



## **VALIDATION OF A COMPUTATIONAL WEAR MODEL FOR TOTAL KNEE REPLACEMENT POLYETHYLENE WEAR PREDICTION**

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### **INTRODUCTION**

Total knee replacements (TKRs) are becoming increasingly prevalent among younger, heavier and more active patients [1], resulting in increased tribological demand. The development of more efficient methods for evaluating and predicting TKR wear could greatly improve the design of TKRs. Computational wear simulations have demonstrated greatly improved time and cost efficiency over the use of knee simulator wear tests, which are the current standard for evaluating TKR wear performance [1]. However, the application of computational wear simulations has previously been limited due to the weak correlation strength ( $R^2 < 0.65$ ) of the available computational wear models compared to knee simulator wear test results [2, 3].

In the present research, a recently developed computational wear model was validated for the prediction of TKR tibial insert polyethylene wear. The recently developed time-dependent cross shear and energy dissipation wear model [4] was implemented within the colloidal boundary lubrication model (CBL) recently developed by O'Brien et al. [5]. The greatly improved tribological representation of the TKR conditions by the CBL computational wear model was anticipated to result in greatly improved predictive capabilities over the previously available computational wear models.

### **METHODS**

The CBL computational wear model was implemented for the prediction of Pin-on-disk (POD) and knee simulator wear test results. The newly developed CBL model incorporates the strengths of the time-dependent cross shear and energy dissipation wear model, which provides consideration for the time dependent directional strain hardening of polyethylene. The CBL model also includes the first ever TKR lubrication wear model [5].

The accuracy of the CBL model was evaluated through the comparison of the CBL predicted wear rates to a wide range of POD and knee simulator wear test results. For each POD and knee simulator experiment, computational simulations were conducted to replicate the conditions of the *in-vitro* experiment. Each computational simulation included dynamic finite element simulations, performed according to a previously established protocol [6, 7], to assess contact mechanics. The contact mechanics results were then implemented in the CBL wear model to predict lubrication conditions and wear of the tibial insert [5]. POD and knee simulator experiments were selected from the literature which had implemented broad ranges of conditions in order to thoroughly establish the predictive capabilities of the CBL wear model. Computational predictions were compared to the results of 71 POD experiments from 6 published studies in the literature [8-13]. The computational wear predictions were also compared to 20 knee simulator wear test studies (Table 1). The acceptance criteria for the validation of the CBL model was specified as a Validation Metric greater than 0.8 [14].

Table 1: Comparisons of kinematic, kinetic, design, materials, and lubrication conditions considered for the verification of the CBL model.

Comparison	Experiment Numbers (References)
Kinematics (decoupled)	K1[15], K2[15], K3[15], K4[15]
Kinematics (high/intermed.)	K5[16], K6[16], K7[16], K8[16]
Loading	K10[17], K11[17]
Conformity	K5[16], K6[16], K7[16], K8[16]
XPE Crosslink Density	K5[16], K9[18]
Modularity	K16[19], K17[19, 20]
Lubricant (volume)	K12[21], K13[21], K14[21], K15[21]
Lubricant (concentration)	K16[19], K18[22]
Lubricant (composition)	K16[19], K19[23], K20[23]

## RESULTS AND DISCUSSION

Computational wear simulations using the CBL model were performed to predict the results of 6 POD studies from the literature. The POD tests required the prediction of wear under greatly varying contact pressure, cross shear, kinematics and lubrication conditions [8-13]. The CBL wear model predicted the POD test results with an overall coefficient of determination ( $R^2$ ) of 0.85.

Following the completion of the POD experiments, the results of 20 knee simulator wear tests were compared to analyze the CBL wear models abilities to accurately predict wear under varying kinematic, kinetic, design, materials, and lubrication conditions (Table 1, Figure 1).

The first knee simulator wear test experiment (TKR 1) considered the influence of each kinematic motion on wear: flexion, internal-external rotation (IE), anterior motion of the femoral component (+AP), and posterior motion of the femoral component (-AP) [15]. Next, the second knee simulator wear test (TKR 2) evaluated the wear models' ability to predict wear under high kinematics and intermediate kinematics with reduced anterior-posterior motion [16]. The second knee simulator wear test (TKR 2) also enabled a conformity comparison through the analysis of wear for both the PFC-Sigma TKR and the wear of a modified version of the PFC-Sigma which had the articular surface of the tibial insert machined to provide a flat surface. The third knee simulator wear test (TKR 3) involved the

prediction of wear for the PFC-Sigma TKR under the standard (ISO 14243-3) loading and under increased loading conditions in which the load was increased 1.7 fold beyond the standard loading conditions [17]. The fourth knee simulator wear test (TKR 4) considered the prediction of wear for the PFC-Sigma with XPE tibial inserts which had been subjected to different levels of crosslinking radiation [16, 18]. For the fifth knee simulator wear test (TKR 5) wear was predicted for a TKR design with and without a modular tibial interface, to evaluate the wear models' ability to accurately predict the wear of the distal tibial insert surface [19, 20]. The sixth knee simulator wear test experiment (TKR 6) considered the effects of varying lubricant volume in knee simulator wear tests where the lubricant was not circulated [21]. In the seventh knee simulator wear test (TKR 7), the wear of the AMK under the ISO standard was compared to under reduced anterior-posterior translation and greatly increased protein concentration [19, 22]. Finally, for the eighth knee simulator wear test experiment (TKR 8), the wear rates of the AMK under the ISO standard using alpha calf, newborn calf and bovine calf sera lubricants were analyzed [23].

