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The effect of manufacturing tolerances on the mechanical environment of taper junctions in modular TKR

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Abstract

Taper design is known to influence corrosive behavior in taper junctions used in modular orthopaedic devices. Manufacturing tolerance of bore-cone tapers is a critical design parameter due to the effect on taper fit, but the effect of variations in manufacturing tolerance on the mechanics of taper junctions has not been well characterized, particularly in modular total knee replacement (TKR). The purpose of this study was to investigate the effect of manufacturing tolerance on stress and micromotion of modular TKR taper junctions. A 3D finite element (FE) model of a modular TKR taper junction was developed and assigned elastoplastic material properties. Model taper geometry was varied by perturbing the angle mismatch by 0.05° between $\pm 0.25^\circ$ and represented expected variation in manufacturing tolerance. Stress and micromotion were calculated during dynamic FE simulations for each taper junction geometry under varying activity loads and material combinations. Although an increase in angle mismatch generally resulted in higher stress and micromotion, plastic material behavior disrupted this trend for larger angle mismatches. Model predictions corresponded with corrosion behavior evident in vitro. If the FE results obtained here apply in vivo, the absence of elastoplastic material properties in a taper model may grossly overestimate the micromotion and underestimate corrosion behavior and ion release. It is recommended that manufacturing tolerances of bore-cone tapers in modular TKR designs should produce angle mismatches within 0.1° at the taper junction.

Keywords

Finite element analysis; Modular TKR; Manufacturing tolerance; Stress; Micromotion; Angle mismatch

1. Introduction

Initially invented in 1864 for joining machining tools, the bore-cone taper junction was introduced into orthopaedics in the 1970s as an alternate design to “mono-block” hip replacements (Hernigou and Lachaniette, 2013). Taper modularity has since become a common design feature in orthopaedic devices including hip replacement, total knee replacement, intramedullary nails and dental implants due to the versatility it provides

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Appendix A. Supplementary data

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surgeons intraoperatively to address patient-specific needs. During revision total knee replacement (TKR), the bore-cone taper junctions allow surgeons to augment modular TKR components with intramedullary stem extensions for improved stability and bone fixation in patients with poor bone quality or defects (Rawlinson et al., 2008; Scott and Biant, 2012). Despite these advantages, taper junctions have been associated with corrosive behavior because of mechanical instability (Harman et al., 2011; Jones et al., 2001; Lieberman et al., 1994; Pourzal et al., 2018) causing adverse tissue responses and limiting device longevity (Cooper et al., 2012; Lombardi, 2014; McMaster and Patel, 2013). Mechanically assisted corrosion (MAC) is a commonly recognized corrosion mechanism in taper junctions, and involves the combination of localized stresses under loading and fretting, or micromotion between contacting surfaces (Gilbert et al., 1993; Goldberg et al., 2002).

In response to the concerns surrounding modular taper junctions, the effect of taper design parameters on corrosion have been investigated. Both retrieval analyses on explanted taper junctions of modular total hip replacements (THR) (Goldberg et al., 2002; Langton et al., 2012; Higgs et al., 2015) and in vitro studies (Jani et al., 1997; Goldberg and Gilbert, 2003; Jauch et al., 2014; Gilbert et al., 2009) have supported the occurrence of MAC mechanisms and confirmed that taper design parameters influence corrosion. However, retrieval analysis offers limited information regarding *in vivo* mechanics and *in vitro* studies are inefficient to perturb and repeat. Finite element (FE) analysis provides an efficient numerical approach to overcome these limitations and has been used to analyze the effect of taper design and material combination on contact mechanics (e.g. stress and micromotion) for various biomedical applications including modular bone replacement prostheses (Chu et al., 2000), dental implants (Bozkaya and Muftu, 2003; Maietta et al., 2018), and modular THR (Shareef and Levine, 1996; Dyrkacz et al., 2015; Bitter et al., ; Fallahnezhad et al., 2017; Ashkanfar et al., 2017; Donaldson et al., 2014). Although retrieval analyses have also shown evidence of MAC mechanisms in modular TKR (Arnholt et al., 2014; Panigrahi et al., 2018), no FE studies have been completed to date analyzing the effect of taper design in modular TKR.

