Table S1a: Summary of studies carrying out third body wear simulation with particles in the hip

Abbreviations: MOP: Metal-on-polyethylene, XLPE: cross-linked polyethylene, PE: polyethylene, COP: ceramic-on-polyethylene, MOM: Metal-on-metal, COC: ceramic-on-ceramic, COM: ceramic-on-metal, PEEK: polyetheretherketone

Author and year	Materials	Particle type and diameter (µm)	Method	Anatomical (A) /Inverted (I)	Single or multiple dose of particles	Embedded particles?	Characterisation of surfaces	Wear of materials
Affatato et al, 2002[55]	MOP	PMMA with 10% $BaSO_4$, 170 µm	Particles added to serum 1 g/l	I	Multiple	Yes	Looping scratches on metal heads	>3-fold increase in wear rate compared to testing in a clean environment
Bragdon et al, 2003[39]	MOP	Aluminium oxide particles, 1 µm, PMMA with $BaSO_4$, <30 µm	Particles added to serum (0.15 g/1), maintained in suspension with peristaltic pump	A	Multiple	No	Scuffs and scratches on the metal heads after damage with aluminium oxide, fine scratches with PMMA cement	Increase in wear rate with both particle types, greater increase with aluminium oxide. Lower wear rate of XLPE than conventional PE
Bragdon et al, 2004[61]	MOP	Chromium particles, 1-2 µm PMMA ± $BaSO_4$ BaSO4 particles 1 µm Al2O3 particles 1 µm	Comparison between particles introduced directly into the articulation (implant assembled inverted with particles in cup then tested anatomically) and particles added to serum	A	Multiple	Yes, when particles introduced directly into articulation	Damage to CoCr heads highest with alumina particles with a dull non-reflective appearance	Wear rates highest with Aluminium oxide particles
Bragdon et al, 2005[42]	MOP	PMMA with $BaSO_4$, <30 µm	Particles added to serum (0.15 g/l)	A	Multiple		Multidirectional scratches on all femoral heads	XLPE more resistant to 3rd body wear than conventional PE
De Fine et al, 2021[92]	COC	Ceramic particles (Biolox® Forte (up to 111 µm)	Particles added to serum (48 g/l)	A	Multiple		Dull/opaque regions on the Biolox® Forte ceramics, no dull regions on the alumina cups	Low wear of ceramics under these third body wear conditions

		or pure Alumina (up to 39 µm))						
De Villiers et al, 2015[79]	MOP	PMMA + $BaSO_4$ 0.3 – 138 µm Alumina 0.7 – 5.3 µm	Particles added to serum, 5 g/l PMMA 0.15 g/l alumina	A	Multiple, additional testing in clean lubricant	PMMA and alumina particles embedded in metal and PE	Addition of PMMA did not influence R_z of metal heads, increase in R_z when tested in alumina	Addition of PMMA doubled the wear rate of PE, wear rates returned to baseline levels for 28mm diameter heads when tested in clean lubricant, no such reduction in wear rate with 52mm heads or when alumina used a third body particle.
De Villiers et al, 2015[80]	MOP and with and without Chromium Nitride (CrN) coating of metal	Alumina 0.7 – 5.3 µm	0.15 g/l	A	Multiple, additional testing in clean lubricant	Particles embedded in PE	Scratches 2 µm depth in metal following damage simulation, increase in R_a from 0.02 – 0.03 µm, increase in R_z from 1.7 – 2.7 µm	Increased wear rate of PE with PMMA, wear rate remained high against scratched CoCr, CrN more scratch resistant than non-coated CoCr.
Halim et al, 2014[28]	MOM	CoCr beads (68 – 213 µm), Ti6Al4V particles (175 – 422 µm), PMMA flakes from an explanted knee (58 – 342 µm)	5 mg particles added to 1 ml lubricant, simulator run for 10 cycles	A and I	Single	No	Abrasion with PMMA less than with metallic particles, lip height measurements an order of magnitude higher with metal particles than PMMA	No wear test
Halim et al, 2015[81]	MOM	CoCr beads, Ti6Al4V particles, PMMA flakes as Halim et al[28]	5 mg of particles added every 0.5 MC	I	Multiple	No	Highest R_a when tested with Ti6Al4V particles (159 nm), lower with CoCr (145 nm) and lowest with PMMA (13 nm)	Addition of Ti6AL4V particles led to the highest wear rate (6.4 mm^3/MC), lower wear with CoCr (4.1 mm^3/MC) and lowest with PMMA

