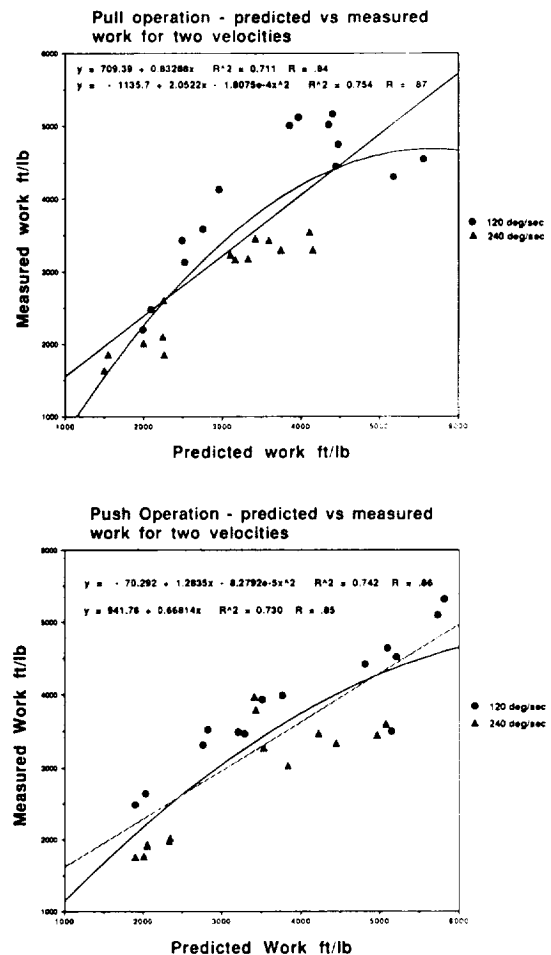
Figure 9 shows a plot of the actual vs model torques for a male and female. This is an example set consisting of one male and one female. The two cases are extreme cases (strong male, weaker female). Trends in the data indicate that the model values are matched over five to 40 degree range of the ratchet motion. The initial and final few degrees (0-5, 40-45 degrees) do not match-up with our predicted results. These stages of the motion are related to the start-up and slow down processes involved [3] which are not currently part of our modeling effort. This result indicates that a similarity in magnitude and shape exists within subjects. Statistical tests are now in progress to study in detail the "goodness of fit" between the model and measured data for individual subjects in order to determine the limitations and enhancements to be made for the current model.

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Male Ratchet Pull data:
Predicted vs Measured

