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A finite element study on the mechanical response of the head-neck interface of hip implants under realistic forces and moments of daily activities: Part 2

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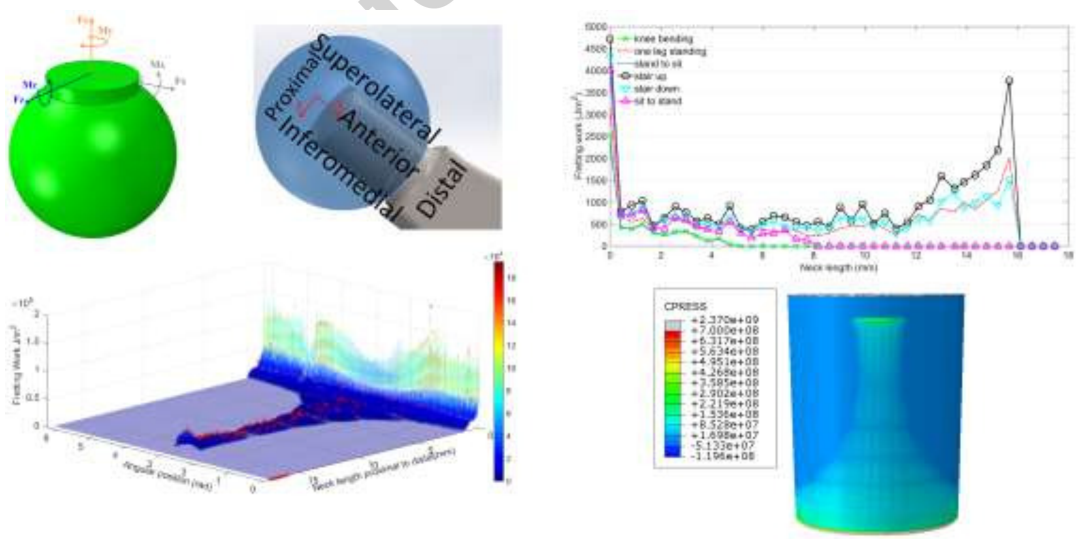
Abstract

A finite element model was developed to investigate the effect of loading regimes caused by various daily activities on the mechanical behaviour of the head-neck taper junction in modular hip replacements. The activities included stair up, stair down, sit to stand, stand to sit, one leg standing and knee bending. To present the real mechanical environment of the junction, in addition to the force components, the frictional moments produced by the frictional sliding of the head and cup were applied to a CoCr/CoCr junction having a 12/14 taper with a proximal mismatch angle of 0.024°. This study revealed that stair up with the highest fretting work per unit of length (1.62×10^4 J/m) was the most critical activity, while knee bending and stand to sit with 1.96×10^3 J/m were the least critical activities. For all the activities, the superolateral region of the neck was identified as the most critical region in terms of having larger values of fretting work per unit of area. This study showed also that the relative micro-motions and contact stresses occurring at the head-neck interface for all the studied activities are mostly in the range of 0-38 μm and 0-350 MPa, respectively. These ranges may be accordingly employed for conducting relevant *in-vitro* tests to more realistically represent the mechanical environment of taper junctions with the same materials and geometry studied in this work.

Graphical Abstract



Keywords: CoCrMo implants; Taper junction; Daily activities; Fretting; Finite element analysis.

1. Introduction

Previous studies on modular total hip replacements have identified the occurrence of fretting wear in the head-neck taper junction of hip joint implants. This phenomenon can generate metal debris that is proven to have detrimental effects on various body tissues such as spleen, bones and liver [1-3].

To date, many retrieval studies as well as *in-vitro* tests have been conducted to understand the occurrence and intensity of the fretting wear damage to the head and neck materials [4-7]. Geometric and mechanical parameters such as taper angle mismatch, head size, assembly force, head centre offset, body weight, material combination and surface finish were found as the main factors that play a role in fretting wear [8-13]. The head-neck taper junction provides a complex three dimensional (3D) mechanical environment in which there are 6 degree of freedom loads (forces and moments), frictional contact and a tapered geometry with a mismatch angle. At present, *in-vitro* tests are performed under idealised conditions which may or may not reflect the *in-vivo* mechanical environment. Pin-on-disc tests have been performed across different ranges of normal contact stress and micro-motion. Swaminathan et al. [14] employed normal stresses (in the range of 0-1,100 MPa) and micro-motions (50 μm) to investigate the effect of mechanical and electro-chemical parameters on the fretting corrosion behaviour of cobalt chromium (CoCr) and titanium alloy specimens. Maruyama et al. [6] performed pin-on-disc tests to study the fretting wear behaviour of a CoCr head and CoCr neck in both air and a phosphate buffered saline solution. They used a 25 μm displacement under 1 MPa, 3 MPa and 5 MPa normal stresses. This raises the important question of what range of micro-motions and normal stresses should be used in these simplified *in-vitro* tests to represent the mechanical environment at the interface of the head and neck components under realistic loads of daily activities.

Although direct measurements of the mechanical environment are difficult, finite element (FE) analysis can be used to gain an understanding of the contact pressure and micro-motion throughout an activity [15-17]. The mechanical behaviour of the head-neck junction was investigated by Donaldson et al. [18] using a stochastic finite element model. According to their study, the key parameters which can influence the fretting work were angular mismatch, body weight and offset of the head centre. In their model, two cycles of three dimensional gait loading were applied to the centre of the head. The critical positions of the neck were demonstrated by various FE contours in the complete, proximal and distal contact cases. Dyrkacz et al. [19] investigated several geometric and loading factors which can influence the micro-motion at the head–neck interface. In their simulations, a tension-compression loading was applied at an angle of 30° away from the centre axis of the neck.