Despite the common objective in the aforementioned studies of determining the optimal taper junction design, a great deal of uncertainty surrounds this topic. The previous ASTM Standard F-1636 specified manufacturing tolerances for specific bore-cone taper pairs, but was discontinued leaving industry without guidance on appropriate manufacturing tolerances for taper designs (F1636-95e2 and Standard, 1995). Although manufacturing tolerance has been established as a design parameter critical to taper junction corrosion (Goldberg et al., 2002; Jani et al., 1997; Shareef and Levine, 1996; Donaldson et al., 2014), the isolated effects of incremental changes in manufacturing tolerance on the contact mechanics is still poorly understood. With the goal of minimizing taper junction corrosion, there is a need to define target manufacturing tolerances based on the effect it has on the taper junction mechanical performance.

The purpose of this study was to utilize parametric FE analysis in order to investigate the effect of manufacturing tolerance on stress and micromotion of modular TKR taper junctions. In this study, the angular mismatch between the cone and bore taper angles represented manufacturing tolerance and was perturbed in 0.05° increments between $\pm 0.25^\circ$ by modeling different cone taper angles. The effect of manufacturing tolerance on the taper

junction mechanical environment was investigated under multiple material combinations and applied loads representing various activities of daily living. The intent of the study was to provide insight to engineers as to what manufacturing tolerances should be targeted during taper junction design.

2. Methods

In this study, FE taper junction model was applied to perform a parametric analysis on taper junction geometry, in particular angular mismatch between the bore and cone taper angles. The FE model implemented elastoplastic material models, and was validated against experimental data acquired through collaboration. The effect of geometric variations on stress and micromotion was analyzed under loading conditions representing various activities of daily living.

2.1. Development of taper junction finite element model

A 3D FE generalized bore-cone taper junction model was developed from a retrieved modular TKR tibial component. Initial model geometry exhibited a 5° angle for both tapers, and thus a 0° angle mismatch between the bore and cone tapers representing a perfect fit (Fig. 1). To account for the inherent manufacturing tolerances, the angle mismatch, defined as the bore angle minus the cone angle, was varied from 0° to ± 0.25° at 0.05° increments by perturbing the angle of the cone taper located on the tibial baseplate (Table 1). The positive mismatch condition is defined as the bore taper angle being greater than the cone taper angle, and contrarily the negative mismatch condition is defined as the bore taper angle being smaller than the cone taper angle. In order to isolate the effects of the angle mismatch (i.e. manufacturing tolerance), all other geometric parameters remained constant. ABAQUS (v6.14, Dassault Systemes, Waltham, MA) was used to perform the deterministic finite element analysis (Fig. 1).

Material properties of cast CoCrMo (ASTM F75) were assigned to the cone taper and the bore taper was assigned material properties of either wrought Ti6Al4V (ASTM F136) or wrought/forged CoCrMo (ASTM F1537/F799). Taper junction material combination will be specified as bore material-cone material. From this point forward, CoCrMo material designation will represent cast CoCrMo when in application of the cone taper of the baseplate and wrought/forged CoCrMo when in application of the bore taper of the stem; the Ti6Al4V designation will be in representation of wrought Ti6Al4V. An elastoplastic material model was developed for each material using published experimental stress-strain data (ASM Materials for Medical Devices Database Committee, 2009; Berlin et al., 1999; Berry et al., 1999; Cohen et al., 1978; Devine and Wulff, 1975; Dobbs and Robertson, 1983; Hodge and Lee, 1975; Hollander and Wulff, 1974; Mishra et al., 1999; Spires et al., 1987; Kumar et al., 1985; Lippard and Kennedy, 1999; Murr et al., 2009; Ploeg et al., 2009) and a power law approximation, defined as

$$\sigma = K\epsilon^n$$

where σ is the stress, ϵ is the strain, K is the strength coefficient, and n is the strain hardening coefficient (Hosford, 2010). Optimization of the power law parameters to match the experimental data resulted in the parameters listed in Table 2 and stress-strain curves displayed in Fig. 2. All materials were assumed to behave isotropically.

