# ROBUST REGRESSION EQUATIONS TO PREDICT THE PASSIVE VISCOELASTIC MOMENTS OF THE HUMAN KNEE JOINT FROM ANTHROPOMETRIC PARAMETERS

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*Abstract* **-** The purpose of the present investigation was to generate regression equations to predict the passive properties of the knee joint (*in vivo*) during full range flexion-extension. The independent variables were various anthropometric parameters of the thigh, knee, leg, and whole body while the dependent variables, the passive elastic moments and the angular damping coefficients, were determined from experiments on seventeen males (22-31 years). The elastic moments were determined using an arthrograph based on a stiffness approach. The damping coefficients were measured using the small oscillation technique. Due to a number of outlying points, a robust regression analysis was adopted and twelve regression equations were generated at fixed knee angles (7 elastic, 5 damping). For the elastic moments, predictability varied across the range of motion of the knee joint ($0.501 \leq R^2 \leq 0.977$) with the best results occurring at high flexion angles (≥ 130º). The damping coefficients were less predictable ($0.426 \leq R^2 \leq 0.957$) but the results were also better at high flexion angles (130º).

## INTRODUCTION

Muscle force prediction models are constructed in an attempt to predict the force contribution of individual muscles crossing a joint during a specific movement pattern. It has been hypothesized that the passive structures spanning a joint may also contribute to or oppose the net joint moment and possibly should be included in a model to enhance its fidelity [1].

A number of studies have been performed to determine the passive elastic moments of the knee joint in flexion-extension [2], [3], [4], [5]. However, many were based on small samples (n≤4) and those which did study a larger sample did not include prediction equations. Only one study determined the angular damping coefficient of the knee joint and this was based on only one subject [4].

The purpose of this investigation was to generate a set of regression equations to predict the passive elastic moments and the angular damping coefficients of the knee joint over the full range of flexion-extension motion.

## METHODS

Twenty-two anthropometric parameters (independent variables) of the whole body, right thigh, knee, and leg were measured on each of seventeen healthy male subjects between the ages of 22 and 31 years. The passive elastic moment (dependent variable) was measured on an arthrograph by rotating the secured leg through the complete range of motion while transducers recorded the moment and angle data ([4], [6]). The angular damping coefficient (dependent variable) was determined using the small oscillation method ([4], [7]) at knee angles of 10º, 45º, 90º, 110º, and 130º.

All of the anthropometric parameters, including higher order and multiplicative terms, were input into a database within *Number Cruncher Statistical System* software. A correlation matrix and scatter plots were generated for every potential independent variable (IV) versus every dependent variable and only those IVs showing linear trends were considered for further analysis. Due to the observation of a number of obvious outlying points in the data set, a robust multiple linear regression analysis was employed. Robust regression techniques are iterative procedures which seek outlying points and minimize their influence by weighting the data. Stepwise regression was run on the weighted data set such that predictors were added until the mean squared error did not change by more than 1%. Since this procedure often added more predictors than was desired (maximum of three), predictors were then systematically removed based on their influence on the cumulative $\boldsymbol{R^2}$- statistic. In order to produce stable coefficients, an equation was maintained only if the probability of each coefficient being equal to zero was less than 0.125. For the elastic component the analysis was performed at seven knee angles: 0º (full extension), 10º, 45º, 90º, 110º, 130º, and 140º while for the damping component the analysis was carried out at five angles: 10º, 45º, 90º, 110º, and 130º.

## RESULTS

For the elastic component (Table 1), depending on the knee angle, about 50% to 98% of the variance in the passive elastic moments can be accounted for by the anthropometric parameters. Predictibility tended to be higher at high flexion angles and lower in the midrange.

For the damping component (Table 2), depending on the knee angle, about 43% to 96% of the variation in the damping coefficients could be accounted for by the independent variables.

## DISCUSSION AND CONCLUSION

For the elastic component predictability was better at the extremes of joint motion, especially flexion, compared to the midrange. This is probably due to the differences in the constitutive behaviour of various tissues becoming more apparent at higher strains. With respect to the damping component, predictability was only moderate except at 90º and 130º. It may be that cross-sectional area is not as important as intrinsic rheological properties of the ground substance and synovial fluid.

In conclusion, regression equations were generated which will allow modellers to incorporate the effects of the passive tissues into their biomechanical models.

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**Table 1**. Regression equations for predicting the passive elastic joint moment (in N·m) at each of seven different knee angles. W is in kg; all other measures are in cm. Positive values are extension moments.

| Knee Angle (º) | Robust regression equation | $R^2$ |
|---|---|---|
| 0 | 10.403 - 0.206 * W + 0.010 * $KB^3$ | 0.866 |
| 10 | 25.086 - 2.625 * KD + 0.888E-02 * $KB^3$ | 0.876 |
| 45 | 8.991 + 0.566 * GFD - 0.670 * LTC + 0.185E-01 * LTCSA | 0.944 |
| 90 | 13.527 - 0.299 * CL - 0.423E-04 * $KC^3$ | 0.501 |
| 110 | 30.625 - 0.122 * H - 2.320 * KB + 0.308 * LTC | 0.734 |
| 130 | -39.429 - 0.649 * MC + 0.125 * [KC*KB] - 0.377E-01 * $KB^3$ | 0.977 |
| 140 | -86.271 - 8.248 * GFD + 5.624 * MC - 0.402E-01 * $KB^3$ | 0.950 |

KB=Knee Breadth; KD=Knee Depth; GFD=Gluteal furrow depth; LTC=Lower thigh circumference; LTCSA=π*LTB*LTD where LTB = Lower thigh breadth and LTD = Lower thigh depth; CL=Calf length; KC=Knee circumference; H=Height; MC=(UTC+2*MTC+KC)/4 where UTC=Upper thigh circumference and MTC=Mid thigh circumference. Depths are in the Sagittal plane and breadths are in the frontal plane. Lower thigh values are taken at 20% of the thigh length from the knee centre while mid thigh values are taken at 50%. Hip angle=90º Ankle angle=0º(neutral).

**Table 2.** Regression equations for predicting the angular damping coefficients (in N·m·s/rad) at each of five different knee angles. W is in kg; all other measures are in cm.

| Knee Angle (º) | Robust regression equation | $R^2$ |
|---|---|---|
| 10 | -2.916 + 0.347 * CD | 0.609 |
| 45 | 3.202 +0.416 * LTB + 0.539E-02 * LTCSA | 0.426 |
| 90 | -1.462 + 0.275*KD + 0.152E-02 * LTCSA - 0.141E-02 * $KC^2$ | 0.945 |
| 110 | 0.950 - 0.222E-01 * W + 0.314E-02 * LTCSA | 0.622 |
| 130 | -4.298 + 0.339 *AB - 0.737 * MTD + 0.233 * (MTC+CC) | 0.957 |

CD=Calf depth; AB=Ankle breadth (across malleoli); MTD=Mid thigh depth; CC=Calf circumference. All other definitions and details are supplied in the footnotes of Table 1.

## ACKNOWLEDGEMENTS


This study was partly funded by the Natural Sciences and Engineering Council and the Research Committee of the University of Ottawa.