To achieve a reliable FE model, a precise loading pattern is of paramount importance. Some previous experimental studies have presented hip gait loading patterns induced by routine activities [20, 21]. Farhoudi et al. [22] developed an analytical method to determine bending and torsional moments acting on the head-neck junction as a result of frictional sliding between the head and cup. Although there have been several studies on the geometric parameters and also loading parameters such as assembly force [23, 24], strength of the head-neck junction against torsional moments [17, 25] and mechanical behaviour of the junction subjected to walking cyclic loading [18], the influence of the loading regimes caused by different physical daily activities on the mechanical environment of the head-neck junction has not been investigated yet. Furthermore, the effect of the bending and torsional moments produced by the frictional sliding of the head and cup on the mechanical response of the head-neck junction is still unknown.

This study aims to evaluate the mechanical behaviour of the head-neck taper junction, in particular a CoCr/CoCr junction with a 12/14 taper design and a proximal mismatch angle of 0.024°, that is subjected to mechanical loads of common daily activities. A range of contact stresses and relative micro-motions will also be determined which may be accordingly used in relevant *in-vitro* tests to represent a wide range of routine activities for this type of taper junction.

2. Methodology

A previously developed three dimensional FE model of the head-neck junction [17], which was verified by a set of experimental results (reported in [24]), was further developed to investigate the mechanical behaviour of the junction subjected to the loads associated with six different activities of daily living: knee bending, sit to stand, stand to sit, stair up, stair down and one leg standing. It is noted that the results for walking are presented and discussed in Part 1; however, some comparisons and discussions are reported in this part.

In this study, a 12/14 taper design with a proximal head-neck contact (in which the taper angle of the head is greater than the trunnion angle of the neck) with a taper angle mismatch of 0.024° [24] was modelled for a CoCr/CoCr material combination. The simulation was accomplished in two stages. At the first stage, a 4 kN uniaxial push-on load was applied to assemble the head and neck components; and at the second stage, the loading of each activity was applied. As shown in Figure 1, the forces and moments in this model were applied to the neck while the external surface of the head sphere was fixed in all directions. For each activity, all the three force components [20] and three moment components produced by the head and cup frictional sliding [26] were applied to the head-neck junction (Figure 2). Micro-motions and contact pressure are found as the most important mechanical parameters which can control fretting wear and thereby fretting corrosion [14, 27]. Accordingly, fretting work, as the product of friction coefficient, contact pressure and micro-motion, can help to understand how different loading regimes may result in surface damage to the head-neck materials. Therefore, a python code was developed to extract the contact pressure and micro-motions data of the contacting nodes at a critical loading instance during the gait cycle (the instance at which the resultant load and contact stress were maximum). Moreover, a MATLAB code was developed to compute the relative micro-motion of each node in the contact area.

3. Results

Figure 3 shows the distribution of normal contact stresses (contact pressure) in the superolateral region of the neck under the maximum resultant load of the six studied activities. The superolateral region of the neck was found as the most critical region in terms of stress magnitudes and the size of contacting area. The contours clearly show the contact area of the neck with the head where the contact stresses are positive. For a better demonstration of the contact area in the contours, the maximum magnitude of the contact stress was limited to 700 MPa for all the activities. This means that a very thin band from the proximal edge of the neck, at which there is a very high stress concentration, was excluded from the contours. However, the maximum magnitude of the contact stress is still included in the legend of the contours.

Figure 4 illustrates fretting work per unit of area (J/m^2) versus the length and perimeter of the neck for all the activities. It can be seen that the proximal side of the neck, which is firmly fixed to the head (because of the assembly force), has the maximum fretting work in all the activities. Figure 4 also shows that in stair up, stair down and one leg standing, the distal side has higher levels of fretting work compared with the middle side of the neck (between the proximal and distal sides). This is due to the bending effect caused by the loading pattern in these three activities. As shown in Figures 2(a,b,e), the maximum magnitude of F_y and F_z, that are dominant forces, is approximately 1,500 N for stair up, stair down and one leg standing, while for the other activities, these are about 1,000 N. Therefore, for stair up, stair down and one leg standing, F_y and F_z are big enough to cause bending over the neck length which influences more the distal side and makes a contact between the head and neck in this side as well.

In Figure 4, the superolateral region was found as the most critical region of the neck in terms of fretting work. The maximum values of fretting work in each division of the neck length over the neck circumference were identified and shown in the profile of each activity with small red circles. The track of the fretting work maximum values over the length of the neck for all the activities is shown in Figure 5. The same method was used to produce similar graphs for normal contact stresses, shear stresses and relative micro-motions.

As can be seen in Figure 5, the maximum fretting work per unit of area for all the activities occurred at the proximal side. Stair up had the highest fretting work per unit of area 4,720 (J/m^2). This was followed by stair down, sit to stand, one leg standing, knee bending and stand to sit activities with 4320, 4020, 3140, 2520 and 2320 (J/m^2), respectively. While for stand to sit, knee bending and sit to stand, the fretting work per unit of area becomes zero after approximately 5-8 mm from the proximal side, for the other three activities, the fretting work is non-zero over the entire length of the neck and increases in magnitude at the distal side.

As Figure 6 shows, the highest contact pressure (2,500 MPa) is induced by one leg standing; and knee bending causes the lowest contact pressure (1,940 MPa) both at the highly stressed edge of the proximal side. However, all contact stresses drop significantly to less than 500 MPa immediately after this edge (only 0.4 mm away) for the remainder of the neck length towards the distal side. A similar pattern is observed for shear stresses (a reduction from 563 MPa to less than 100 MPa right after the edge), as shown in Figure 7.

As demonstrated in Figure 4, the superolateral region was the most critical region for all the activities. Stair up, stair down and one leg standing were the three activities in which the contacting area was greater compared to the other activities. From Figure 6, the contact length over the neck surface for the activities can be found as: 4.4 mm (stand to sit), 4.6 mm (knee bending), 8.2 mm (sit to stand), 16 mm (one leg standing, stair up and stair down). The last three activities made a complete longitudinal contact between the head and neck in the superolateral region. Figure 8 shows the contact stress contours of the head for stair up and sit to stand as two activities that can represent the activities with a complete and incomplete contact between the head and neck, respectively, at the critical loading instance. The legend of the contours was limited to 400 MPa to better demonstrate the contact area. Unlike the sit to stand activity, there is a complete longitudinal contact in the superolateral region of the head for stair up.