Female Ratchet Pull data:
Measured vs Predicted

Male Ratchet Push data:
Predicted vs Measured
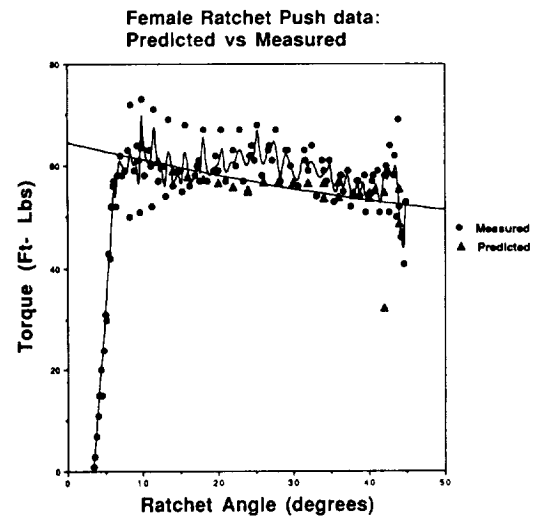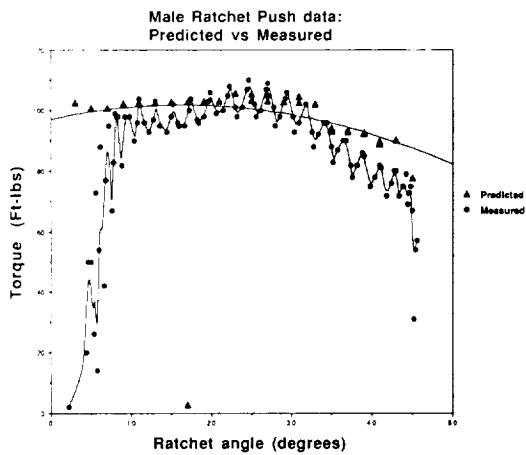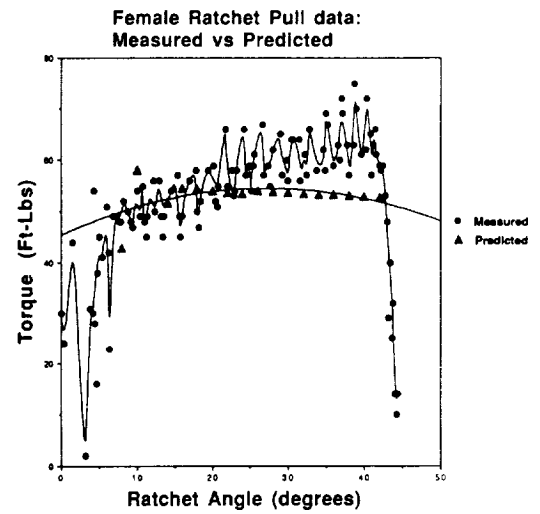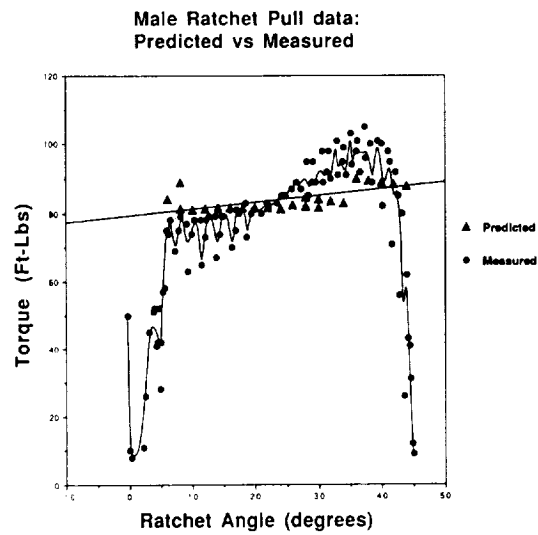
Female Ratchet Push data:
Predicted vs Measured

Figure 9: - Measured vs Model values for ratchet wrench maneuver.

(weight * 1-%body fat) vs Torque -pull
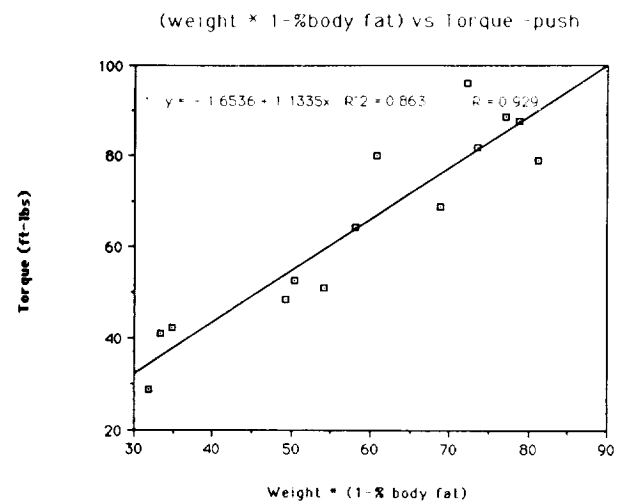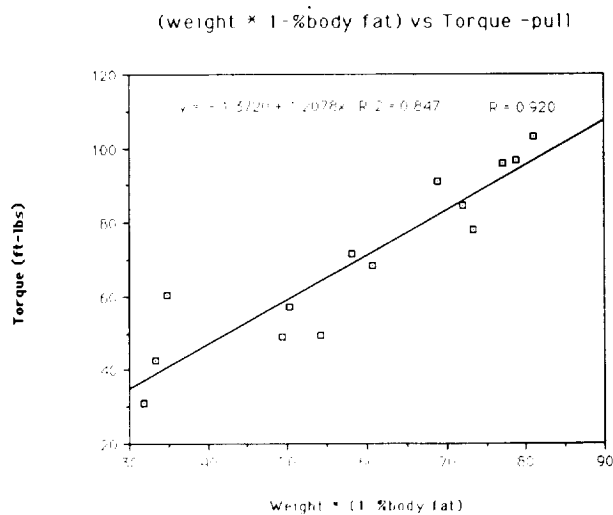
(weight * 1-%body fat) vs Torque -push