Hembus et al, 2018[89]	MOP (ion treated metal) COP	PMMA + ZrO_2 100-200 µm	5 g/l particles added, 10% particles by weight to the cup and lightly rubbed into the inserts (low force, low motion)	I	Multiple, every 0.5MC	No	Small scratches on the metal and ceramic heads, decrease in R_a of metal and ceramic heads compared to controls, no significant difference between metal and ceramic	5-fold increase in wear rate of polyethylene with third body particles against metal and ceramic heads compared to smooth implants
Heuberger et al, 2014[78]	MOP, COC	Calcium sulphate hemihydrate, 0.5-100 µm	10 g/l calcium sulphate hemihydrate added to lubricant	A	Multiple, additional testing in clean lubricant to simulate wear after bone void filler has resorbed	No, $CaSO_4$ is resorbable so not anticipated to become embedded *in vivo*	Scratches observed on the metal heads but no significant difference in Ra between scratched and smooth implants	39% increase in wear rate of MOP with calcium sulphate in lubricant, wear rates returned to baseline when tested in a clean lubricant). Calcium sulphate had no influence of wear of COC
Liao et al, 2010[72]	COM MOM	HA particles, <100 µm	0.28 g particles added	I	Multiple, every 0.5 MC			Addition of particles had no influence on COM wear, wear rate of MOM with particles significantly higher than COM
Kubo et al, 2009[70]	MOP COP	PMMA + 10% $BaSO_4$, mean 160 µm, <500 µm	Test run in PMMA slurry (5 g/l)	I	Multiple	PMMA in PE before cleaning, removed by cleaning	Roughness of CoCr and Al_2O_3 remained low	PE wear rate increased with PMMA, COP minimised wear under 3rd body condition
Sorimachi et al, 2009[71]	MOP	PMMA	10 g/l particles	I	Multiple	No	Visible scratching on metal heads after simulation with PMMA	Wear rate of PE increased with PMMA cement
Wang and Essner, 2001[54]	MOP COP	PMMA + 10% $BaSO_4$, mean 160 µm, <500 µm	1-10 g/l PMMA particles	A	Multiple, additional testing carried out	Acetone used to dissolve		For MOP, >5 mg/ml PMMA particles required to elevate wear, PMMA particles had no

					in clean lubricant	PMMA particles		influence on wear of COP
Wang and Schmidig, 2003[59]	MOP COP	PMMA + 10% $BaSO_4$, mean 150 µm, <300 µm	5 g/l PMMA in lubricant	A	Multiple, additional testing carried out in clean lubricant	Acetone used to dissolve PMMA particles	CoCr heads R_a 0.01 µm pre-test, 0.06 µm post-test; ceramic more resistant to scratches than CoCr	Testing with PMMA increased wear rate of MOP (>10x) and COP (3-4x) compared to smooth implants, further testing without PMMA returned wear rates to baseline for MOP and COP
Weisenburger et al, 2018[76]	MOP	Pulverised PMMA particles	0.7 g/l particles	A				No change in wear of PE with addition of PMMA particles

Table S1b: Summary of studies carrying out third body wear simulation with particles in the knee

Author and year	Materials	Particle type and diameter (µm)	Method	Single or multiple dose of particles	Embedded particles?	Characterisation of surfaces	Wear of materials
Cowie et al, 2019[90]	MOP	Calcium sulfate bone void filler crushed *in situ* to a powder	Bone void filler (5cc) added to tibial components, run dry to create damage before adding lubricant	No, single dose of calcium sulfate	No	R_a ~0.03 µm, R_p ~0.04 µm following damage simulation	Damage created by bone void filler did not have a lip height of sufficient magnitude to influence wear compared to smooth components
Metcalfe et al, 2013[74]	MOP	PMMA 0.5-1 mm, 1-2 mm	Particles added to tibial, run for 100 cycles, lubricated with water	Multiple, 3 sets of 100 cycles	Yes	Polyethylene deformation similar to retrievals, minimal scratching of femoral component	No wear simulation
Paulus et al, 2015[83]	MOP UKR	Porcine bone, 672 µm, PMMA + ZrO_2, 644 µm	5 g/l debris added to lubricant				10-fold increase in number of PE particles with PMMA debris compared to bone, no influence on particle size or morphology
Schroeder et al, 2013[75]	MOP UKR	Bone, 672 µm, PMMA + ZrO_2, 644 µm	5g/l of debris added to lubricant	Multiple	Yes, bone particles	With bone particles, pitting of UHMWPE, with PMMA, abrasion, pitting and scratching	Bone debris had little effect on the wear rate but cement debris led to a significant increase in wear rate
Zietz, et al, 2012[77]	MOP COP	PMMA + ZrO_2, mean 5 µm, <30 µm	14 mg of particles added to each knee (7 mg/condyle), first 50 cycles of each 0.5 MC run without lubricant, then lubricant added	Multiple, every 0.5 MC	Yes	Scratches visible on the CoCr femoral components, no scratches on ceramic femoral components	Wear of PE inserts with ceramic femoral components lower than CoCr implants under third-body wear conditions