As mentioned previously, fretting work per unit of area could be a good indicator for comparing the effect of various activities on the fretting wear of the junction, as its formulation includes both the relative micro-motion and contact stress components. The area under the curve of fretting work per unit of area (Figure 5) was computed for each activity. This gives fretting work per unit of length (FWPUL). The bar chart of Figure 9 shows FWPUL calculated for all the activities including walking. Stair up was found as the most critical activity with the highest FWPUL (1.62×10^4 J/m), while knee bending and stand to sit with 1.96×10^3 J/m had the lowest FWPUL. Such a 720% difference between these activities indicates the effect of type of physical activity on the fretting wear of the head-neck junction. The FWPUL for walking was also computed as 1×10^4 J/m.

It can be seen from Figure 10 that the relative micro-motions for the studied activities are not more than 32 μm which is related to stair up. It is also obvious from this figure that the relative micro-motion for stair up, stair down and one leg standing is remarkably higher than the other activities particularly in the distal side of the neck.

Figure 11 shows the maximum contact stresses versus their corresponding relative displacements and the maximum relative displacements versus their corresponding contact stresses at several divisions through the neck length. From this figure, it can be understood that most of the critical points of the neck have a contact stress in the range of 0-350 MPa and a relative displacement in the range of 0-32 μm. It is noted that for each activity, there is a data point having a high contact stress which was due to the stress concentration at the edge of the proximal side of the neck. Therefore, these points were excluded from the reasonable ranges as shown with the red lines.

4. Discussion

As pointed out in the previous section, the superolateral region of the neck was the most critical region of the junction in aspects of having the highest magnitudes of contact stress and fretting work. This can be justified by focusing on the loading structure of the physical activities used in this work. According to Figures 1 and 2, F_y (in the longitudinal axis of the junction) and F_z (towards the superolateral region) are the most dominant load components for all the studied activities. The significant magnitude of F_z was found to cause a bending in the superolateral region resulting in higher contact stresses in that region.

It was found from Figure 9 that after stair up and stair down, walking and one leg standing were the most critical activities in terms of fretting work. Generally, it can be said that activities, in which patients raise one leg for a while during a gait cycle such as stair up, stair down, walking and one leg standing, have greater fretting work levels in comparison with the activities having both legs in contact with the ground. This could be explained by the load components of each activity (Figure 2). For stair up, stair down and one leg standing, their F_y and F_z components reach approximately 1,500 N during the gait cycle. This amount of force not only increases the normal and shear stresses between the contacting surfaces, but also can lead to a complete contact between the head and neck due to the bending caused by the F_z component.

In Figure 11, the ranges of normal contact stress and micro-motion obtained for the six activities in this work were comparable to those determined for walking in Part 1 of this study (0-275 MPa for contact stress and 0-38 µm for micro-motion). This may suggest that to develop *in-vitro* tests close to the real mechanical environment of the head-neck junction with the same material combination and geometry, the contact pressures and relative micro-motions may vary up to a maximum of 350 MPa and 38 µm, respectively, so that most common daily activities of a patient are covered in the tests. Comparing these findings with previous *in-vitro* tests, Swaminathan et al. [14] applied greater magnitudes (contact stresses up to 1,100 MPa and a micro-motion of 50 µm) which may be found to be conservative. In another pin-on-disc study [6], the micro-motion was 25 µm which is well in the range of micro-motions suggested by the present work. Moreover, the contact stresses were only between 1 and 5 MPa, which are low compared to the contact stresses of up to 350 MPa reported in this work. Geringer et al. [28], applied a micro-motion of 40 µm to a pin-on-disc testing system, while the contact surface was under normal stresses of 12-25 MPa. The applied micro-motion was found to be very close to the proposed range, while the normal contact stresses were again low.

It should be noted that the results obtained in this study are limited to a CoCr/CoCr head-neck junction with a 12/14 taper design and a proximal mismatch angle of 0.024° that was assembled with a 4 kN assembly force. To expand these findings, further research is required to investigate other material combinations, head/neck geometries and assembly forces. In addition, the behaviour of the head-neck junction under cyclic loading and the influence of cyclic loading patterns on the mechanics of the junction materials need to be investigated.

Conclusions

A finite element model was used to investigate the influence of various daily activities on the mechanical response of a CoCr/CoCr taper junction in modular hip replacements. The superolateral region of the junction was found as the most critical region for all the studied activities. Stair up with the fretting work per unit of length of 1.62×10^4 J/m was the most critical activity. After stair up, the ranking of the critical activities (from the most critical to least critical) was stair down, walking, one leg standing, sit to stand, stand to sit and knee bending. It was found that the activities in which patients raise one leg during the gait cycle cause greater amounts of fretting work; and consequently, could be more damaging in comparison with the activities with both legs in contact with the ground. This study suggests a range for both relative micro-motion (0-38 μm) and normal contact stress (0-350 MPa) that may occur at this type of head-neck interface with the specified materials and geometry during all the seven common activities studied in Parts 1 and 2 of this work. These ranges may be used to conduct more realistic *in-vitro* tests on this type of head-neck taper junctions.

Acknowledgments

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Conflict of interest statement

The authors declare that there is no conflict of interest.

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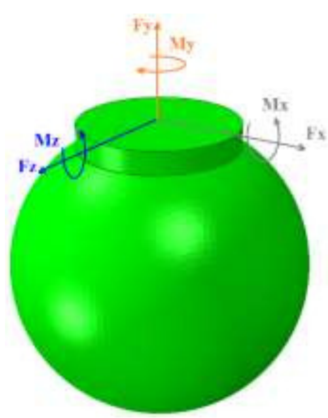

Figure 1. The head-neck taper junction model under three dimensional force and moment components of daily activities.