Contact was modeled using contact pairs with the cone taper assigned the master surface and the bore taper the slave surface. Surface-to-surface contact was enforced using the penalty method and finite sliding formulation. Quadratic tetrahedral elements with improved surface stress formulation (C3D10I) were used in the regions of contact (Tadepalli et al., 2011), and linear tetrahedral elements (C3D4) were used in non-contacting regions for computational efficiency. Mesh convergence resulted in a total of 52950 tetrahedral elements in the FE model with 34669 elements at the contacting regions. The coefficient of friction (COF) at the taper interface was defined as a function of the contact pressure using an exponential decay model (Oden and Martins, 1985) fit to experimental data (Swaminathan and Gilbert, 2012) represented by

$$\mu = \mu_0 + (\mu_\infty - \mu_0)e^{-d_c P}$$

where P is the contact pressure, μ_0 is the coefficient of friction at zero contact pressure, μ_∞ is the coefficient of friction at increasing contact pressure, and d_c is the decay factor. The decay factor, d_c , was optimized in order to match in vitro test data for Ti6Al4V-CoCrMo and CoCrMo-CoCrMo interfaces, respectively. Both material pairs had $\mu_0 = 0.8$ and $\mu_\infty = 0.3$ with varying d_c of 0.056 for Ti6Al4V-CoCrMo and 0.079 for CoCrMo-CoCrMo (Fig. 3).

2.2. Model loading and boundary conditions

A dynamic, implicit simulation was completed in two steps: (1) a compressive axial assembly load equivalent to surgical impaction force to seat the cone taper into the bore was applied and (2) a physiological activity loading profile composed of vertical compressive forces along with flexion-extension and internal-external moments. Gait, stair descent, and chair rise/sit activities were each simulated individually. During the assembly step, a 4400 N assembly load, measured to be the average impaction force applied by orthopaedic surgeons in a study by Heiney et al., was applied (Heiney et al., 2009). Loading conditions for all activity cycles were defined from published telemetric data (Fig. 4) (Kutzner et al., 2010). The resultant compressive force ($-F_z$) was split 55% medial–45% lateral (Zhao et al., 2007) and distributed in a circular pattern about 4 nodes in the respective regions on the superior surface of the tibial baseplate generating an abduction-adduction moment (M_y) in the frontal plane.

Moment and force profiles assumed a 940 N body weight for each activity, and were applied to the corresponding axes via a reference node coupled to the superior surface of the baseplate (Fig. 1) (Kutzner et al., 2010). The physiological loading step required two loading cycles for each activity in order to allow the taper junction to stabilize. Boundary conditions were representative of a worst-case scenario of distal stem fixation without support of the proximal tibial bone (Fig. 1)

2.3. Validation of taper junction finite element model

Through collaboration with a previous study (Donaldson et al., 2014), the FE models were validated against experimental micromotion measured on two sets of bore-cone pairs, generating 4 different angular mismatch combinations (Fig. 5). The experimental testing implemented a 5000 N axial compressive load followed by a 0–5000 N ramp load at 45° off-axis. The experimental taper junction was machined out of 6061 aluminum at approximately a 3:1 scale in order to meet micromotion measurement capabilities and to allow for accurate measurement of taper angles on the machined parts. Experimental micromotion of the isolated bore-cone taper junction was measured using two differential variable reluctance transducers (DVRTs) capable of 600 nm accuracies axially aligned across the taper interface. Although the initial intent of the experimental setup was for modular THR application with varying center offsets, the largest center offset of 60 mm well represented the loading condition of the modular TKR taper junction being modeled in this study; hence, only micromotion data from this condition was used for validation. The experimental study resulted in micromotion at superior and inferior regions due to the inclination of the taper junction in THR which translated to the lateral and medial regions in TKR based on the orientation of the resultant moment acting on the taper junction. Further details for the experimental setup can be found in the previously published study by Donaldson et al. (2014). Separate FE models were created to match the exact geometry of the four different experimental bore and cone taper parts and the experimental loading and boundary conditions resulting in four simulations. Experimentally measured and model predicted micromotion were compared for each bore-cone taper pair.