Overall, the CBL wear model was demonstrated to provide TKR wear predictions that fell within 1 standard deviation of the knee simulator wear test results (apart from a slight deviation in TKR 6 for the 75ml lubricant volume). The CBL wear model demonstrated a coefficient of determination of  $R^2=0.96$  for the prediction of knee simulator wear test results. The validation metric was also calculated, according to Oberkampff and Trucano [14], for the prediction of the 20 knee simulator wear test results using the CBL model. The CBL model demonstrated a validation metric of  $VM=0.85$  for the prediction of knee simulator wear test results.

The CBL model was evaluated through the prediction of 6 POD experimental studies and 20 different knee simulator wear tests. The experiments included a large range of PE and XPE materials, contact conditions, kinematics, kinetics, and lubrication conditions. To the best of the authors' knowledge, these POD and knee simulator evaluation experiments represent the most extensive attempt to evaluate the

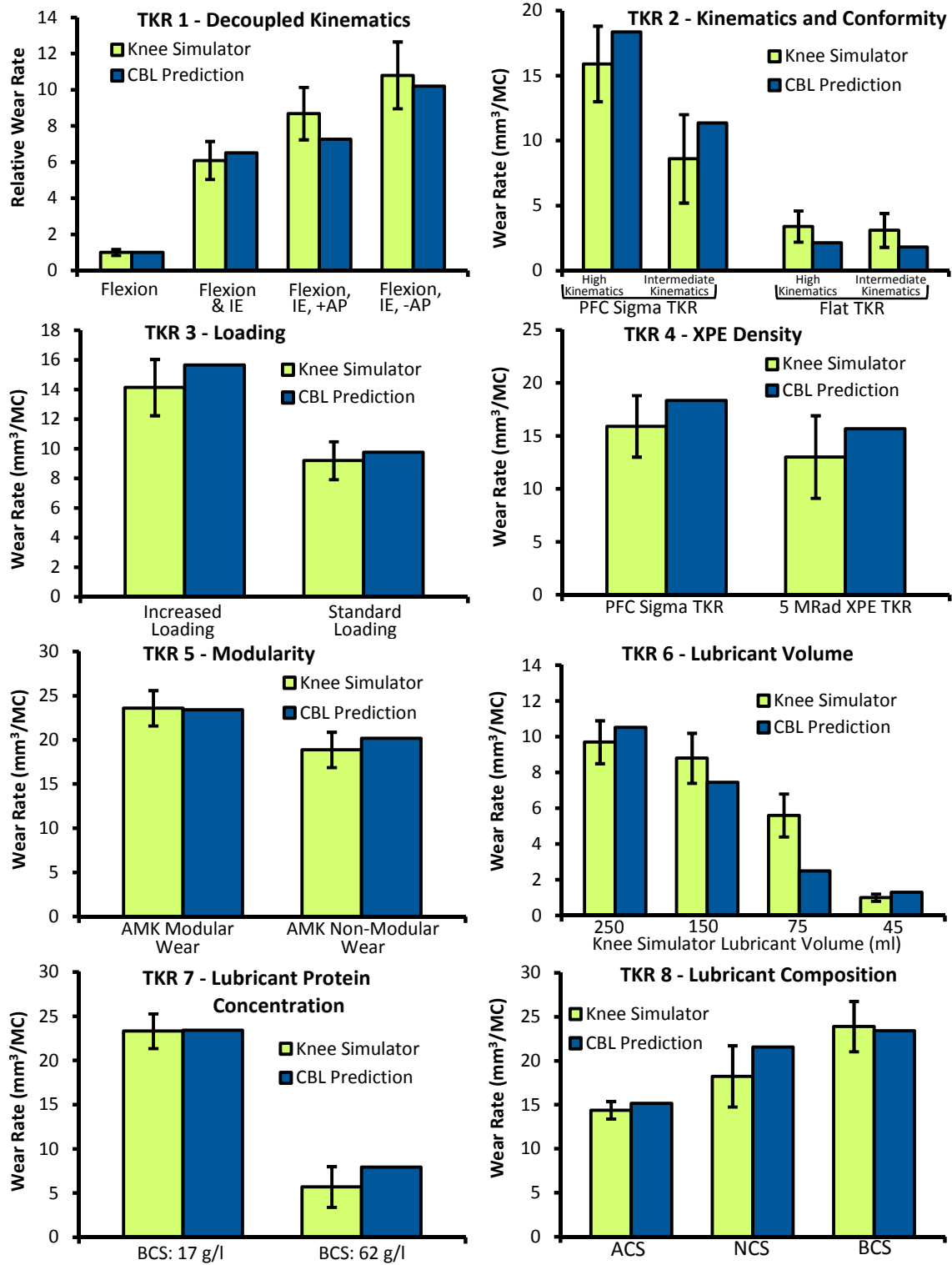


Figure 1: Comparison of experimental results and computational wear predictions for knee simulator wear tests conducted under varying conditions (tests summarized in Table 1).

predictive capabilities of a TKR computational wear model. The CBL model was demonstrated to have the greatly improved predictive capabilities over previously available computational wear models in the literature (Table 2).

Table 2: Comparison of the predictive correlations for various computational wear models.

Wear Model	Reported TKR Correlation (R <sup>2</sup> )	Reference
Archard	0.12	[3, 24]
Turell	0.60	[3, 12]
Strickland	0.65	[2]
O'Brien	0.96	

## CONCLUSION

The CBL model demonstrated excellent predictability compared to the POD and knee simulator wear test results. To the author's best knowledge, this is the first TKR computational wear model to provide consideration for the lubricant. Although this model could still benefit from further development, the CBL model has demonstrated the high level of accuracy (Validation Metric: 0.85) necessary for utilization in the TKR design process, which may improve the long term success of these necessary clinical devices.

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