


# Wear of Femoral Head Taper Connections of Contemporary Total Hip Prostheses: An Experimental Study

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**Purpose:** Progress in the design of total hip prostheses has enhanced the long-term results of total hip arthroplasty. However, recent clinical failures have raised concerns regarding the long-term performance of taper connections. Issues at the taper connection of the femoral head can lead to implant failure and revision surgery. There is scarcity of published studies on the wear performance of contemporary femoral head taper connections in carefully controlled laboratory tests. This work aims to help remedy this shortcoming.

**Methods:** The study comprised dynamic load frame tests and multidirectional hip joint simulator tests for two contemporary prosthesis designs with titanium alloy femoral stems and CoCr and zirconia toughened alumina (ZTA) femoral heads of 36 mm diameter and medium neck length against vitamin E stabilized, highly cross-linked polyethylene liners (n = 3). Worn surfaces were analyzed by optical and scanning electron microscopy (SEM).

**Results:** Wear was more prominent in the inferior and distal parts of the CoCr head tapers, and these regions aligned with those of the trunnions that showed most wear. Wear marks on CoCr heads were relatively mild, indicative of fretting due to micromotion. Material displacement occurred locally without dislodged debris. ZTA heads mainly showed titanium transfer by adhesive wear. ZTA femoral heads outperformed CoCr heads regarding wear resistance and surface stability. The 12/14 tapers showed more pronounced wear and surface modifications compared with Type 1 tapers. EDX analysis confirmed the absence of adhesion between CoCr and Ti alloy, and increased oxygen percentage on worn regions.

**Conclusion:** The wear marks were mild. No serious damage was observed. The wear behavior of the taper connections appeared satisfactory, and not a cause for concern in the short term.

**Keywords:** biomechanics, biomaterials, medical device, modular femoral head, taper connection, servo-hydraulic load frame, hip joint simulator, micromotion, fretting, wear

## Introduction

Total hip arthroplasty has become a widely accepted and successful procedure for the treatment of various hip joint disorders. In 2021, Switzerland, Germany, Finland, and Austria reported some of the highest rates of hip and knee replacements compared to other countries with available data, with the average rate for hip replacement among OECD countries being 172 per 100,000 inhabitants.<sup>1</sup> The modularity of the total hip replacement system allows for customization by altering head materials, sizes, and neck lengths to meet individual patient needs, which has significantly advanced the field.<sup>2</sup> One critical interface in the system is the femoral head taper connection, which transmits loads between the femoral stem and the femoral head and plays a pivotal role in the overall stability and functionality of the implant.<sup>3,4</sup>

Understanding the tribological aspects of this interface is essential for progress in hip replacement surgery and improving patient results.<sup>5</sup> The various designs of head-trunnion interfaces can impact the bending moment, potentially resulting in different complications.<sup>6</sup> Despite progress in prosthesis design, wear and micromotion at the taper connection remain prevalent issues, which may lead to implant failure and the need for revision surgeries.<sup>7</sup> The objective of wear



testing is to assess the wear performance of potential implant materials and designs under conditions that mimic those experienced in vivo.

Recent notable clinical failures, such as the ASR XL and Pinnacle CoCr-on-CoCr, have raised concerns about the long-term performance of not only the bearing surfaces but also the taper connections, particularly in the context of adverse local tissue reactions and early implant loosening.<sup>8,9</sup> Retrieval studies show less taper wear for CoCr-on-polyethylene articulations compared with CoCr-on-CoCr<sup>10</sup> that is no longer used in clinical practice, but substantial taper damage has been observed even with CoCr-on-polyethylene.<sup>11</sup> The use of ceramic heads is on the rise, and the use of metallic heads is declining.<sup>12</sup> Retrieval studies show less taper damage with ceramic heads compared with metallic heads.<sup>13</sup> While previous research has provided valuable insights into this topic,<sup>14–17</sup> there is a scarcity of published studies on the wear performance of taper connections of contemporary designs in carefully controlled laboratory test conditions.

The present study focuses on two widely used, state-of-the-art total hip prostheses with CoCr-on-polyethylene and ceramic-on-polyethylene articulations. Established load frame tests were complemented by hip joint simulator tests. Hip joint simulators have mostly been used in the testing of the articulation of the femoral head against the acetabular liner. Since the wear rate of contemporary highly cross-linked polyethylenes has been shown to be very low,<sup>18,19</sup> the need for wear testing of acetabular liners has decreased considerably. Multidirectional hip joint simulators that have been shown to produce clinically relevant wear in walking simulation may be used for other types of testing, such as that of taper connections. Since the liner wear produced has been shown to be clinically relevant, it is reasonable to assume that the stresses, micromotion, corrosion and wear mechanisms produced at the taper connection also have clinical relevance, which is to be proven. The questions to be answered by the present study, based on critical wear testing, were as follows. Is there a difference in taper connection wear produced by the use of (1) metallic vs ceramic head, (2) small and smooth vs large and ridged taper trunnion, (3) fixed vs constantly changing the direction of loading, and finally and more generally, (4) does the taper connection wear still appear as a cause for concern?

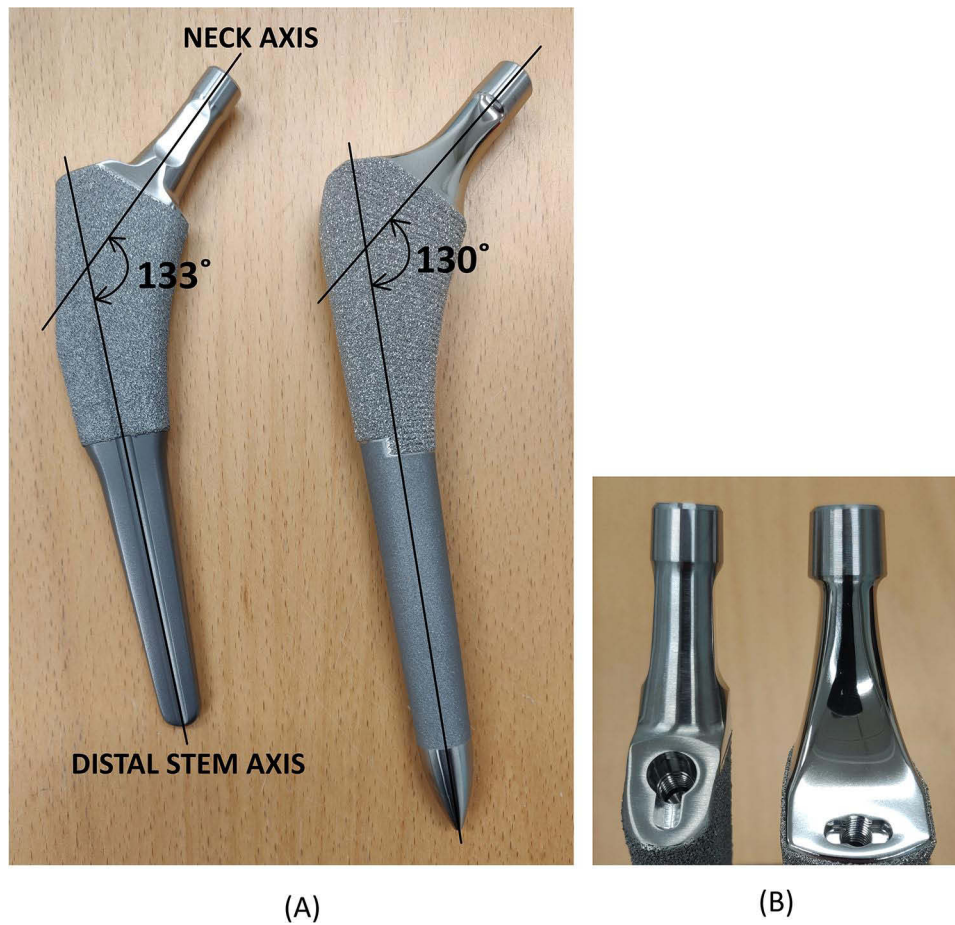
## Methods

Titanium alloy femoral stems and 36 mm diameter femoral heads were purchased from the Coxa hospital stock (Table 1). The widely used stem designs were Taperloc Complete with Type 1 Taper (Zimmer Biomet, Warsaw, IN, USA) and Summit with 12/14 Taper (DePuy Synthes, Warsaw, IN, USA) (Figure 1A and B). With both designs, the most common femoral head materials, CoCr and zirconia toughened alumina, ZTA (BioloX Delta, CeramTec, Plochingen, Germany), were tested. Despite the different manufacturer neck length designations (Table 1), the femoral heads represented the so-called medium neck length type, as the head center was not far from the taper center (Figure 2 and Table 2). To avoid confusion, the expression “medium neck length” was systematically used in the present study. Two types of tests for the taper connections were carried out: load frame (LF) tests and hip joint simulator (HJS) tests. In all tests, the sample size was 3. Hence, a total of 24 stems, 12 CoCr heads and 12 ZTA heads were tested. The test procedures were as follows.