2.4. Experimental design of study

A total of 66 simulations were run in order to analyze the effect of angular mismatch on the mechanics of the taper junction when the bore-cone material combination and activity simulated are varied (Fig. 5). Micromotion and von Mises stress were the mechanical parameters analyzed. Micromotion was calculated as the magnitude of relative tangential motion in the two directions perpendicular to the surface normal of the contact elements at the location where bore-cone taper contact existed. The micromotion reported represented the maximum magnitude calculated across the taper interface, and is not an accumulative value, but instead calculated relative to the end of the previous loading step. To compare the stresses in the taper junction across all analyses, von Mises stress, σ , defined as

$$\sigma = \sqrt{\frac{3}{2} S_{ij} S_{ij}}$$

where S_{ij} is the deviatoric stress tensor, was chosen due to a triaxial stress environment within the taper junction as well as the general use of the von Mises yield criterion in stress analysis of isotropic ductile metals.

The maximum von Mises stress was recorded for both the bore and cone tapers at the end of the assembly step, activity cycle 1, and activity cycle 2 when only nominal loads were being applied; thus, the reported stresses represent residual stresses. A plastic strain magnitude, ϵ_{pl} , defined as

$$\varepsilon_{pl} = \sqrt{\frac{2}{3} E_{ij} E_{ij}}$$

where E_{ij} is the plastic strain tensor, was recorded to analyze the elastoplastic material behavior under different angular mismatches and activity cycles. Finally, spearman's rank correlation coefficient was used to analyze the correlation between parameters of interest and angular mismatch.

3. Results

Experimental and model predicted micromotion showed good agreement in trends and an average absolute difference of $25.5 \mu\text{m}$ [$\pm 12 \mu\text{m}$] (Fig. 6). The variation in micromotion could be attributed to the precision of machining and measuring the physical taper parts as the FE models were developed from nominal dimensions of the taper design specifications. Additionally, higher accuracy is expected for the true size models compared to the scaled up validation geometry.

The parametric analysis of angular mismatch revealed distinct stress distributions for positive and negative angle mismatches regardless of bore-cone material combination or activity simulated. A perfect fit resulted in a relatively uniform stress distribution while positive and negative mismatches lead to distal and proximal stress concentrations, respectively (Fig. 7). As the angle mismatch transitioned from a positive to a negative mismatch, the maximum stress shifted from the cone to the bore taper. In further analyzing the stress environment of the taper junction, triaxial compression was experienced by the cone taper with the two principal stress components in the transverse plane corresponding to radial and tangential, or hoop, stress as the cone penetrates the bore taper during compressive loading. The stress environment in the bore taper was similar to that of the cone with the exception of a tensile hoop stress in response to the bore taper expanding outward to impede further penetration of the cone taper.

Residual von Mises stress at the cone and bore tapers peaked at $+0.25^\circ$ and -0.25° of mismatch, respectively, but followed distinct trends as angle mismatch increased. Stress in the bore taper was a minimum near 0° angle mismatch and increased as angle mismatch increased regardless of mismatch direction. Stress in the cone taper increased from -0.25° mismatch towards $+0.25^\circ$ until reaching approximately 100% yield stress at $+0.10^\circ$ (Fig. 8). Beyond $+0.10^\circ$, cone taper stress remained relatively constant with increasing positive mismatch up to $+0.25^\circ$. The stair descent activity generated higher stresses compared to the gait and chair rise/sit activities, but stress in the cone taper converged across the three activities as mismatch increased, especially for positive mismatch (Fig. 8).