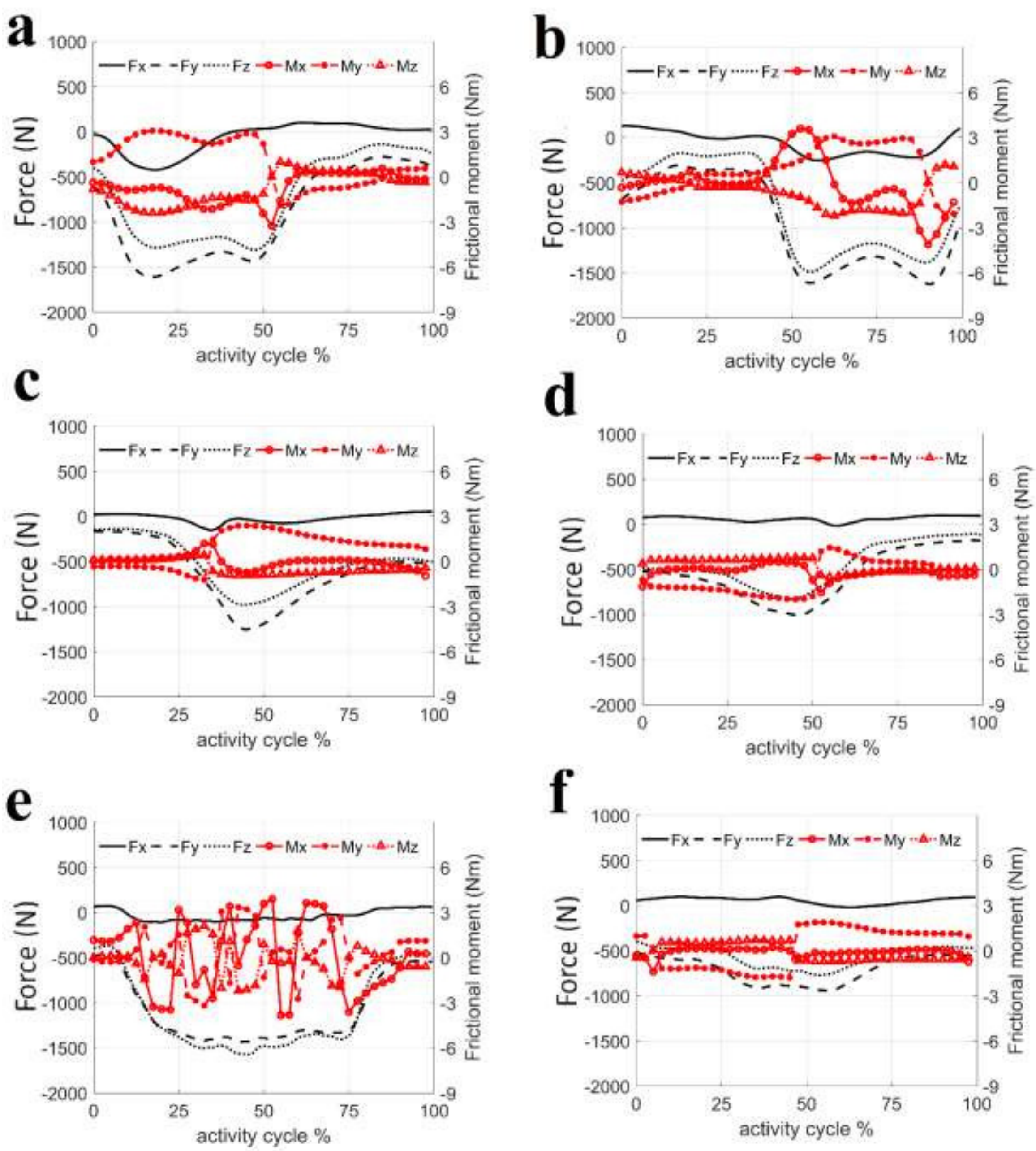

Figure 2. Force (N) profiles [20] and moment (Nm) profiles [26] for: (a) Stair up, (b) Stair down, (c) Sit to stand, (d) Stand to sit, (e) One leg standing, and (f) Knee bending activity cycles.