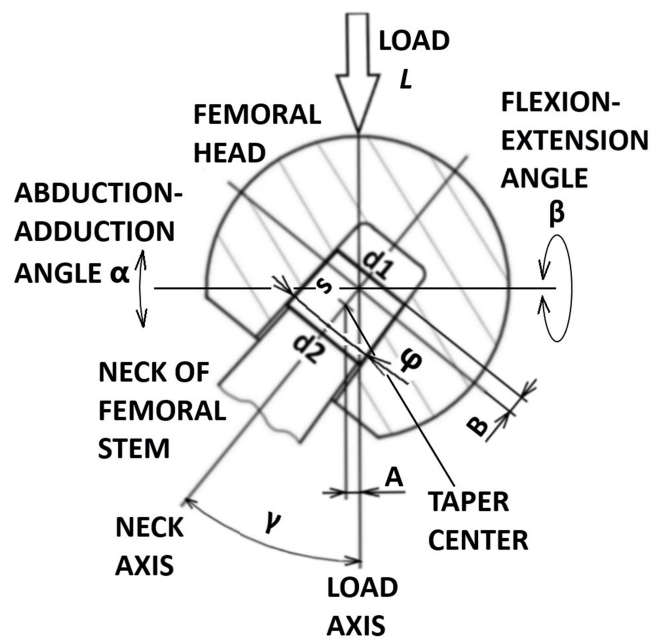
Load frame (LF) tests based on ISO 7206–6<sup>20</sup> (Figures 2, 3A–D and 4A–C). The direction of load relative to the taper connection was constant (Table 2). Dynamic load was applied to the femoral head fixed to the femoral stem in an MTS 858 Table Top System servo-hydraulic load frame (MTS Systems Corporation, Eden Prairie, MN, USA). The load sinusoidally varied between 0.55 kN and 5.34 kN at a frequency of 20 Hz, that was readily achieved since rigid stem holders were made from steel. The high frequency was necessitated by time constraints, as there were 12 tests to be

**Table 1** Components of Present Study

Design	Component	Taper designation	Catalog #	Number
Taperloc Complete	Ti alloy stem	Type 1 Taper	51-103200	12
	CoCr head	Type 1 Taper, Standard Neck	11-363662	6
	ZTA head	Type 1 Taper, Standard Neck	650-0661	6
Summit	Ti alloy stem	12/14 Taper	1570-01-180	12
	CoCr head	12/14 Taper, +5	1365-52-000	6
	ZTA head	12/14 Taper, +5	1365-36-320	6



**Figure 1** (A) Titanium alloy femoral stems of present study with neck angles, left Taperloc Complete (Zimmer Biomet, 20x160 mm standard offset, Type I taper), right Summit (DePuy Synthes, size 10 STD 170 mm, 12/14 taper). (B) Close-up of tapers, left smooth "Type I", right ridged "12/14".



**Figure 2** Taper connection with medium neck length femoral head, see Table 2 for quantities and numeric values of symbols.

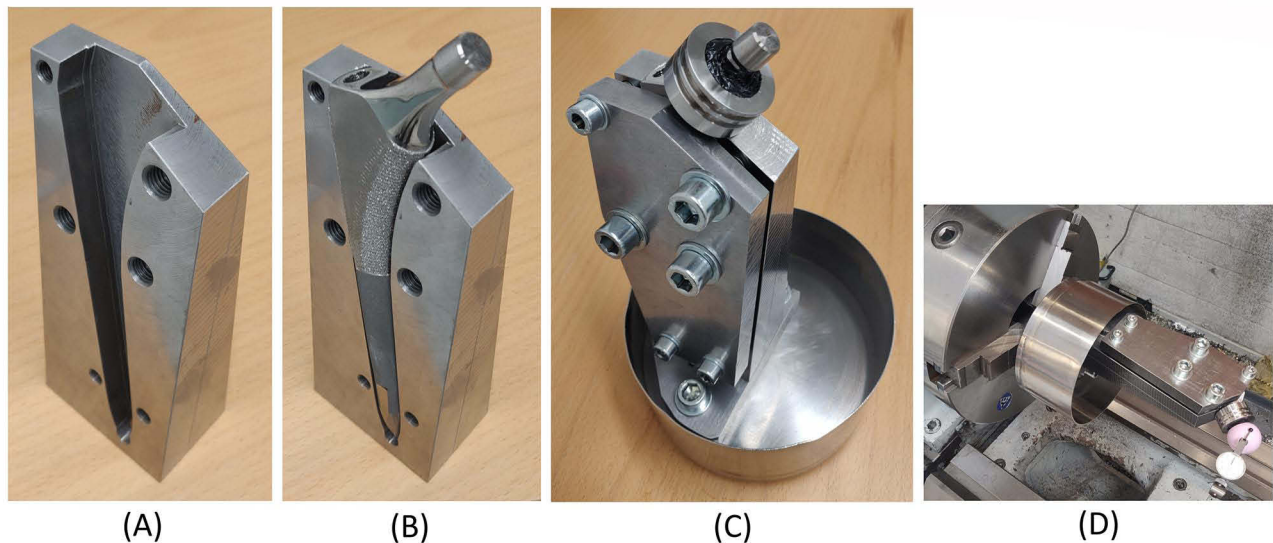
**Table 2** Caliper Measurements and Calculations for 2 Types of Taper Connections Tested with LF and HJS

Symbol	Quantity	Unit	Designation	12/14
			Type I	
d1	Minimum diameter of contact	mm	11.50	12.61
d2	Maximum diameter of contact	mm	12.06	13.61
s	Contact length	mm	8.4	10.5
$\phi$	Taper angle = $2\arcsin((d2-d1)/2s)$	°	3.8	5.5
B	Distance from center of femoral head to end of taper contact	mm	1.3	3.0
$\gamma^a$	Neck axis to load axis angle when $\beta = 0^{ob}$	°	37.0	40.0
	$\beta = 9^{oc}$	°	37.9	40.8
	$\alpha = 0^\circ, \beta = 23^{od}$	°	42.7	45.2
	$\alpha = -6^\circ, \beta = 0^{oe}$	°	31.0	34.0
	$\alpha = 0^\circ, \beta = -23^{of}$	°	42.7	45.2
	$\alpha = 6^\circ, \beta = 0^{og}$	°	43.0	46.0
A <sup>h</sup>	Moment arm of load relative to taper center when $\beta = 0^{ob}$	mm	1.8	1.4
	$\beta = 9^{oc}$	mm	1.8	1.5
	$\alpha = 0^\circ, \beta = 23^{od}$	mm	2.0	1.6
	$\alpha = -6^\circ, \beta = 0^{oe}$	mm	1.5	1.3
	$\alpha = 0^\circ, \beta = -23^{of}$	mm	2.0	1.6
	$\alpha = 6^\circ, \beta = 0^{og}$	mm	2.0	1.6
$(L \times A)_{max}$	Bending moment maximum at taper center in LF tests <sup>c</sup>	Nm	9.7	7.8
	HJS tests <sup>f</sup>	Nm	6.0	4.8

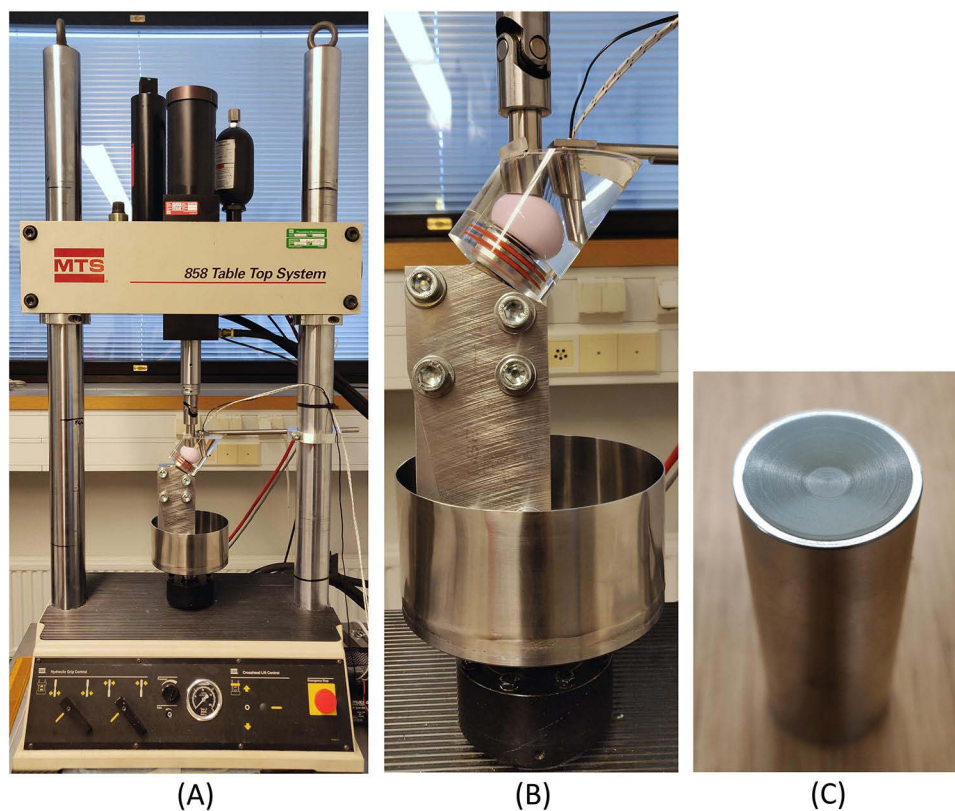
**Notes:** <sup>a</sup>Determined by (I) Neck axis to distal stem axis angle, (II) LF test requirement (ISO 7206–6) that adduction of distal stem axis = 10° and  $\beta = 9^\circ$ , and (III) HJS test motion that was biaxial and nearly sinusoidal so that  $\beta$  ranged  $\pm 23^\circ$  and  $\alpha$  ranged  $\pm 6^\circ$  with  $\pi/2$  phase shift. <sup>b</sup>Neutral position, adduction of distal stem axis = 10°. <sup>c</sup>LF test position,  $\gamma = \arccos(\cos\gamma_{\beta=0^\circ}\cos9^\circ)$ ,  $L_{max} = 5.34$  kN. <sup>d</sup>HJS test position at 0% of gait cycle,  $\gamma = \arccos(\cos\gamma_{\beta=0^\circ}\cos23^\circ)$ ,  $L = L_{min} = 0.4$  kN. <sup>e</sup>25%,  $\gamma = \gamma_{\beta=0^\circ} - 6^\circ$ ,  $L = 2.7$  kN. <sup>f</sup>50%,  $\gamma = \arccos(\cos\gamma_{\beta=0^\circ}\cos(-23^\circ))$ ,  $L = L_{max} = 3.0$  kN. <sup>g</sup>75%,  $\gamma = \gamma_{\beta=0^\circ} + 6^\circ$ ,  $L = 1.3$  kN. <sup>h</sup> $A = ((\sqrt{(s^2 - ((d2 - d1)/2)^2})/2) - B)\sin\gamma \approx (s/2 - B)\sin\gamma$ .

carried out with only one available LF unit. The frequency is likely to affect the repassivation phenomenon. The test length was 10 million cycles, and the test environment was a 9.0 g/l solution of analytical grade sodium chloride (NaCl) in deionized water at  $37 \text{ }^\circ\text{C} \pm 2 \text{ }^\circ\text{C}$ . In ASTM F1875-98,<sup>21</sup> dynamic loading between 0.3 kN and 3.3 kN is recommended for fretting tests of the taper connection. However, the higher load of ISO 7206–6<sup>20</sup> was chosen and implemented, with the assumption that wear and corrosion would become more evident. In ASTM F1875-98,<sup>21</sup> it is recommended that the loading point on the femoral head is not exposed to saline. In the present tests, it was. However, the loading contact was against a polyethylene disk, not a metallic one.