Post-yield stresses and plastic deformation only occurred in the cone taper under positive mismatch conditions. For positive angle mismatches $> 0.10^\circ$, plastic strain was produced during assembly and was further increased under stair descent loading conditions only, with the exception of $+0.25^\circ$ angle mismatch which experienced increases in plastic strain during

all activity loading cycles. Positive mismatch conditions -0.10° only produced plastic strain after subsequent stair descent loading cycles.

Overall, micromotion increased with increased angle mismatch, and exhibited less variation for gait and chair rise/sit simulations compared to stair descent. The maximum micromotion experienced across all activities was $32.1\text{ }\mu\text{m}$, and occurred at -0.25° mismatch under stair descent conditions for a Ti6Al4V-CoCrMo taper junction. A 0° angle mismatch, the ideal condition, consistently resulted in the lowest settled micromotion across all simulations. For the gait and chair rise/sit activities, micromotion ranged from 0.2 to $8.9\text{ }\mu\text{m}$ for both cycles, and varied less than a $1.7\text{ }\mu\text{m}$ between the two activities across all angle mismatches (Fig. 9). The stair descent activity varied as much as $28.1\text{ }\mu\text{m}$ between the first and second activity cycle (Fig. 9), and calculated a range in micromotion of $11.5\text{--}32.1\text{ }\mu\text{m}$ during the first cycle compared to $1.5\text{--}10.0\text{ }\mu\text{m}$ during the second.

Strong correlations were seen between angle mismatch and stress within the taper junction for both material combinations under all activity levels with stronger correlations for stress in the bore taper compared to the cone taper (Table 3). In general, as the angle mismatch became more negative or more positive the stress within the taper junction increased. Correlations between angle mismatch and micro-motion were not as strong, and were weaker for micromotion during cycle 2 relative to cycle 1. In most cases, an increase in mismatch in either the positive or negative direction led to a greater micromotion. Overall, material combination and physiological activities showed similar trends in correlations.

Comparison of material combination predicted greater stresses in the CoCrMo-CoCrMo combination and greater micromotion in Ti6Al4V-CoCrMo. In negative mismatch conditions, the CoCrMo-CoCrMo taper junction generated up to a 37.7% increase in stress on the bore taper and 31.5% increase on the cone taper (Fig. 10). The Ti6Al4V-CoCrMo and CoCrMo-CoCrMo taper junctions produced very similar stress results in the positive mismatch condition when the stress is concentrated on the cone taper. This trend in differences in stress between the two material combinations was evident in all activities simulated. Comparing micromotion, the Ti6Al4V-CoCrMo taper junction generated greater micromotion in comparison to CoCrMo-CoCrMo in all three mismatch conditions, and was more apparent under stair descent activity loading (Fig. 11). The greatest difference was a 58.1% increase at negative mismatch for stair descent.

4. Discussion

This study characterized relationships between manufacturing tolerance and taper mechanics for modular TKR taper junctions. An elastoplastic FE taper junction model was used to predict stresses and micromotion within the modular TKR taper junctions under simulated assembly and activity loading conditions while parametrically perturbing the angular mismatch between the bore and cone tapers. Although an increase in angle mismatch generally resulted in higher stress and micromotion, inclusion of plastic material behavior disrupted this trend for larger angle mismatches exhibiting the importance of modeling elastoplastic material properties. Model predictions were consistent with corrosion behavior reported in vitro, demonstrating the utility of computational modeling to supplement

experimental studies investigating corrosion mechanisms. In agreement with a previous ASTM standard for THR modularity, a manufacturing tolerance range of $\pm 0.1^\circ$ is recommended for modular TKR tapers.

In vitro studies have demonstrated that stress can alter corrosion behavior and increase corrosion rates (Panigrahi et al., 2015) and metal ion release (Bundy et al., 1991). Although calculated stress magnitudes in the current study were less than the material yield strength across large areas of the taper junction interface (Figs. 7, 8 and 10), stress below the yield point can still enhance ion release (Bundy et al., 1991) and corrosion rates can peak at stresses of 50–75% yield strength (Panigrahi et al., 2015) in Ti6Al4V and CoCrMo alloys. These combined findings suggest stress is a key factor contributing to taper corrosion behavior and it is influenced by small variations in angular mismatch. Considering that FE model stress predictions are directly influenced by the material model implemented, characterizing material behavior properly is essential for linking *in vitro* and *in vivo* corrosion behavior.

