Proceedings of the ASME 2008 Summer Bioengineering Conference (SBC2008)
June 25-29, Marriott Resort, Marco Island, Florida, USA

SBC2008-193169

PREDICTION OF INTERNAL CONTACT FORCES AT THE KNEE FROM EXTERNAL MEASUREMENTS

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INTRODUCTION

As the baby boomer generation ages, knee osteoarthritis (OA) will become increasingly prevalent in our society. Articular cartilage damage in the knee is highly dependent upon subject-specific kinematics and load distribution inside the joint. In particular, researchers have hypothesized that overloading of the medial compartment is a primary contributing factor to development of the disease [1]. However, since medial compartment load cannot be measured non-invasively *in vivo*, researchers typically use the external knee adduction moment during stance phase as a surrogate measure. This quantity has been correlated with medial tibial contact force measured from an instrumented knee implant [2] and with risk of disease progression over time [3].

Despite these correlations, there remains no method for predicting medial contact force directly from external measurements. The forces at the knee calculated from inverse dynamics provide only a lower bound on the actual articular contact forces. Theoretically, musculoskeletal computer models could be used to predict knee contact forces based on predicted muscle forces, but contact force predictions at the knee generated by such models have yet to be validated. If medial, lateral, and total contact force in the knee could be reliably estimated from external measurements, the estimates could be valuable for devising new treatment approaches and possibly for identifying those at highest risk for developing knee OA.

This study used previously published *in vivo* gait data [2] to investigate whether medial, lateral, and total tibial contact force can be reliably estimated from inverse dynamics forces and torques at the knee. The hypothesis tested was that external forces and torques along with basic gait characteristics (e.g., speed, stride length, maximum vertical ground reaction force, and knee flexion range during stance phase) could be used to predict internal contact forces accurately for three different gait speeds.

MATERIALS AND METHODS

Previously published data [2] collected from a single patient with an instrumented knee implant (male, right knee, age 80, mass 68 kg, height 1.705 m) eight months after surgery were used for this study. Institutional review board approval and patient informed consent were obtained. The subject performed three trials of his normal gait pattern at three different speeds: normal (1.24 ± 0.03 m/s), fast (1.52 ± 0.04 m/s) and slow (0.80 ± 0.05 m/s). *In vivo* tibial force data were recorded simultaneously with video motion (Motion Analysis Corporation, Santa Rosa, CA) and ground reaction data (GRF) (AMTI Corporation, Watertown, MA). For each of the nine gait trials, data from one complete motion cycle (i.e., right heel strike to subsequent right heel strike) were analyzed.

Inverse dynamics forces and torques at the knee were calculated using a patient-specific skeletal model. Joint positions and orientations and inertial parameter values in the model were calibrated using previously published methods [4]. The calibrated knee joint center was close to the midpoint between medial and lateral femoral epicondyles. Corresponding medial, lateral, and total tibial load at the same time points were provided by the instrumented implant.

Linear regression was used to fit the internal contact force data as a function of the external inverse dynamics results. Regression was performed for three different scenarios. First, each of the nine gait trials was fit separately using Eq. (1) below:

$$F_{total/medial/lateral} = a_0 + a_1 F_x + a_2 F_y + a_3 F_z + a_4 T_x + a_5 T_y + a_6 T_z \qquad (1)$$

where F_i and T_i ($i = x, y, z$) are the inverse dynamics forces and torques, respectively. Second, all possible combinations of 8 gait trials were fit simultaneously using Eq. (1), and the resulting coefficients were used to predict medial, lateral, and total contact force for the one omitted trial. This approach (called a PRESS analysis) allowed us to perform a quantitative evaluation of the fitting process. Third, the PRESS analysis was repeated but with primary coefficients a_i (i = 0, …, 6) in Eq. (1) replaced with secondary coefficients b_{ij} (i = 0, …, 6, j = 0, …, 4) as shown in Eq. (2):

$$a_i = b_{i0} + b_{i1}S + b_{i2}L + b_{i3}V + b_{i4}R \qquad (2)$$

where S is gait speed, L is stride length, V is maximum vertical ground reaction force, and R is knee flexion range during stance phase. The linear relationship in Eq. (2) was chosen to investigate whether trial-to-trial variability in these gait characteristics could explain trial-to-trial variability in the primary coefficients.

RESULTS

Primary fitting of individual trials produced reasonable contact force estimates (Fig. 1, Primary Individual). The average R^2 value for medial, lateral, and total contact force was 0.86 while the average root-mean-square (RMS) error was 107 N, or about 16% of body weight (BW). Primary coefficients were variable between trials. Primary fitting of 8 trials simultaneously, with errors calculated using the prediction made for each omitted trial, produced somewhat worse results (Fig. 1, Primary PRESS), with average R^2 and RMS values of 0.75 and 22% BW, respectively. When primary coefficients were replaced with secondary coefficients and the PRESS analysis repeated, the increased number of degrees of freedom in the fitting process did not result in reduced errors (Fig. 1, Secondary PRESS), with average R^2 and RMS values of 0.71 and 25% BW, respectively. Though lateral contact force had the smallest RMS errors for each fitting method, it also has the lowest R^2 values.