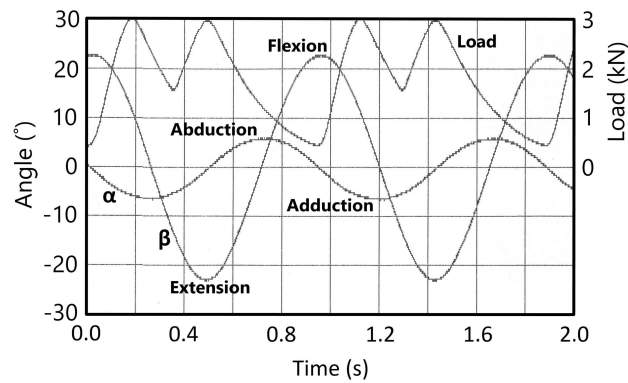
Hip joint simulator (HJS) tests based on ISO 14242–1<sup>22</sup> (Figures 2, 5, 6A–D and 7A–E). The direction of load relative to the taper connection changed continuously as normal level walking was simulated (Table 2). The established, multidirectional HUT-4 hip joint simulator,<sup>23</sup> that was used for these tests, has been shown to produce wear similar to that produced in ISO 14242–1 conditions for the acetabular liner.<sup>24</sup> Therefore, the simulator, as its commercial variant, was considered appropriate for wear testing of the taper connection as well.<sup>25,26</sup> The continuously changing direction of loading and the additional torsional stresses caused by the multidirectional frictional torque from the articulation were expected to produce more realistic stresses, micromotions, corrosion and wear mechanisms at the taper interface, together with the physiologic 1 Hz frequency. The high frequency in the LF test may have an effect on repassivation. The proximal part of the femoral stem was fixed to the abduction-adduction cradle, the base plate of which was replaced with a new, wider one made from stainless steel AISI 316. Acetabular components of an earlier study were used as their liners showed no detectable wear.<sup>27</sup> The liner material was Vivacit-E (Zimmer Biomet, Warsaw, IN, USA), and the acetabular abduction angle was 40°. The lubricant was HyClone alpha calf serum SH30212 (HyClone Laboratories, Logan, UT, USA) diluted 1:1 with ultrapure deionized water. The protein concentration of the lubricant was 20 mg/mL. To prevent microbial growth, antibiotic/antimycotic HyClone SV30079 was added to the lubricant at 10mL/l. Alpha calf serum has



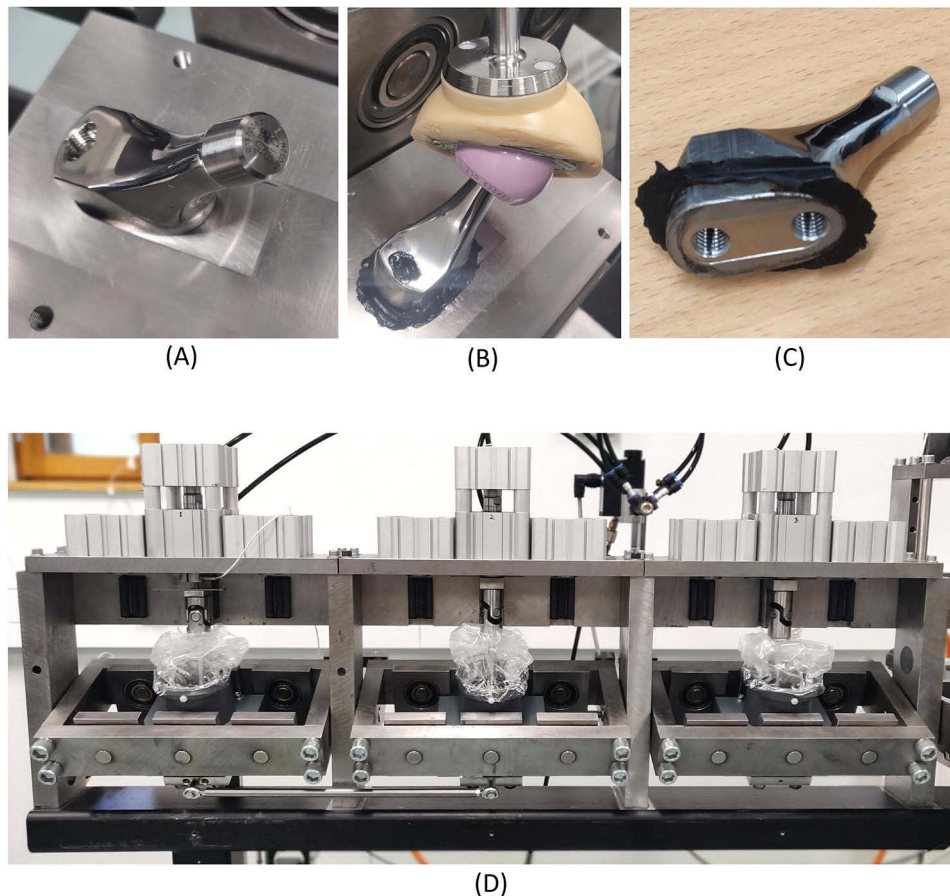
**Figure 3** (A) Femoral stem holder for LF test, made from steel, and recess milled to fit for (B) Summit stem. Adduction of distal stem axis =  $10^\circ$  and  $\beta = 9^\circ$  (see Figure 2 and Table 2). Stem profile was digitized by coordinate measuring machine and resulting file was used in numerical control milling. (C) Stem clamped and holder fixed to base disk. Double o-ring sleeve made from stainless steel was fixed to neck of stem by polyurethane sealant so that saline environment at  $37 \pm 2^\circ\text{C}$  could be provided for taper. Base disk was brimmed to protect force transducer of load frame from possible leakage of saline chamber. (D) Alignment of femoral head to load axis using lathe and dial gauge.



**Figure 4** (A) Test ongoing in servo-hydraulic load frame with Taperloc stem and ZTA femoral head. (B) Close-up, note saline chamber (volume = 125 mL) with temperature control and universal joint above loading bar to prevent possible bending of loading cylinder. (C) Loading bar (upside down) with loading end that had self-centering shape of concave truncated cone ( $15^\circ$ ). Loading end was thin disk (central thickness = 1.5 mm), made from vitamin E stabilized, highly cross-linked ultra-high molecular weight polyethylene. Disk was press fit in recess of highly corrosion resistant NiCrMo alloy (Hastelloy C276, ASTM B564/2.4819) bar. Disk protected bearing surface of femoral head against wear and corrosion. As disk was thin and radially supported, its deformation was low, hence 20 Hz test frequency was readily realized.

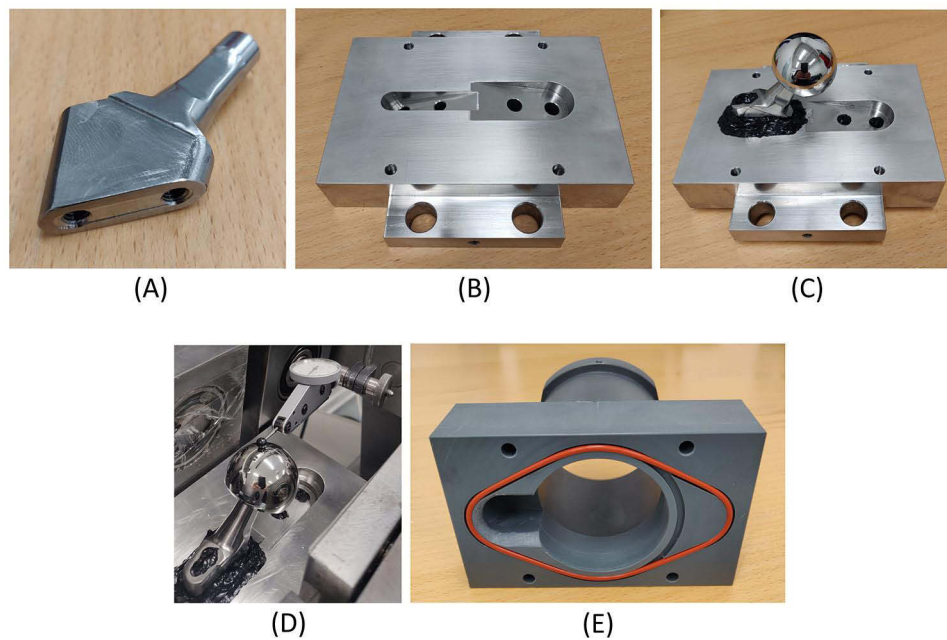


**Figure 5** Measured motions and load of HUT-4 Hip joint simulator. Note  $\pi/2$  phase shift between abduction-adduction  $\alpha$  and flexion-extension  $\beta$  that was essential for multidirectional relative motion. Cycle time = 0.94 s. Peak load of 3 kN was from ISO 14242-1.