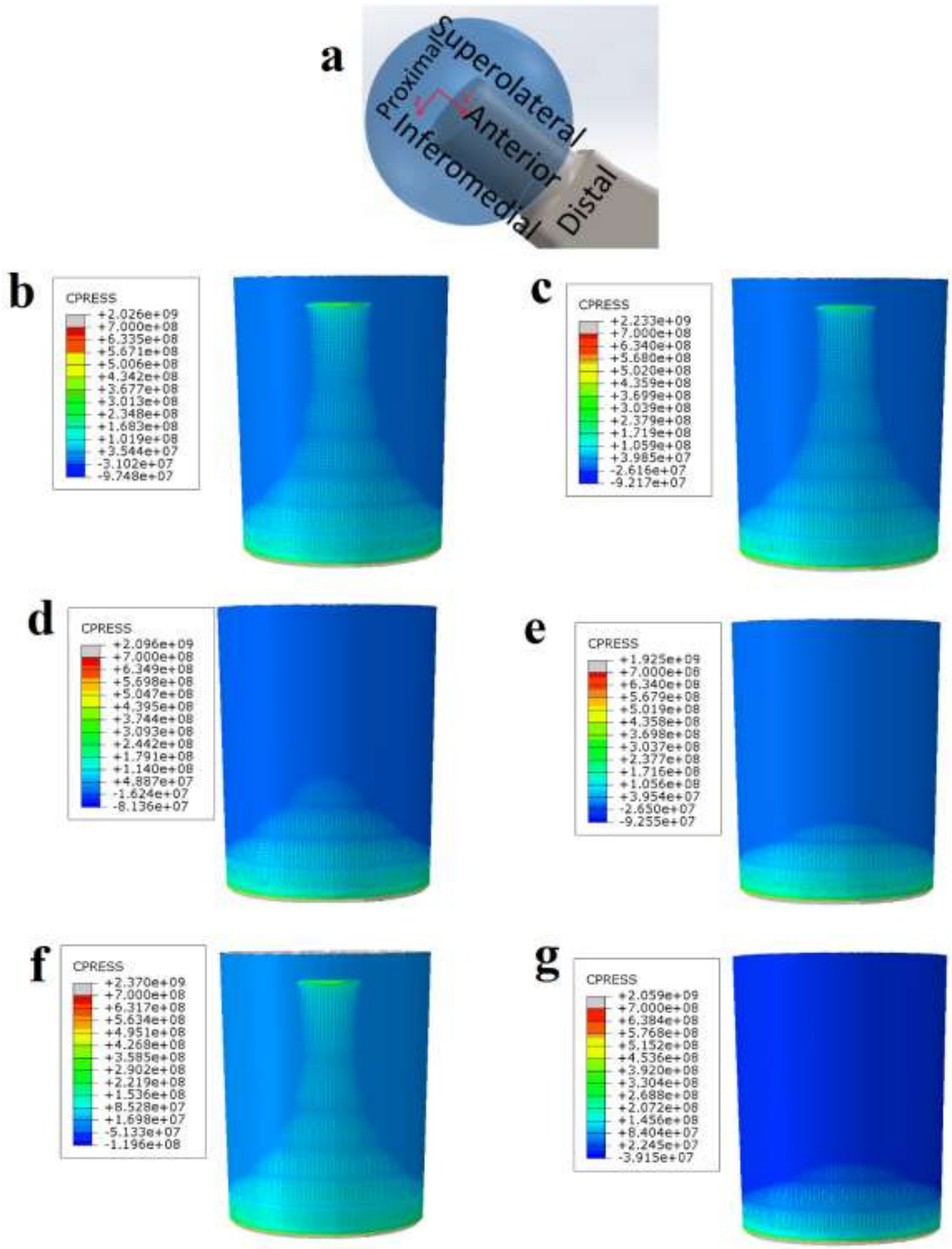

Figure 3. Normal contact stress (Pa) distribution in the superolateral region of the neck at the critical loading instance (when the resultant load and contact stress were maximum): (a) the head-neck junction with its regions, (b) stair up, (c) stair down, (d) sit to stand, (e) stand to sit, (f) one leg standing, and (g) knee bending. Stresses are in Pa. (Maximum contact stress occurs at the proximal edge of the neck. For a better demonstration, maximum magnitude of the contact stress was limited to 700 MPa for all the activities).

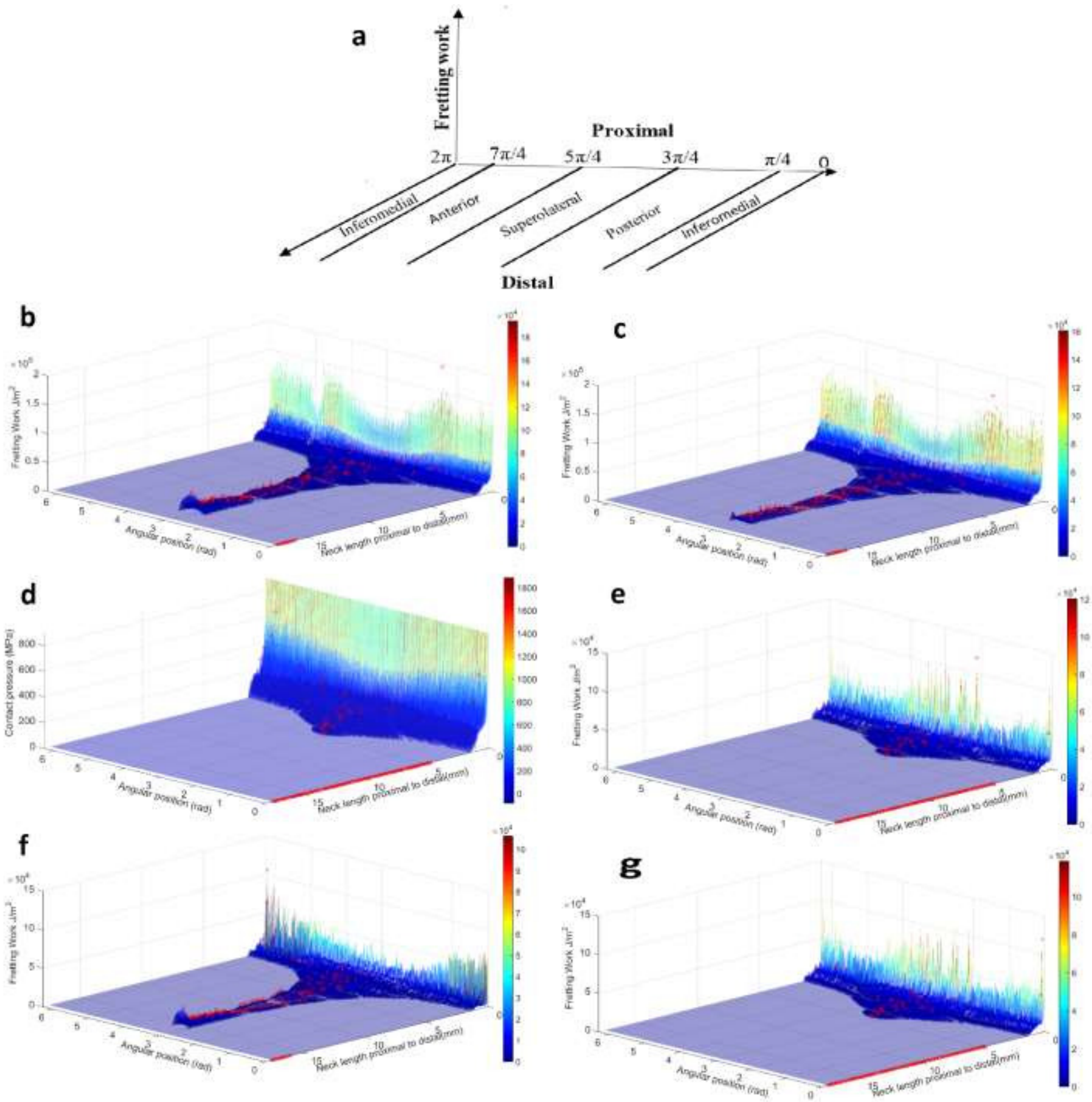

Figure 4. Fretting work per unit of area (J/m^2) versus the length (mm) and perimeter of the neck (rad) at the critical loading instance (when the resultant load and contact stress were maximum): (a) regions and angles over the neck surface, (b) Stair up, (c) Stair down, (d) Sit to stand, (e) Stand to sit, (f) one leg standing, and (g) Knee bending.