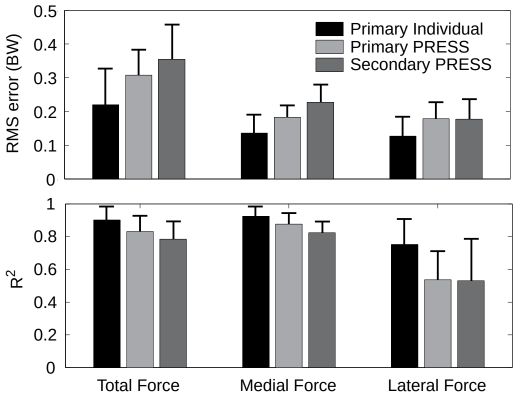

Figure 1. Regression results for primary individual trial fitting, primary PRESS fitting, and secondary PRESS fitting. Error bars indicate 1 standard deviation.

DISCUSSION

This study used inverse dynamics forces and torques calculated at the knee during gait to predict internal contact forces measured with an instrumented knee replacement. Overall, medial contact force was fit the best, followed by total contact force, and finally lateral contact force. Use of the selected secondary variables to account for trail-to-trial variability in the primary coefficients did not improve the PRESS results. Furthermore, subtracting medial contact force predictions from corresponding total contact force predictions did not yield significantly improved lateral contact force predictions. To generate the best possible internal contact force estimates for this subject performing other gait tasks, all nine gait trials should be fit simultaneously and the resulting coefficients used.

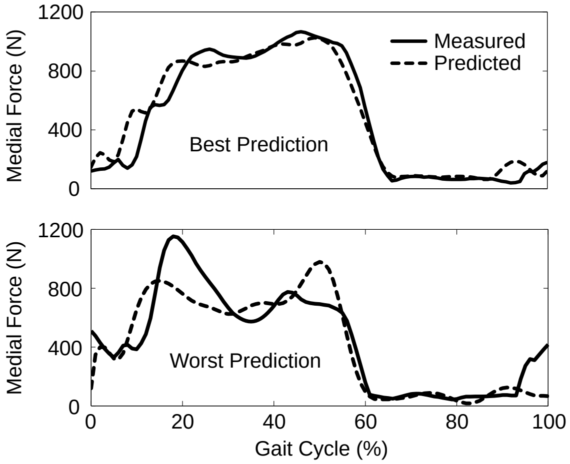

Figure 2. Best and worst medial contact force predictions generated by primary PRESS fitting.

Inverse dynamics force and torque curves from neighboring joints could have been used in the fitting process as well. Knee reactions were chosen because of the similarities and proximity to the contact forces and because of the strong correlation between the knee adduction torque and medial contact force [3]. While adding more inverse dynamics curves to the fitting process could reduce prediction errors further, it would also involve solving for a larger number of primary coefficients. Furthermore, as shown by the secondary PRESS analysis, adding more coefficients will not necessarily improve the fit quality for every trial. In our case, use of secondary coefficients created improvements in some cases but not in most. Use of PRESS analyses allowed us to evaluate worst-case fitting accuracy without requiring additional gait trials.

The primary limitation of this study is the use of only a single subject for developing and evaluating the predictions. Nonetheless, the ability to measure *in vivo* tibial contact forces for even a single patient provides a unique opportunity for evaluating new predictive methodologies. Further evaluation of the fitting process and resulting coefficients is needed using additional gait data from the current patient as well as gait data collected from other instrumented knee patients. A larger number of trials per gait pattern would also be beneficial.

ACKNOWLEDGMENTS

This study was funded by an NSF CARRER Award to B.J.F and by the Shiley Center for Orthopaedic Research and Education.

REFERENCES

1. Buckwalter, J.A., Saltzman, C., and Brown, T., “The impact of osteoarthritis: implications for research,” Clin. Orthop. Rel. Res., vol. 427 Suppl, pp. S6-S15, 2004.
2. Zhao, Z., Banks, S.A., Mitchell, K.H., D'Lima, D.D., Colwell, C.W., and Fregly, B.J., “Correlation between the knee adduction torque and medial contact force for a variety of gait patterns,” J. Orthop. Res., 2007, Vol. 25, pp. 789-797.
3. Miyazaki, T., Wada, M., Kawahara, H., Sato, M., Baba, H. and Shimada, S., “Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis,” Ann. Rheum. Dis., 2002, Vol. 61, pp. 617-622.
4. Reinbolt, J.A., Haftka, R.T., Chmielewski, T.L., and Fregly, B.J. “A computational framework to predict post-treatment outcome for gait-related disorders,” Med Eng Phys, 2007, in press.