**Figure 6** (A) Proximal part of Summit stem fixed to base plate of abduction-adduction cradle of HUT-4 Hip joint simulator, (B) with polyurethane sealant, ZTA head and acetabular components (abduction angle =  $40^\circ$ ), and loading bar above them, made from stainless steel (C) after HJS test, note threaded fixation holes, (D) HUT-4 HJS test ongoing with 3 test stations. Note flexible plastic covers over lubricant chambers that protected serum lubricant against contamination and prevented evaporation.

been widely used as a lubricant in wear testing of orthopedic biomaterials since the 1990s because of its suitable protein composition. It is used as a surrogate for synovial fluid that is not available in sufficient quantities for wear testing. Due to frictional heating of the articulation and the sealed plastic cover that prevented evaporation cooling (Figure 6D), the lubricant bulk temperature was typically close to  $37^\circ\text{C}$  during testing. The test length was 5 million cycles at 1.07 Hz, which took 8 weeks to run. At intervals of 625 000 cycles (once a week), the test was stopped; the specimens and all



**Figure 7** (A) Proximal part of Taperloc stem for HJS test, note fixation surface prepared with threaded fixation holes, (B) base plate of abduction-adduction cradle of HUT-4 Hip joint simulator, and (C) with fixed proximal stem, CoCr head and polyurethane sealant. Base plate was made from AISI 316 stainless steel. As it was practical to make fixation surface perpendicular to threaded hole of inserter (Figure 1B), slopes were milled to base plate so that distal stem axis, had distal stem not been cut off, would be at  $10^\circ$  adduction, as in LF tests. Hence, at above neutral position of base plate,  $\gamma = 37^\circ$  with Taperloc and  $\gamma = 40^\circ$  with Summit (see Figure 2 and Table 2). (D) Alignment of femoral head using dial gauge with non-damaging plastic tip. (E) Lubricant chamber (bottom view, volume = 400 mL) made from PVC, note o-ring seal and cavity for proximal stem.

parts that had been in contact with the lubricant were cleaned using detergent and a soft brush, rinsed with warm tap water and deionized water, with the exception of the femoral components that were firmly fixed to the test machine and therefore cleaned with multiple paper towels soaked in water and finally in ethanol. After this, the test was continued with fresh lubricant. Five million cycles may be considered to correspond to  $2\frac{1}{2}$  years in vivo.<sup>28</sup>

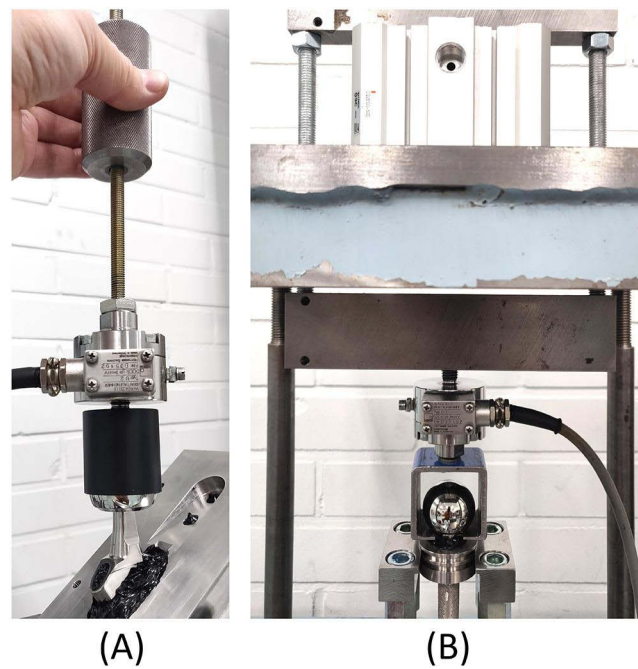
All heads were assembled and disassembled only once. The assembly force was considered an important test parameter. Based on a cadaver study,<sup>29</sup> a value of 2.3 kN was chosen and systematically used for all tests (Figure 8A). It appears that the frequently mentioned “recommended” value of 4 kN<sup>7</sup> is not commonly achieved in surgery.<sup>29</sup> The disassembly force after the tests was also measured (Figure 8B).<sup>30</sup> After the disassembly, the taper surfaces were cleaned, the stem tapers were cut off, and the heads were cut into superior and inferior halves (Figure 9A and B).

Surface roughness of the stem and head tapers before and after the tests was measured with a Mahr MarSurf PS 10 surface roughness measurement device (Mahr GmbH, Göttingen, Germany). The mean surface roughness values  $R_a$  were calculated from at least 10 measurements made axially (traversing length 4.0 mm, cut-off length 0.8 mm) on various locations, not specifically emphasizing the most damaged zones, but rather being representative of the entire contact zone.

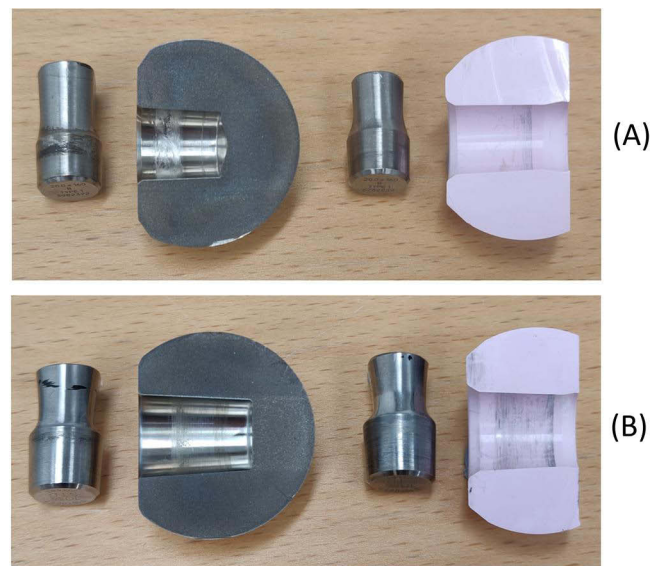
The specimens were analyzed using a Zeiss Stemi 508 Stereo Microscope and a Zeiss Merlin Field Emission Scanning Electron Microscope (SEM) equipped with Bruker Quantax Energy Dispersive Spectrometer (EDS) and Electron Backscatter Diffraction (EBSD) detectors, the former being used for the Energy Dispersive X-ray Spectroscopy (EDX) analysis (Carl Zeiss Microscopy GmbH, Jena, Germany). Corrosion and fretting damage at the taper connections were assessed based on the morphology and extension of the damage using the Goldberg scoring system.<sup>14</sup>

## Results

The disassembly forces of the femoral heads are presented in Figure 10, and the surface roughness of the tapers in Figure 11. Stereomicroscope and SEM analysis indicated that there was more wear and damage on the inferior part of the femoral head compared to the superior part, with greater damage observed on the distal regions than on the proximal ones. In this context, damage refers to the physical and mechanical deterioration of the surface due to repeated

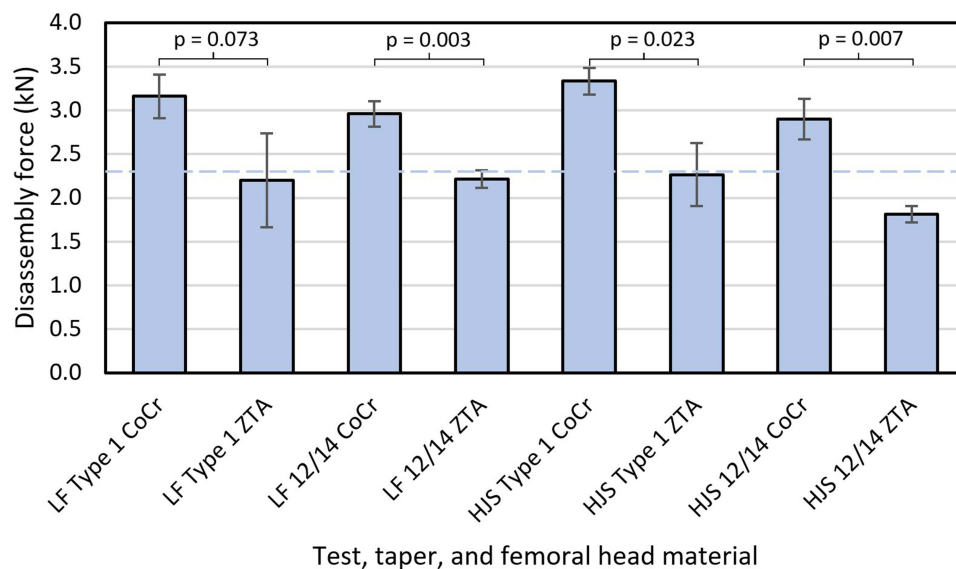


**Figure 8** (A) Assembly of CoCr femoral head to Type I taper with drop weight impact tool and force transducer for HJS test. Force signal of 1 ms width and target magnitude of 2.3 kN was captured with oscilloscope. To avoid damage to bearing surface, 2 mm of polyacetal (within black polyacetal guide sleeve) separated bearing surface from force transducer. (B) Measurement of disassembly force, generated by pneumatic cylinder, of CoCr femoral head from Type I taper after LF test. Disassembly force measurement trials with impact tool were successful as well. Force transducer U2 (HBM, Germany) was calibrated for both tension and compression by calibrated 5 kN weight.