The elastoplastic FE taper junction model calculated post-yield stresses that influenced the predicted mechanics of the taper junction. Stress distributions within the bore-cone taper junction were a direct result of the proximal and distal contact conditions set forth by a negative and positive angle mismatch, respectively, similar to contact pressure distributions predicted for taper junctions in THR (Ashkanfar et al., 2017). The contact area between the bore and cone tapers decreased with increasing positive mismatch resulting in a stress concentration at the leading edge of the cone taper that produced post-yield stresses and consequently, plastic material behavior. Similar to the role plastic deformation plays in limiting the pull-off strength of a tapered interference fit (Bozkaya and Muftu, 2003), plastic deformation produced in the taper junction during assembly limited the increase in stress that would have otherwise been predicted by increasing angle mismatch. As the angle mismatch increased, the stress generated during the assembly step exceeded the yield strength leading to plastic material behavior and plateauing of stress in the taper junction (Figs. 8 and 10). These observations agree with other computational and *in vitro* studies suggesting the stress environment is established during assembly (Ashkanfar et al., 2017) and support the importance of this step during the surgical procedure (Dyrkacz et al., 2015; Fallahnezhad et al., 2017; Heiney et al., 2009; Rehmer et al., 2012).

Without inclusion of elastoplastic material properties, FE models of taper junctions are not predictive of nonlinear mechanics evident in *in vitro* experiments (Bozkaya and Muftu, 2003). Although plastic deformation of surface asperities play an important role in taper junction mechanics (Lundberg et al., 2015), asperities in surface topography make interfacial stresses at the contacting surfaces of bore-cone tapers difficult to characterize (Swaminathan and Gilbert, 2012). The current study shows that plastic deformation influences taper junction mechanics even in macroscale FE analysis.

It has been established that mechanically-driven damage modes in modular tapers involve a combination of stress and micromotion (Pourzal et al., 2018; Gilbert et al., 1993; Goldberg et al., 2002; Jani et al., 1997; Swaminathan and Gilbert, 2012; Jauch et al., 2011). Fretting corrosion *in vitro*, in particular, is affected by normal load (directly proportional to stress)

and micromotion (Swaminathan and Gilbert, 2012; Baxmann et al., 2013), with compliance (i.e. localized deformation) between contacting surfaces leading to the onset of sticking behavior at lower normal loads and a decrease in micromotion (Swaminathan and Gilbert, 2012). Likewise, different wear mechanisms in tribocorrosion can be fundamentally characterized by the interaction between normal load and sliding distance (i.e. micromotion) (Royhman et al., 2013; Mathew et al., 2011). Although different contact regimes (e.g. full slip, partial slip, sticking) expected during fretting behavior (Swaminathan and Gilbert, 2012) were not directly implemented in the current model, contact pressure dependent COF was assigned to improve micromotion predictions. Furthermore, effects of compliance at the taper contact interface were captured by the elastoplastic material behavior implemented in the model.

In the current study, introduction of an angle mismatch produced a pivot point located at either the proximal medial (negative mismatch) or distal medial (positive mismatch) contact region, generating a rocking motion about this point. Similar to taper junctions in modular THR (Jani et al., 1997; Ashkanfar et al., 2017), the positive mismatch condition exposed the taper junction to a larger moment arm from the pivot point to the medial compressive load, effectively generating a greater frontal plane moment and higher micromotion compared to negative mismatch. The calculated micromotion of the modular TKR taper junction modeled in the current study was within ranges measured *in vitro* for modular THR (Jauch et al., 2011, 2014; Gilbert et al., 2009; Grupp et al., 2010) supporting observed similarities in fretting corrosion damage for modular TKR and THR retrievals (Arnholt et al., 2014; Panigrahi et al., 2018). In contrast, other computational studies (Chu et al., 2000; Shareef and Levine, 1996; Dyrkacz et al., 2015) that assigned linear elastic material properties report much higher magnitudes of micromotion. Use of an elastoplastic FE model of the taper junction better represents the mechanical behavior of taper junctions.