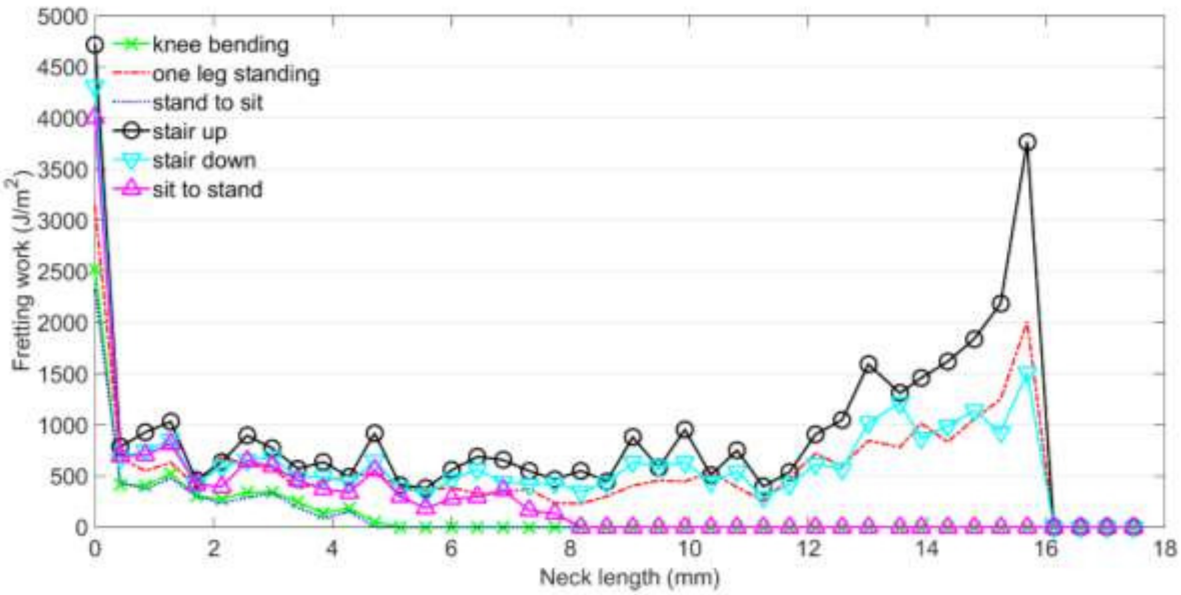

Figure 5. Maximum values of fretting work per unit of area (J/m^2) across the neck circumference versus the neck length (mm).

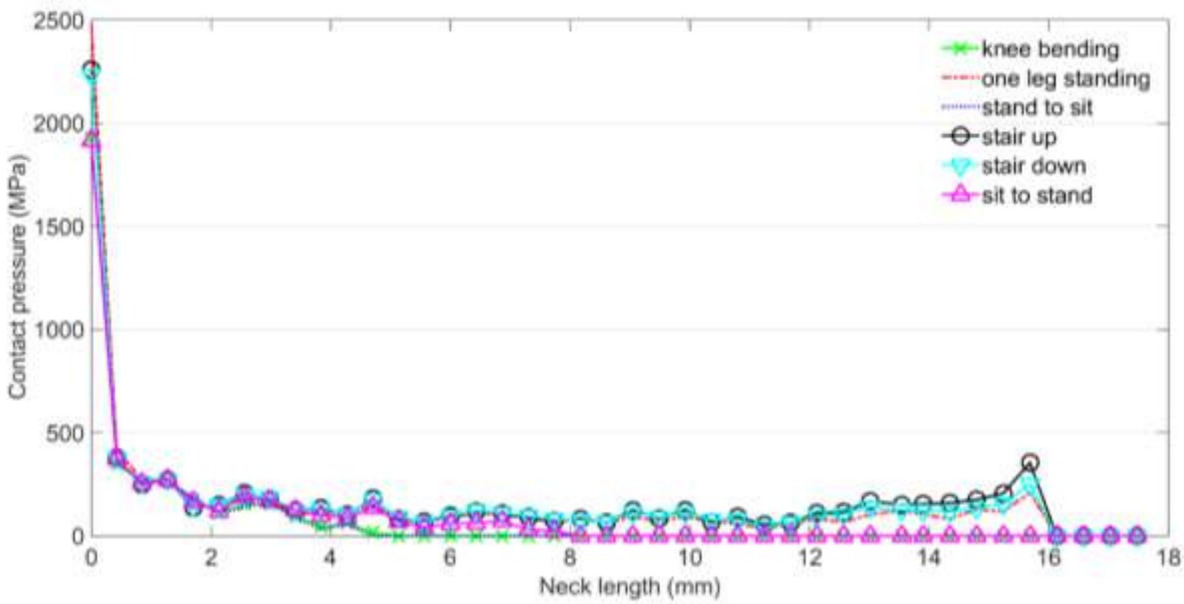

Figure 6. Maximum magnitudes of normal contact stress (pressure) in MPa across the neck circumference versus the neck length (mm).