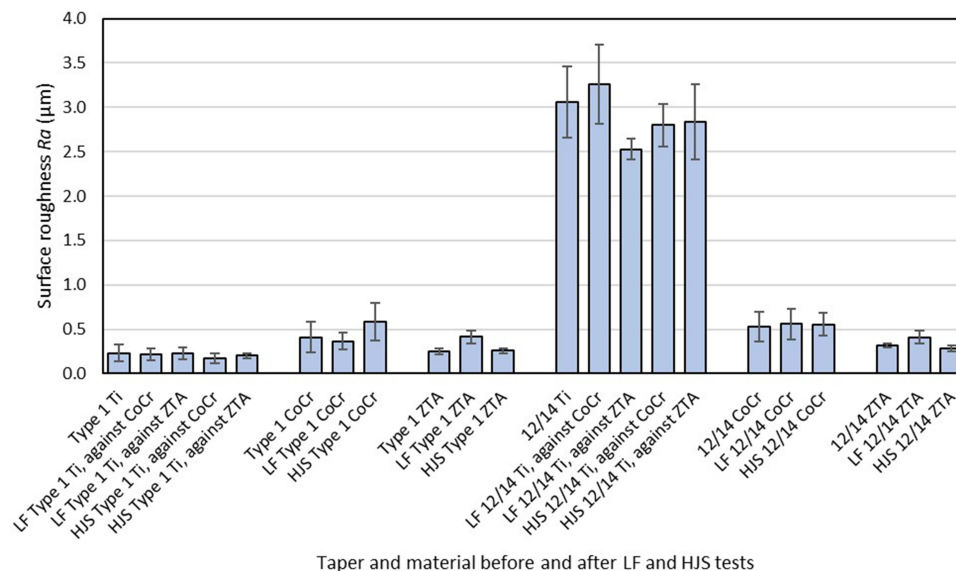


**Figure 9** Specimens prepared for microscopy. CoCr heads (left) were cut by wire electrical discharge machining and ZTA heads (right) by diamond saw into superior and inferior halves. Fixation to diamond saw required cutting top calotte off first. (A) Type I from HJS tests, superior taper surfaces. (B) 12/14 from LF tests, inferior taper surfaces. Marks of micromotion can be seen on CoCr heads. Ti transfer was typical of ZTA heads.

movement, loading, or interaction with biological fluids and may include surface roughening or other alterations not necessarily involving material loss. Wear, on the other hand, is limited to the loss of material from a surface due to relative motion under load. For ceramic head tapers, stereomicroscope images (Figure 12) revealed no actual wear regardless of the test performed, LF or HJS, or the type of taper. Instead, only metal transfer was observed. For CoCr head tapers, stereomicroscope images showed that the HJS CoCr samples with Type I taper exhibited the most noticeable

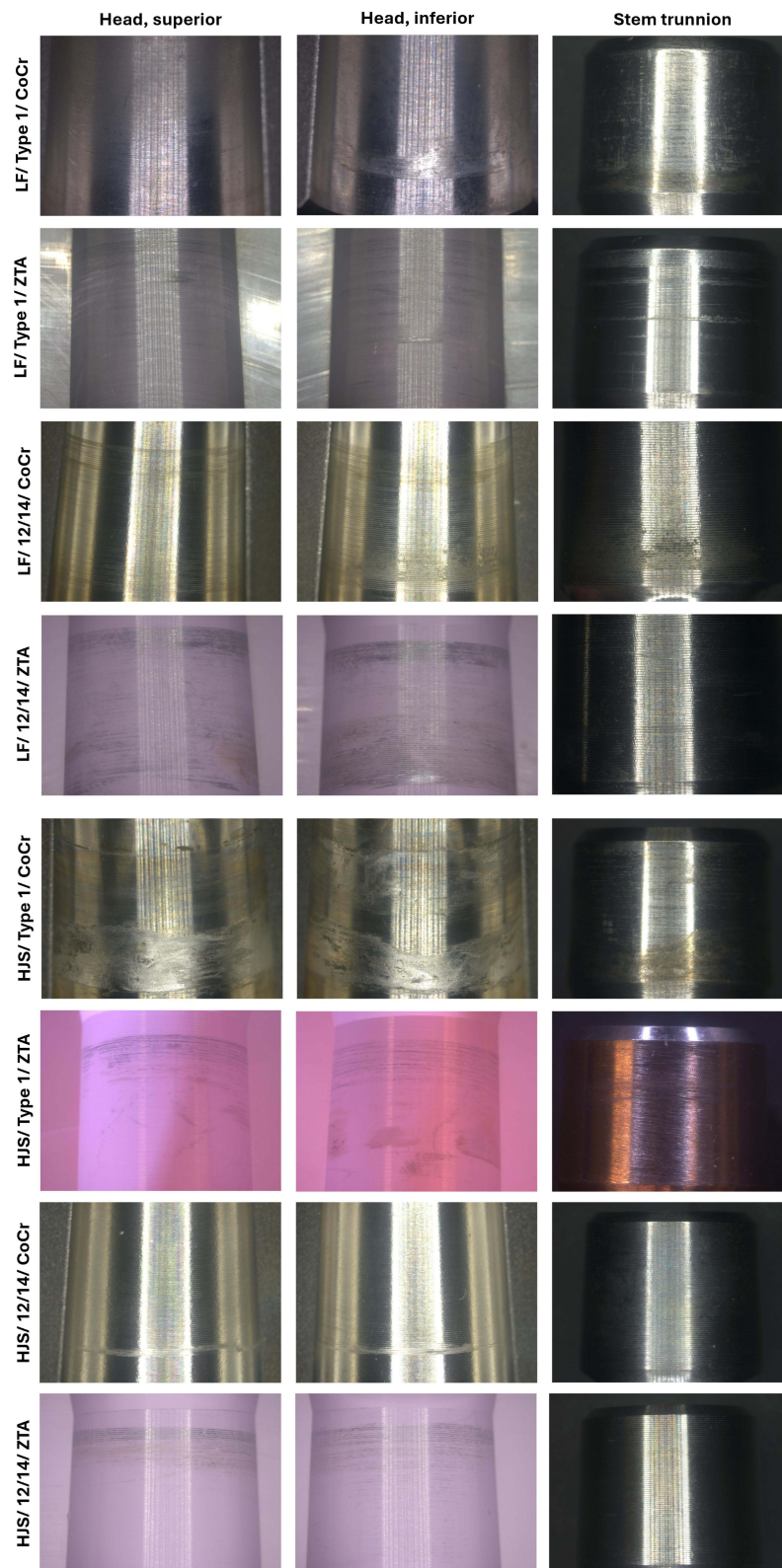


**Figure 10** Disassembly force, mean  $\pm$  SD, of femoral heads after LF and HJS tests. Dashed line indicates assembly force, 2.3 kN.

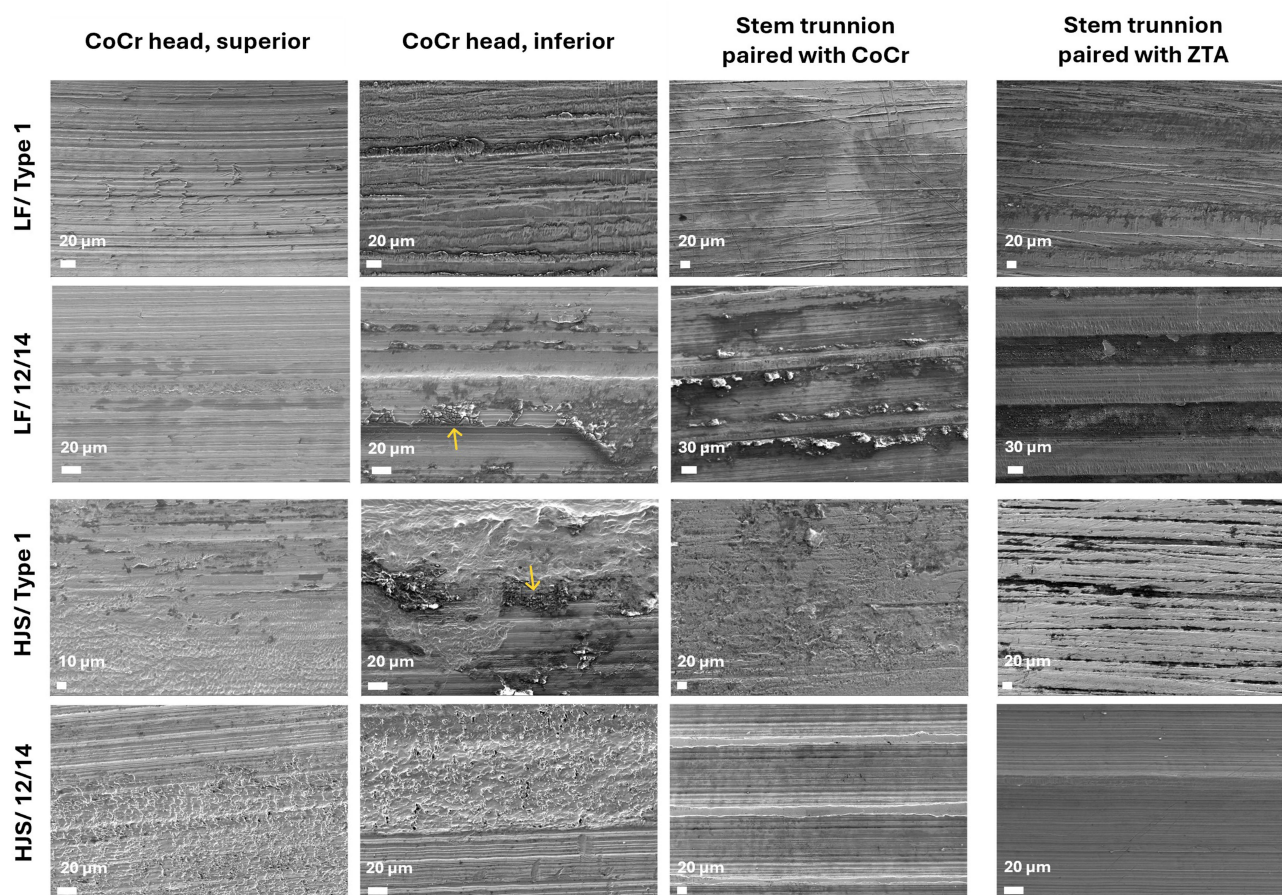


**Figure 11** Arithmetic average surface roughness  $R_a$  ( $\mu\text{m}$ ), mean  $\pm$  SD, of stem and head tapers before and after LF and HJS tests.

wear. However, the SEM images (Figure 13), where the surface microstructure of specimens was visible, indicated that the samples with the most wear included both HJS CoCr samples, Type 1 and 12/14. The least worn sample in SEM images was the LF CoCr sample with Type 1 taper. In the SEM micrographs of the CoCr head specimens, both Type 1 and 12/14, that underwent the HJS test, a layer caused by adhesive wear could typically be observed superiorly and inferiorly (Figure 13). For the LF and Type 1 configuration, corrosion received a score of 1 (none), with no visible discoloration or other signs of corrosion. Fretting was scored as 2 (mild), attributed due to localized fretting marks. In the LF and 12/14 configuration, corrosion was scored as 2, characterized by localized surface discoloration, mainly on the stem trunnions, and fretting also received a score of 2, with visible fretting across a few machining lines. For the HJS and Type 1 configuration, both corrosion and fretting were scored as 2, based on localized discoloration and visible fretting. In the HJS and 12/14 configuration, corrosion had a score of 1, showing no signs of discoloration, debris, or pitting. While fretting was scored as 2, due to the presence of mild fretting on the CoCr head taper.