The effect of angular mismatch on stress and micromotion support the discontinued ASTM Standard F-1636 for modular THR, which specified a maximum individual taper tolerance of $\pm 0.1^\circ$ with all nominal angle mismatches being positive. In this tolerance range, micromotion was less than $3.4 \mu\text{m}$ for all activities and maximum stresses were generally less than 50% of yield strength (Figs. 8–9). A previous FE model of modular THR recommended the same $\pm 0.1^\circ$ taper tolerance based on predicted volumetric wear rates within $0.05\text{--}0.07 \text{ mm}^3/\text{million cycles}$ (Ashkanfar et al., 2017). Defining threshold mechanical parameters for the prevention of corrosion is difficult due to the complex interplay of numerous factors, but less than $5 \mu\text{m}$ of micromotion has been recommended for clinical success in THR (Jauch et al., 2014). The $\pm 0.1^\circ$ manufacturing tolerance range meets this criterion based on the model predictions and is suitable if the design intent was for a nominal perfect fit (0°) between the bore and cone tapers.

It is acknowledged that assembly conditions (Dyrkacz et al., 2015; Fallahnezhad et al., 2017; Heiney et al., 2009; Rehmer et al., 2012), biomechanical loading conditions (Bitter et al.,), bone defects (Conlisk et al., 2015) and other design parameters also influence the mechanical performance of modular taper junctions (Higgs et al., 2015; Gilbert et al., 2009; Dyrkacz et al., 2015). The current study focused on manufacturing tolerance due to the uncertainty surrounding this parameter and the interrelationship between manufacturing

tolerance and taper junction mechanics evident in the literature (Lieberman et al., 1994; Goldberg et al., 2002; Jani et al., 1997; Shareef and Levine, 1996; Fallahnezhad et al., 2017; Ashkanfar et al., 2017; Donaldson et al., 2014). Manufacturing tolerances were limited to variations in taper angle using perfectly round and straight taper contours modeled without consideration for deviations in roundness or straightness that exist in manufacturing (Jani et al., 1997). Evaluating fixation augments, such as set screws and through bolts used to further secure taper junctions was beyond the scope of the current study, and thus was not included in the model.

5. Conclusion

In summary, increases in manufacturing tolerance (i.e. angle mismatch between bore and cone tapers) within expected ranges effectively decreased contact area at the taper interface and increased stress and micromotion. However, plastic material behavior for larger angle mismatches, specifically positive angle mismatch in which the bore taper angle is greater than the cone taper angle, weakened correlations between angle mismatch and stress and micromotion. It was demonstrated that once the angle mismatch reached a threshold, plastic deformation was induced during assembly and further loading did not alter the stress environment. Based on these findings, it is recommended that manufacturing tolerances of bore-cone tapers in modular TKR designs should produce angle mismatches within 0.1° at the taper junction. If the FE results obtained here apply in vivo, the absence of elastoplastic material properties in a taper model may grossly overestimate the micromotion and underestimate corrosion behavior and ion release.

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Fig. 1.
Schematic of the FE taper junction model with applied loading orientations.

Fig. 2.

Engineering stress-strain curves implemented in the finite element analysis to model elastoplastic behavior for each represented material.

Fig. 3.
Fretting COF and normal stress relationship for each bore-cone material combination defined as part of the contact formulation in the finite element analysis.

Fig. 4. Physiological loading cycles for gait, chair rise/sit and stair descent applied in the dynamic finite element simulation with respect to the corresponding axes. HS = heel strike; CHS = contralateral heel strike; CTO = contralateral toe off; CSC = contralateral stair contact.