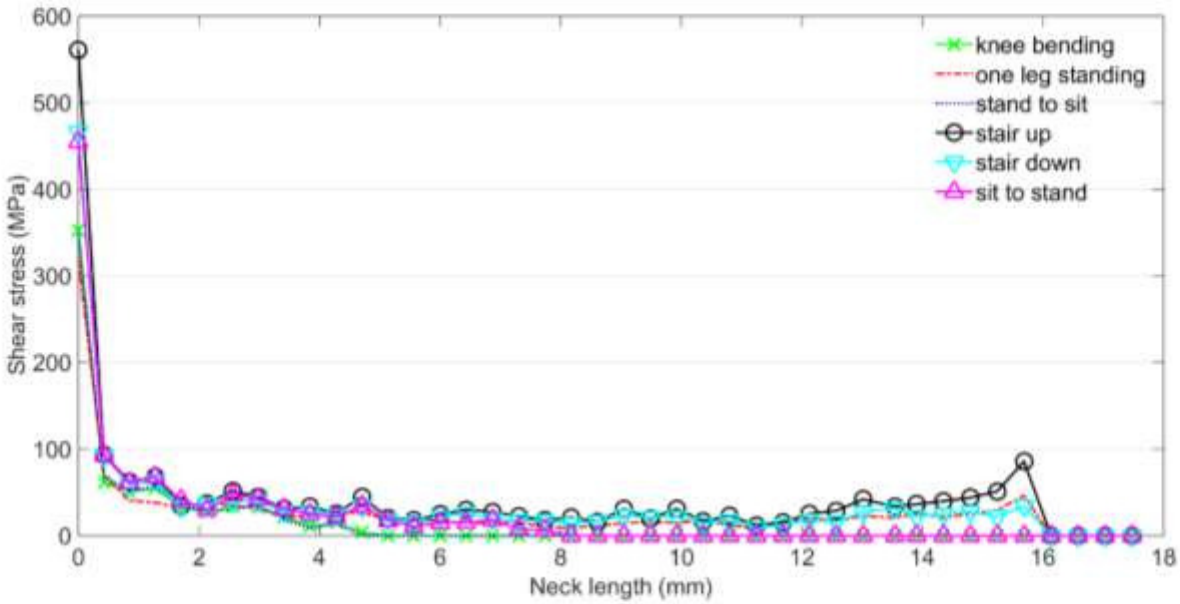

Figure 7. Maximum magnitudes of shear stress (MPa) across the neck circumference versus the neck length (mm).

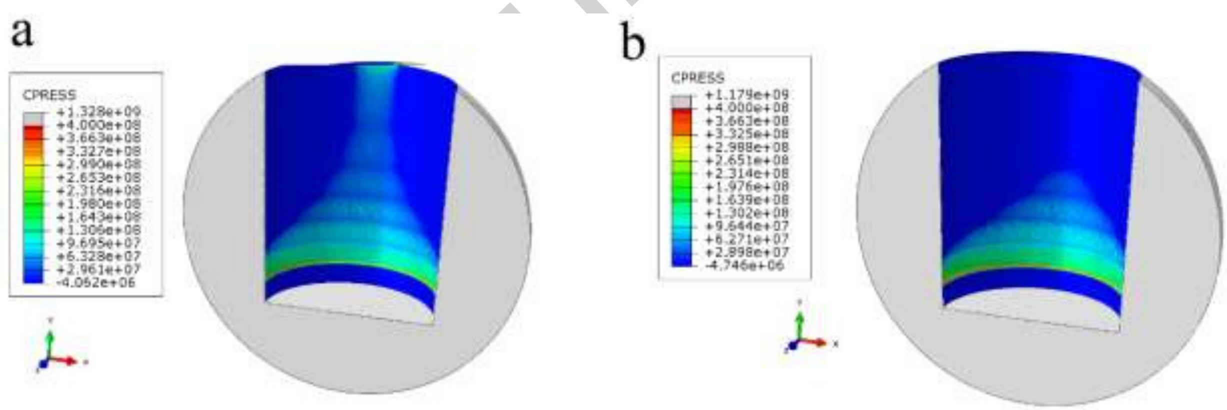

Figure 8. Normal contact stress (Pa) contours of the head for: (a) Stair up, and (b) Sit to stand. (Maximum contact stress occurs at the proximal edge of the head. For a better demonstration, maximum magnitude of the contact stress was limited to 400 MPa for both activities).

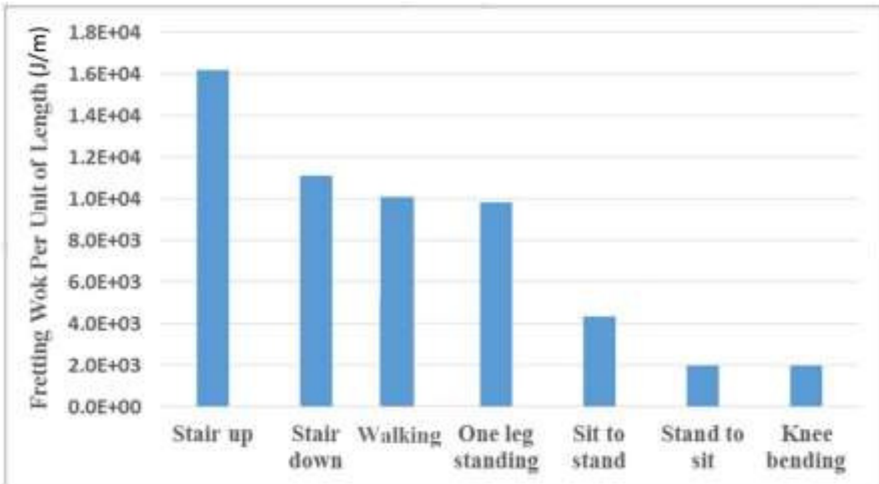

Figure 9. Fretting work per unit of length (J/m) determined for each activity.