**Figure 12** Stereomicroscope images of taper surfaces. Images are organized in 3 columns: superior head taper (left), inferior head taper (middle), and stem trunnion (right). Rows represent different test conditions and materials. Surface features such as wear marks and material transfer are visible.

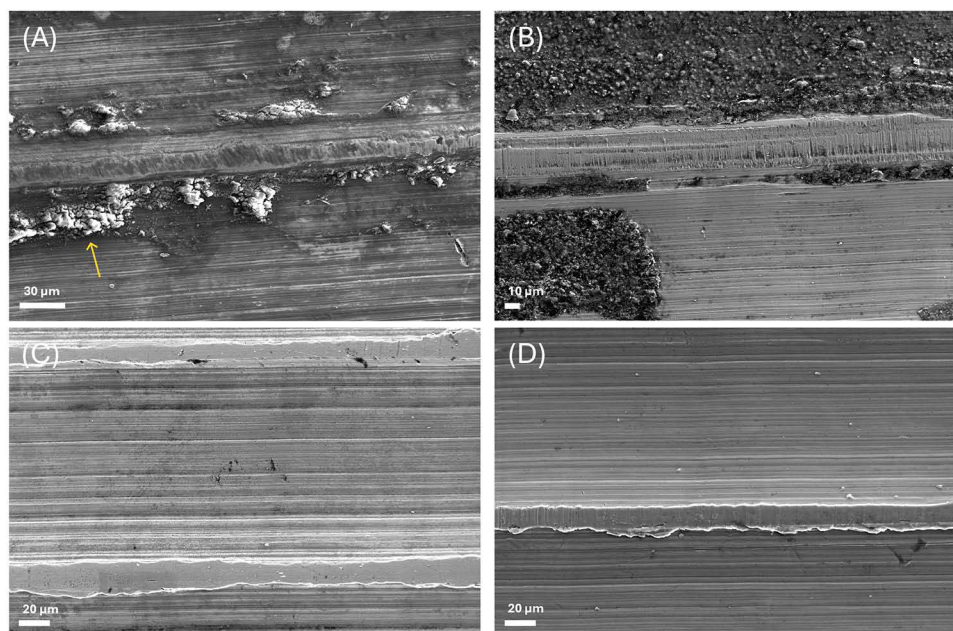


**Figure 13** SEM micrographs of taper surfaces. Images are organized in four rows: LF, Type 1; LF, 12/14; HJS, Type 1; HJS, 12/14. Columns represent different taper surfaces. Surface features such as wear marks are visible. Yellow arrows indicate areas with visible cracking of the oxide layer.

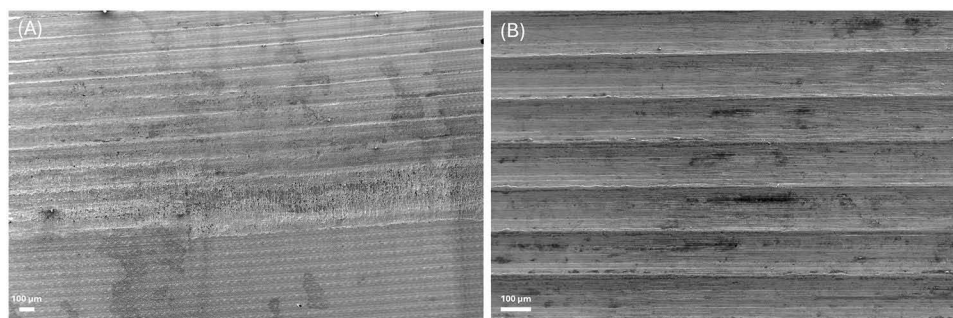
There was noticeable imprinting on the CoCr femoral head tapers paired with the 12/14 stem tapers, regardless of the test type. Localized polishing was observed on the 12/14 stem tapers (ZTA and CoCr heads, and LF and HJS tests), being more prominent on the CoCr head tapers but also visible on the ZTA ones. Surface damage was unevenly distributed across the taper surfaces of the 12/14 stem trunnions. The ridges of these stems appeared polished and exhibited signs of plastic deformation (Figure 14). On the HJS test specimens, minimal damage was present between the ridges of the 12/14 stems, with visible parallel microgrooves. For the LF test specimens, while these microgrooves remained visible, there were also additional signs of wear. These included plastic deformation with flattened ridge peaks, as well as microcracks, dark discolouration, and surface roughening between the ridges, which are signs of fretting.

Stereomicroscope images of the CoCr head tapers showed distinct imprints matching the stem taper ridges (Figure 15A and B). There was a localized dull region, suggesting an increase in surface roughness or slight deformation due to repeated loading. The SEM micrographs (Figure 14) revealed minor smoothing of indentation edges and localized plastic deformation. Variations in brightness suggested subtle textural modifications associated with wear mechanisms such as fretting or adhesive wear. Cracking of the oxide layer can be observed on various components and specimens, particularly on the inferior CoCr head tapers (Figure 13), as well as on the 12/14 stem taper (Figure 14A).

In the EDX analysis of the CoCr 12/14 LF sample, the area with the highest oxygen content was the worn one, which was also the darker and more discolored region. The decrease in cobalt content on the worn region was higher than the decrease in the chromium content. Furthermore, the carbon content was higher on the worn area. On the CoCr 12/14 HJS sample, there was also a different surface composition on the unworn and worn regions. For this sample, there was also an increase in the oxygen content on the worn region. There was also an increase in the carbon content. Cobalt and chromium, the main elements, remained constant, but the chromium peak was slightly enhanced. On the 12/14 stem taper



**Figure 14** SEM micrographs of 12/14 stem trunnions at higher magnification. Images show ridges of stems, which appear polished and exhibit signs of plastic deformation. (A) LF test, paired with CoCr head; (B) LF test, paired with ZTA head; (C) HJS test, paired with CoCr head; (D) HJS test, paired with ZTA head. For HJS test specimens (C and D), minimal damage is present between ridges of 12/14 stems. On LF test specimens (A and B) there are additional signs of wear. Yellow arrow indicates area with visible cracking of the oxide layer.



**Figure 15** SEM micrographs of taper surfaces from (A) CoCr femoral head taper and (B) 12/14 taper, which underwent LF test. When considered alongside their respective scale bars, these images show how the original machining grooves on the 12/14 taper align closely with the imprint pattern observed on the CoCr head taper.

that was paired with the ZTA head taper in the LF test, the surface had a higher oxygen content on the worn region. The titanium content was high, but it decreased slightly, while carbon was present in a slightly higher concentration on the worn region. The aluminum and vanadium contents were constant on both analyzed regions of the stem taper.

It is important to highlight that, even in samples where the SEM micrographs revealed no visible discoloration, the EDX analysis indicated an increase in the percentage of oxygen at the taper connection. This trend was observed when comparing the areas with little or no wear with those exhibiting distinct wear marks. This analysis did not detect titanium present on the surface of the CoCr head tapers, which implies there was no metal transfer from the titanium alloy stem taper to the CoCr head taper surface, unlike what happened with the ZTA heads.

## Discussion

Wear tests were done for femoral head taper connections of contemporary total hip prostheses. For clinical relevance, 2 widely used designs of titanium alloy femoral stems and their tapers, 2 most widely used femoral head materials, the most common head diameter, the most common neck length heads, a realistic assembly force of the heads, a widely used liner material, and

a realistic acetabular abduction angle (HJS tests) were chosen for the present study. As there is no ISO standard specifically for wear testing of the taper connection, the widely used ISO 7206–6,<sup>20</sup> and ISO 14242–1<sup>22</sup> for the simulation of in vivo loading and motions of total hip prostheses were considered mostly relevant for the purpose, and were followed. In addition, in the HJS test, the neck axis angle was consistent with that in the LF test specified in the ISO 7206–6. The ASTM F2009 standard<sup>30</sup> was followed in the head disassembly force measurement. The microscopical and surface roughness analysis represented state-of-the-art methods.