Figure 10- % Torque vs Weight (1- % body fat).

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An important relationship exists which expands the utility of our model in terms of data collection requirements. A simple measurement, percentage body fat, is a good predictor of torque. Figure 10 is a plot of torque produced by all subjects in the ratchet wrench motion vs a calculation based on the body fat and weight (weight x (1- body fat)) for each subject. There is a strong correlation ($r > 0.92$) between torque production capability and the body fat calculation. Once a representative sample of a population has been measured for isolated joint strength, prediction of torque capability of a particular individual may be extrapolated by only two measure-- percentage body fat and weight. Research continues in this area.

Conclusions:

Unlike earlier attempts at strength modeling (based on rotational spring and damper systems) our model is based on empirical data. The shoulder, elbow, and wrist joints were characterized in terms of maximum isolated torque produced, position and velocity in all rotation planes for fourteen subjects. This information was reduced by least squares regression into polynomial equations relating torque produced as functions of position and velocity and tabularized for input to the strength model. This isolated joint information was used to compute (based on a vector sum algorithm and the subject's anthropometric measurements) forces resulting from composite motions-- in this case, the ratchet wrench push-pull. Measured vs model output were compared. (see figure 12)
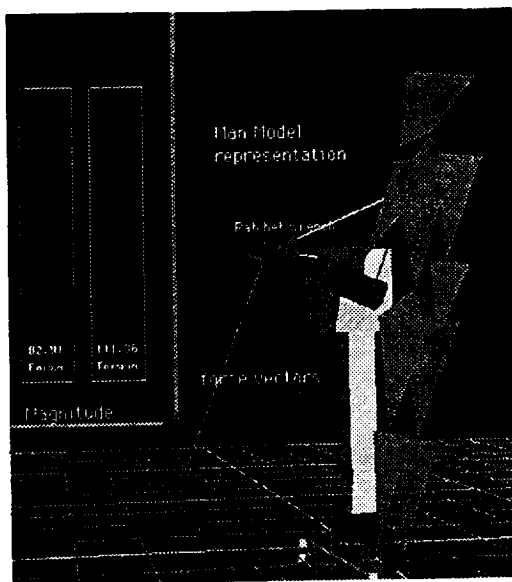

Figure 12 - Human model utilizing a ratcheting tool.

Results indicate that forces derived from a composite motion of joints (ratcheting) can be predicted from isolated joint measures. Model vs measured values for 14 subjects were compared. T values calculated were well within the statistically acceptable limits (alpha = 0.01) and regression analysis revealed coefficient of variation between actual and measured to be within 0.75 to 0.90 . Moreover, the model is flexible in terms of the environments and human motions that can be modeled. It has been demonstrated here that the current model predicts torque produced by a ratchet wrenching. Our overall objective is to incorporate into the existing CAE capabilities a strength model of the NASA crew member population for analytical human factors analysis. To this end, we will continue to cycle through the phases of validation and refinement with more complex motions and with additional isolated joint measures.

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