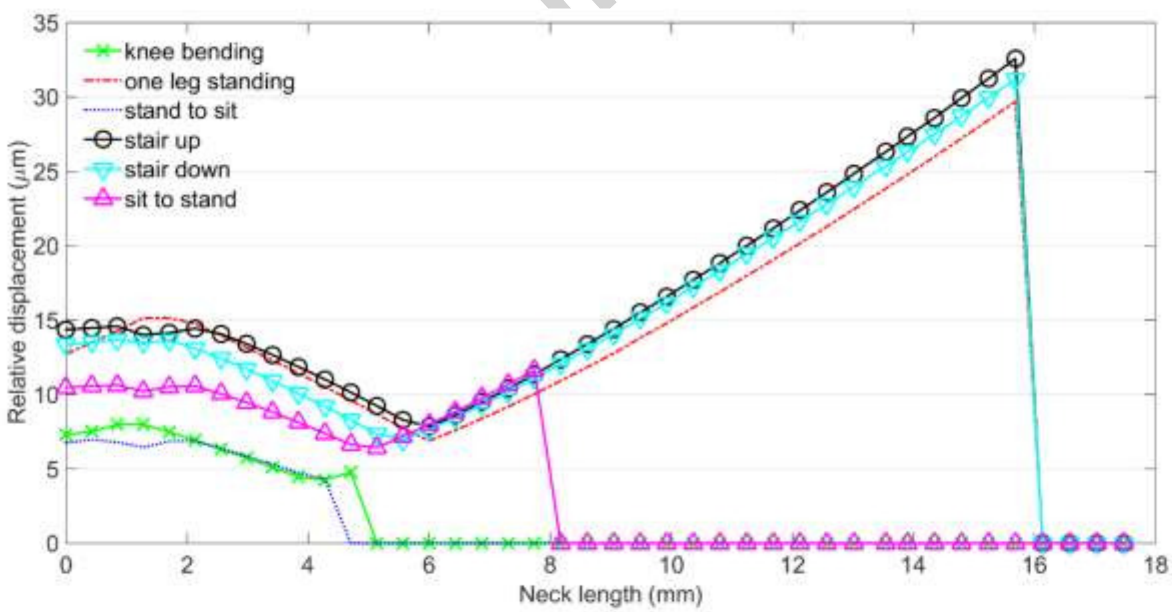

Figure 10. Maximum values of relative displacement (μm) across the neck circumference versus the neck length (mm).

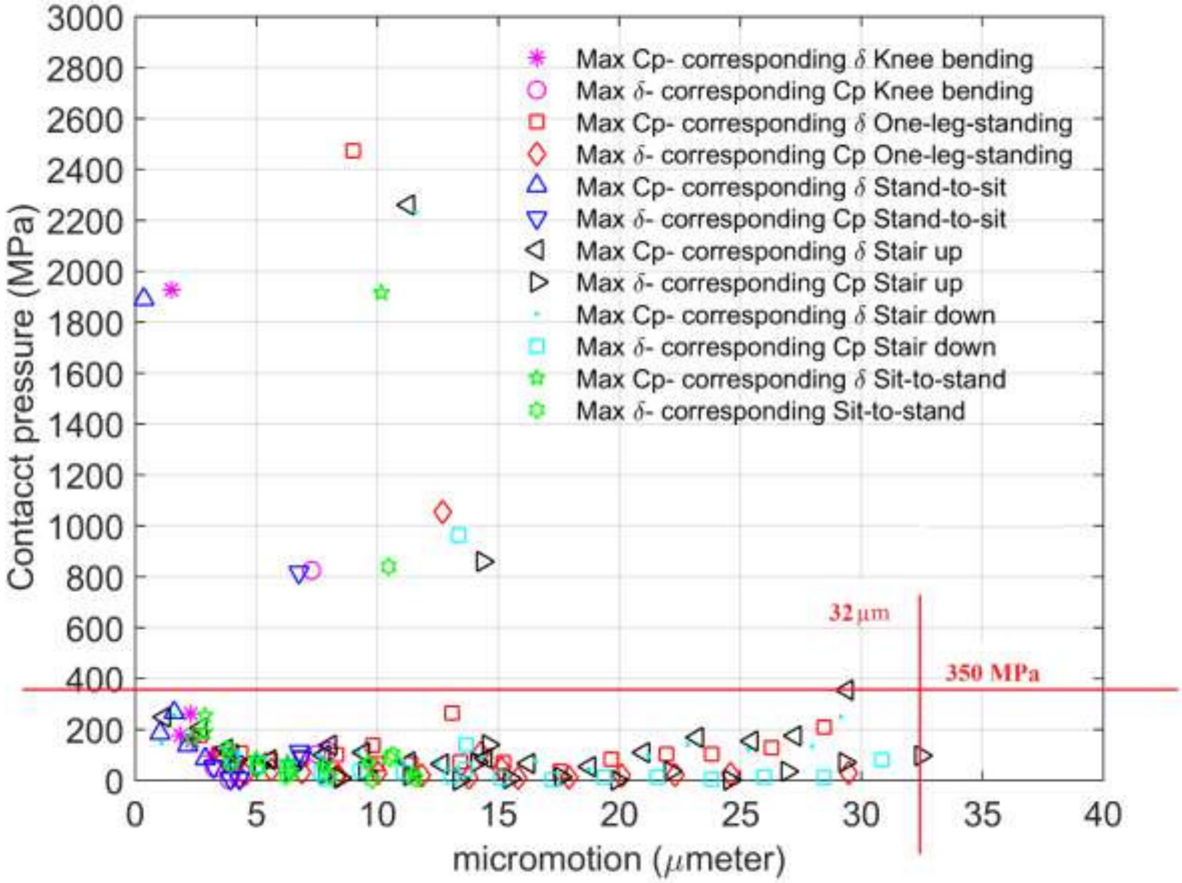

Figure 11. Maximum contact stresses (MPa) and maximum relative displacements (μm) over the neck length (mm) for different activities.

Video 1: Distribution of contact pressure in the superolateral region of the neck over the gait cycle for all the six activities modelled.

Highligths

- Mechanical behaviour of a CoCr/CoCr head-neck taper junction was studied using FEA
- The junction was subjected to gait forces and moments of several daily activities
- Stair up with the largest fretting work per length was the most critical activity
- Micro-motions < 38µm and contact stresses < 350 MPa mostly occurred in the junction