The wear behavior of the taper connections was satisfactory. Wear marks could be described as mild to absent (score  $\leq 2$ ) when using the Goldberg scoring system.<sup>14</sup> Distinct differences in wear patterns between CoCr and ZTA head tapers were found. CoCr head tapers were more prone to wear, especially under HJS conditions, than ZTA head tapers, which exhibited high wear resistance. ZTA head tapers of the LF test showed higher metal transfer than those of the HJS test. The taper design and type of test also influenced the wear mechanisms and surface modifications observed. The present global trend is an increase in the use of ceramics instead of CoCr,<sup>12</sup> mainly because the former is harder and thus less vulnerable to bearing surface abrasion, which could increase polyethylene wear.<sup>31–34</sup> In addition, retrieval studies show that the use of ceramic heads leads to less taper wear.<sup>13</sup>

To the best of the authors' knowledge, the present study was the first to use state-of-the-art femoral stems in HJS wear testing of femoral head taper connections with biological lubrication. The study opens exciting prospects for the utilization of multidirectional hip joint simulators in more extensive taper connection studies, including larger sample sizes, long neck heads and other taper designs. Based on the present tests with only three test stations employed simultaneously, new types of specimen holders have been designed so that the full 12-station capacity of the HUT-4 HJS can be utilized in the future. More testing is needed in order to determine whether HJS tests could eventually replace established LF tests in taper connection studies. The same holds true for longer testing times. It is reasonable to assume that the multidirectional loading in HJS tests with additional stresses from the articulation results in clinically most relevant stresses, micromotion, corrosion and wear mechanisms at the taper connection. The physiological frequency of 1 Hz is still a disadvantage on the practical level, as the tests are very time-consuming. For example, a test of 5 million cycles takes 2 months to carry out. The isolation of the stainless steel loading bar from the serum lubricant can be arranged to make the test electrochemically compatible with the ASTM F1875-98.<sup>21</sup>

Although the observed wear performance appears to be satisfactory for the duration of the present tests, it is essential to bear in mind the potential biological consequences related to taper wear over protracted periods of time. The wear of the femoral head-neck interface can lead to adverse local tissue reactions known as trunnionosis. These reactions may include necrosis, vasculitis, and pseudotumor formation. Previous studies<sup>6,11</sup> suggest that factors such as femoral head size and trunnion design play a role in trunnionosis. The present study was based on LF and HJS tests conducted in vitro. However, there is a significant need for research and analysis of periprosthetic tissues and retrieved implants in order to understand the effect the debris has on patients, especially in the long term, and the wear and corrosion mechanisms.

In earlier pioneering taper connection studies with a hip joint simulator similar to the present one, the Ti alloy trunnions were custom-made for the tests.<sup>25,26</sup> Detectable wear rates of the trunnions were obtained: 0.3 mg/10<sup>6</sup> cycles with ZTA-on-ZTA articulations and 0.2 mg/10<sup>6</sup> cycles with CoCr-on-polyethylene. The heads were periodically disassembled for weighing and then reassembled for the continuation of the tests. It is not known if this procedure affects the measured weight loss. In weighing trials of the present study, it was not possible to observe consistent weight changes considering the resolution of the balance, 0.1 mg (in the range of 60 g to 200 g). In another HJS study,<sup>35</sup> the Ti alloy trunnions were also custom-made, and CoCr and ZTA heads were compared. Damage was much more severe than in the present study, particularly with CoCr heads. In a study by Wight et al,<sup>36</sup> titanium alloy femoral stems of a single design were used with CoCr heads in HJS testing; however, the test length was only one million cycles, the frequency was 3 Hz, and the lubricant was phosphate buffered saline. Damage to taper surfaces was considered mild. Yang et al<sup>37</sup> showed in a short-term HJS study with custom-made Ti alloy trunnion and CoCr head that the role of fretting in disrupting the passive oxide layers at the trunnion-head interface leading to corrosion is complicated by the formation and disruption of an adsorbed protein layer that also plays an important role.

The present tapers were nearly optimal biomechanically in the sense that their moment arm values  $A$  were small, between 1.3 mm and 2.0 mm (Figure 2 and Table 2). This probably explained the observed relatively mild wear marks,

which were favorable findings and may corroborate confidence in the wear performance of the present taper connections. Clinical retrieval studies for the present types of tapers, that could be used as a reference, are scarce but mostly favorable.<sup>38,39</sup> Note that the measurements presented in Table 2 were not intended to be of the utmost precision but of sufficient precision for a reliable approximation of the magnitude of the moment arm  $A$ .

Type 1 trunnion was smaller in both diameter and length, and it was smoother, whereas 12/14 trunnion was larger and ridged (Table 2, Figures 1B and 11). In addition, the taper angle was lower in Type 1 ( $3.8^\circ$ ) compared with 12/14 ( $5.5^\circ$ ). It is difficult to distinguish between the effects of size, surface topography and taper angle on the observed wear behavior. Note that the manufacturers use a variety of different tapers with no standardization. For example, there are several different tapers with the taper angle varying from  $5.5^\circ$  to  $5.8^\circ$  that are inexplicably and misleadingly designated “12/14” by their manufacturers.<sup>40</sup> It is possible that combining incompatible 12/14 or other taper size components from different manufacturers leads to serious consequences clinically due to very high wear and metal release caused by poor fit. Historically, the most common type of taper, 14/16, was intended to unequivocally be a 1:10 taper, ie, the diameter increased from 14 mm to 16 mm in an axial distance of 20 mm. Hence, the taper angle was  $2\arctan(1/20) = 5.725^\circ (= 5^\circ 43' 29")$ . It is unfortunate that over the last decades, the decreasing trend in the taper size has been so incoherent. Standardization of the taper connection would be most desirable. It would, among other benefits, eliminate the possibility of component mismatch clinically. The lack of standardization of not only the taper connection design and dimensions but also its wear testing is likely to complicate regulatory actions. To add confusion, tapers used with modular femoral heads are often incorrectly called “Morse” tapers. In fact, the Morse tapers according to ISO 296<sup>41</sup> are a series of self-holding machine tool shank tapers close to 1:20 (from 1:19.002 to 1:20.047), ie, their taper angle is close to  $3^\circ$ .

The mean disassembly forces of CoCr heads were higher than those of ZTA heads (Figure 10). This could be explained by the 63% difference in the elastic moduli of the head materials (380 GPa vs 220 GPa) so that the more elastic CoCr heads seated tighter in the Ti trunnions, probably aided by fretting wear and plastic deformation. The results show that the fixation of CoCr heads was tightened due to the test loading. The relatively low assembly force did not prove harmful in this sense. The highest disassembly force,  $3.3 \text{ kN} \pm 0.2 \text{ kN}$ , was measured for Type 1 CoCr heads from HJS tests that showed the most pronounced wear marks (Figure 9A).

Regarding changes in surface roughness  $Ra$ , we observed an increase in Type 1 CoCr heads in HJS tests, probably due to micromotion (Figures 9 and 11), increase in both Type 1 and 12/14 ZTA heads in LF tests due to Ti transfer, and decrease in 12/14 trunnions due to flattening of ridges in HJS tests. Noteworthy was also the  $Ra$  constancy of the smooth Type 1 trunnions.

The present HJS tests could be considered to represent  $2 \frac{1}{2}$  years in vivo,<sup>28</sup> which was a limitation of the present study as it could reflect the clinical performance in the short term only. Longer tests are needed for the evaluation of the taper connection performance in the mid and long term. Nevertheless, 5 million cycles is the test length specified in ISO 14242-1.<sup>22</sup> Due to the double-peak load cycle (Figure 5), a 5 million-cycle HJS test contained 10 million load peaks, as did the LF test. An exceptional long-term test of 35 million cycles, which took more than a year to carry out, showed that taper damage may accelerate, even with ceramic heads, after a high number of cycles has accumulated.<sup>42</sup> This test could be considered to represent  $17 \frac{1}{2}$  years in vivo and reflect the clinical performance in the long term. The four tests of the present study extended to 35 million cycles would have taken almost 5 years of testing with the present configuration of the HJS (3 specimens tested simultaneously at 1 Hz frequency), which was not possible in the present study. While 5 million cycles is sufficient to determine the wear rate of the VEXLPE liner that has been shown to remain fairly constant, 30 million cycles would be required to reflect 15 years in vivo, the minimum for a long-term evaluation of the taper connection performance. Such a test would take 12 months and it would then be most desirable to concurrently utilize all 12 test stations of the HJS, which would require substantial modifications for the simulator and the specimen holders, and more specimens and serum. All this is quite feasible, but it would be very cost intensive. The fact that only one type of VEXLPE (Vivacit-E) liner was included in the study could also be mentioned as a limitation. Although the present type of Vivacit-E liner showed no detectable wear in earlier HJS tests,<sup>27</sup> it is possible that other contemporary liner materials may show wear, which would add to the complexity of the test, and their inclusion would have broadened the clinical relevance of the study.

Higher neck length heads are also used, although roughly 10 times less frequently than medium neck length heads. With them, the  $A$  values (Figure 2 and Table 2) would be larger because the trunnion does not locate to them as deep as to medium and short neck length heads. This may substantially increase wear as the bending moment of the load relative to the taper center increases, which could be expected to cause asymmetric contact stress concentrations on the connection superior-proximally and inferior-distally to counteract the increased bending moment.<sup>25,26</sup> Higher neck length heads, however, were outside the scope of the present study. With extreme neck length heads and offset stems the test conditions would have been the worst case, as recommended by the ISO 7206–6. Hence, the medium neck length heads and standard offset stems of the present study deviated from the standard. Another deviation was the embedding medium for the stem. The standard recommends a low-modulus medium, such as acrylic bone cement. However, extensive trials of stem fixation with bone cement were unsuccessful due to interface issues.<sup>42</sup> Therefore, stem holders were machined from steel. This was likely to affect the stress distribution of the stem, but the neck region was unsupported and therefore it was considered reasonable to assume that the embedding medium did not play a major role in the performance of the taper connection. Due to the time constraints of the test, reaching a test frequency of 20 Hz was considered a top priority, and this required a rigid fixation that is not possible with a low-modulus medium. The third deviation was the sample size. The standard recommends a sample size of six, but due to cost issues, a sample size of 3 was realized. Within a sample, the wear marks usually appeared reasonably similar. Inevitably, a lower sample size reduces the statistical power but the project funding was not sufficient for a sample size of six. Even the present compilation of specimens (Table 1) with a total of 24 stems and 24 femoral heads tested was exceptionally large for a study with no industry support. Although the scope of the ISO 7206–6 standard is endurance testing of the neck, it was also proven useful in wear testing of the taper connection.