Fig. 5.

Diagram of the experimental design demonstrating the variable parameters.

Fig. 6.
Validation analysis using experimental micromotion from four different bore-cone taper pairs exhibited to compressive axial and off-axis loading.

Fig. 7.

Frontal section of modular TKR taper junctions displaying von Mises stress distribution under physiological loading of a gait cycle simulation for both Ti6Al4VCoCrMo and CoCrMo-CoCrMo bore-cone material combinations at +0.25°, 0°, and -0.25° angle mismatch. Medial and lateral regions denoted by M and L, respectively.

Fig. 8.

Maximum stress in the bore and cone tapers plotted as the percentage of yield strength for the Ti6Al4V-CoCrMo and CoCrMo-CoCrMo material combination over the entire range of angle mismatches for gait, stair descent and chair rise/sit activities.

Fig. 9. Maximum micromotion at the bore-cone taper interface for the first and second cycle of each activity simulated across all angle mismatches.

Fig. 10.

Comparison of bore and cone stress between Ti6Al4V-CoCrMo and CoCrMo-CoCrMo material combinations under different simulated activities and $+0.25^\circ$, 0° , and -0.25° . Percent difference is presented above each comparison.

Fig. 11.

Comparison micromotion between Ti6Al4V-CoCrMo and CoCrMo-CoCrMo material combinations under different simulated activities and $+0.25^\circ$, 0° , and -0.25° . Percent difference is presented above each comparison.

Table 1

Variation of the cone taper angle design parameter and angular mismatch.

Bore Angle, α_B	Cone Angle, α_C	Angle Mismatch, ($\alpha_B - \alpha_C$)
5.00°	4.75°	+ 0.25°
5.00°	4.80°	+ 0.20°
5.00°	4.85°	+ 0.15°
5.00°	4.90°	+ 0.10°
5.00°	4.95°	+ 0.05°
5.00°	5.00°	0.00°
5.00°	5.05°	-0.05°
5.00°	5.10°	-0.10°
5.00°	5.15°	-0.15°
5.00°	5.20°	-0.20°
5.00°	5.25°	-0.25°

Table 2

Material property parameters assigned to the elastoplastic models for each material.

Material	Cast CoCrMo	Wrought/Forged CoCrMo	Wrought/F orged Ti6A14V
Model	Baseplate with	Stem with	Stem with
Component	Cone Taper	Bore Taper	Bore Taper
Standard	ASTM F75	ASTM F1537, ASTM F799	ASTM F136
Elastic Modulus [GPa]	210	210	110
Poisson's Ratio	0.3	0.3	0.31
Yield Strength* [MPa]	515 [± 37]	935 [± 128]	990 [± 190]
% Elongation*	12[± 4]	23[± 7]	13[± 2]
n	0.1162	0.0739	0.0416
K	1015.7	1438.8	1200.4
Published Sources	[23–32]	[23–25, 31, 33, 34]	[23, 35, 36]

Spearman's rank correlation coefficients between angle mismatch direction and stress and angle mismatch and micromotion (μm) for both material combinations under each activity loading conditions.

Table 3

		Ti6Al4V-CoCrMo				CoCrMo-CoCrMo			
		Stress in		μm		Stress in		μm	
		Bore	Cone	Cycle 1	Cycle 2	Bore	Cone	Cycle 1	Cycle 2
Gait	(+)	1.00	1.00	0.86	-0.14	1.00	1.00	0.83	-0.14
	(-)	-1.00	-0.86	-0.74	-1.03	-1.00	-0.09	-0.74	-0.49
Stair	(+)	1.00	1.00	0.60	1.00	1.00	1.00	0.83	1.00
	(-)	-0.94	1.00	-0.94	-0.57	-1.00	0.49	-1.00	-0.80
Chair	(+)	1.00	1.00	0.83	-0.20	1.00	1.00	0.94	-0.14
	(-)	-1.00	-0.14	-1.00	-1.00	-1.00	-0.09	-1.00	-0.51