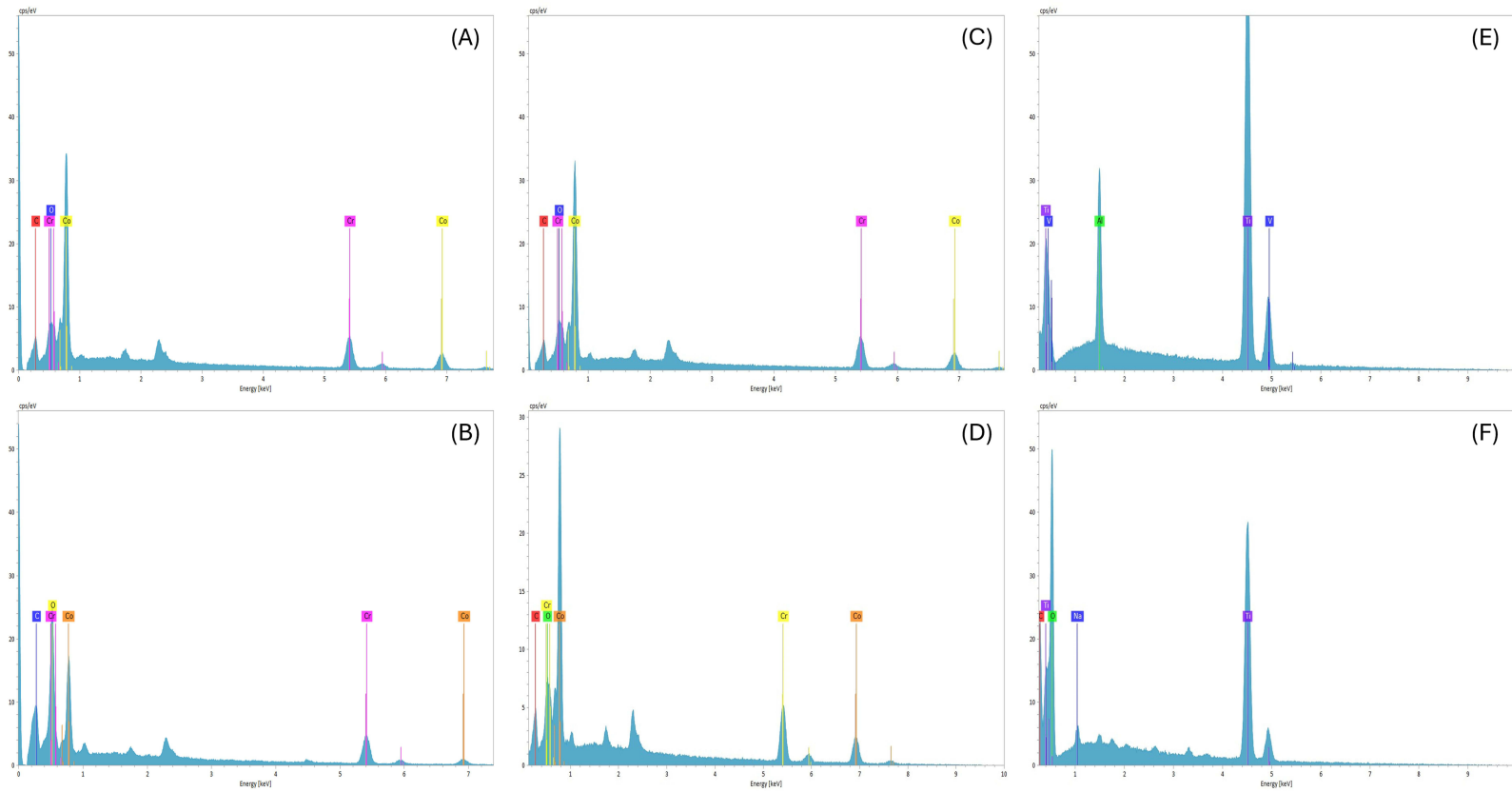
The observed locations of wear (Figure 12) were in agreement with expectations based on mechanical loading and micromotions at the taper connection. More wear on the inferior and distal regions suggested a concentration of contact stresses on these regions during testing. The lack of actual wear on ceramic head tapers agreed with the high wear resistance of the material, with only metal transfer observed from the adhesive wear of the trunnion. In contrast, CoCr head tapers showed wear marks, especially in HJS tests, suggesting that, under these test conditions, the specimens experienced higher mechanical stresses or increased micromotion compared to the LF tests.

The presence of localized polishing on the 12/14 stem tapers (Figures 13 and 14) and imprinting on the CoCr head tapers paired with these (Figure 13) suggested that the interactions between the taper surfaces resulted in surface modifications rather than in severe material loss. The plastic deformation observed on the ridges of the stems indicated that mechanical loading altered the taper surface over time. This pattern has already been reported in studies done by other authors.<sup>38</sup> Visually, both the LF and HJS tests resulted in similar amounts of wear for the respective 12/14 and Type 1 CoCr head tapers. However, one noticeable difference was that the 12/14 tapers of the LF test were likely to show darker regions between the ridges in the SEM analysis. This was indicative of the presence of elements with lower atomic numbers, such as oxygen.

In contrast, the 12/14 tapers that underwent the HJS test mainly exhibited signs of adhesive wear and no visible oxidation layer. The presence of this oxidation layer between the ridges in the LF tests (Figure 14A and B) and their absence in the HJS tests (Figure 14C and D) suggested some minor differences in the extent and or progression wear between the 2 test conditions, possibly due to the different loading conditions which allowed the oxide layer to persist and reform during the LF testing. The visible cracks on the oxide layers (Figure 14A) were likely due to the brittle nature of the oxide layer compared to the original metal, causing it to crack under cyclic loading.

For the CoCr head taper (HJS test, 12/14), both the stereomicroscope and SEM images (Figures 12 and 13) confirmed localized mechanical wear, fretting and adhesive wear, along with plastic deformation and smoothing of the indentation grooves. The dull region in stereomicroscope images indicated surface roughening.

All microscopic findings highlighted how different taper pairings and loading conditions influenced the wear patterns, with CoCr head tapers exhibiting higher susceptibility to wear than ZTA head tapers and the 12/14 taper design showing more substantial surface modifications across different test conditions. The EDX analysis allowed key observations to be made regarding the surface changes that took place during the testing process. The rise in oxygen levels (Figure 16A–F)) indicated that oxidation took place on the tapers. This process led to the formation of oxides, which changed the



**Figure 16** EDX spectra for different specimens. Spectra are organized in 2 rows and 3 columns. First column contains spectra from inferior CoCr femoral head taper paired with 12/14 taper that underwent LF test: **(A)** minimal wear area and **(B)** more visible wear. Second column contains spectra from inferior CoCr femoral head taper paired with 12/14 taper that underwent HJS test: **(C)** minimal wear area and **(D)** more visible wear. Third column contains spectra from inferior 12/14 taper paired with ZTA head that underwent LF test: **(E)** minimal wear area and **(F)** more visible wear.

proportions of the main elements present in each component and consequently led to a decrease in the percentage of these elements.

Additionally, the decrease in the peaks of these elements in the spectra, such as the reduction in cobalt concentration (Figure 16A and B), might also be a result of material loss, which may arise from mechanical wear. The higher oxygen peak in the EDX spectra for the worn regions, despite visible discoloration, suggested oxidation due to adhesive wear. The general carbon content present in the shown spectra can be attributed to pulse pileup effects, which can cause the appearance of false peaks or enhance existing peaks, leading to the misidentification of elements such as carbon.

The evident localized loss of material at the distal end of the CoCr head tapers appears to show that, for the designs studied in this paper, wear was of greater importance than electrochemical effects.

## Conclusions

The wear behavior of the present taper connections with medium neck length femoral heads under demanding LF and HJS test conditions appeared satisfactory and not a cause for concern in the short term. The observed wear marks were considered mild to absent, according to the Goldberg scoring scale. The present tests included CoCr-on-polyethylene and ZTA-on-polyethylene articulations. Regarding Ti trunnion wear marks, there was no consistent distinction between CoCr and ZTA heads in the HJS tests. However, there was a difference when comparing the Type 1 with the 12/14 tapers. Type 1 tapers generally showed less wear than 12/14 tapers, which probably resulted from the difference in surface topography, not from the differences in size or taper angle. Both LF and HJS tests appeared suitable for the evaluation of the wear performance of contemporary femoral head taper connections. Minor differences were observed in wear between the two. LF tests increased metal transfer to the ZTA heads and led to more oxidation-related wear in 12/14 tapers compared with HJS tests. Based on the present test results, no clear preference for either type of test could be claimed.

In the future, longer tests, such as 30 million cycles, corresponding to 15 years in vivo, with the full 12-station capacity of the HJS would be most useful to shed light on the long-term performance of taper connections.

## Data Sharing Statement

The datasets generated and analyzed during the current study are available in the Zenodo repository, <https://zenodo.org/records/14981124>.

## Acknowledgments

The authors thank the following personnel of Aalto University School of Engineering for technical support: Tero Koskenneva, Antti Sinkkonen, Kim Widell, Samuel Akinwamide, Seppo Nurmi, and Janne Peuraniemi.

## Funding

The study was funded by the Research Council of Finland (Scientific Council for Natural Sciences and Engineering, Grant No. 355734) and Aalto University.

## Disclosure

Dr Perttu Neuvonen reports grants from Pirkanmaa hospital district, during the conduct of the study.

Dr Vesa Saikko reports grants from Research Council of Finland, during the conduct of the study. The authors declare that they have no competing interests.

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