Table S1c: Summary of studies carrying out third body wear simulation with particles in simple geometry pin-on-plate or pin-on-disc

Author and year	Materials	Particle type and diameter (µm)	Method	Single or multiple dose of particles	Embedded particles?	Characterisation of surfaces	Wear of materials
Caravia et al, 2000[45]	MOP (stainless steel)	PMMA PMMA + $BaSO_4$ PMMA + ZrO_2 Cancellous bone (bovine) Cortical bone (bovine), 5-355 µm	Particles added to lubricant 10 g/l	N/A	Yes, particles embedded in UHMWPE in all tests	$BaSO_4$ and ZrO_2 additives in PMMA lead to scratching with ZrO_2 creating deeper scratches. Unpolymerised cement did not scratch metal. Cortical bone creates scratches but smaller than from PMMA with additives	No wear simulation carried out
Cooper et al, 1991[23]	COP	PMMA + $BaSO_4$ PMMA + ZrO_2, 5 - 500 µm	Smaller particles are more likely to cause damage			Scratch depth greater with ZiO_2 cement particles.	No wear simulation carried out
Cowie et al 2016[84]	MOP	Bone void fillers, crushed *in situ* to a powder PMMA (+ $BaSO_4$), 500-1000 µm	2-phases, damage simulation followed by wear testing against damaged surfaces	N/A	No	Following damage simulation, R_a <0.02µm on all CoCr plates damaged with bone void fillers and PMMA cement	No significant difference in wear of PE between polished plates and those damaged with particles
Cowie et al 2020[33]	UMWPE-on-PEEK and UHMWPE-on-CoCr	PMMA cement (+ ZrO_2), 500-1000 µm	2-phases, damage simulation followed by wear testing against damaged surfaces	N/A	No	Following damage simulation, CoCr plates R_a ~0.01µm, PEEK plates R_a ~0.05µm	Damage simulation had no influence on wear of PE compared to smooth controls, polishing effect of PE against scratched PEEK plates
Isaac et al, 1987[15]	MOP (stainless steel)	PMMA + ZrO_2 PMMA + $BaSO_4$ Cadaveric cortical bone	Particles trapped between a loaded UHMWPE pin and a metal plate, plate pulled beneath pin	N/A	Yes	Highest surface roughness with ZrO_2 particles, more than twice that of $BaSO_4$ and cortical bone	No wear simulation carried out
Lewicki et al, 2017[87]	MOP	Calcium sulfate bone void filler	Particles trapped between pin and plate	No, single dose to represent	Not investigated	Not investigated	BVF did not steady state wear rate in powder or pellet form compared to controls.

				bone void filler resorption			
Manero et al, 2004[62]	MOP (Ti)	PMMA + $BaSO_4$ PMMA + ZrO_2 PMMA + other radiopaque agents, 37-500 µm	2.5 g cement in 150 ml distilled water (16.6 g/l)				Increased wear in tests run with $BaSO_4$ and ZrO_2 additives.
Minakawa et al, 1998[93]	MOP	PMMA cement with different radiopacifiers, bone, <500 µm	Particles trapped between an UHMWPE pin and SS plate, plate pulled beneath pin	N/A	No	Adding radiopacifiers to PMMA increased the number of scratches, more scratches with ZrO_2 than $BaSO_4$	No wear test carried out
Poggie et al, 1994[29]	MOP with TiN and ZrO_2 coatings COP	Ti6Al4V, 150-250 µm Oxidised titanium powder, 1.48 µm	Debris trapped between articulating surfaces.	N/A	Yes	Abrasion resistance of implant materials proportional to surface hardness	Abrasion damage with Ti6Al4V measured geometrically, with TiO_2, a scoring system was used due to surface contamination
Que et al, 2000[52]	MOP	PMMA ± $BaSO_4$ Bone	0.175 g of particles suspended in 4.5 g water (38.8 g/l)			Scratches on CoCr with bone, PMMA with & without $BaSO_4$	No weight loss of CoCr detected
Sagbas et al, 2016[85]	MOP	PMMA spheres, mean 339 nm	10 g/l in water	N/A	Yes	Pitting of polyethylene and embedded particles	Elevated wear with PMMA particles

Table S2a: Summary of studies carrying out third body wear with simulation by creating discrete scratches on the counterfaces in the hip

Abbreviations: MOP: Metal-on-polyethylene, XLPE: cross-linked polyethylene, PE: polyethylene, PEEK: polyetheretherketone

Author and date	Materials	Method	Characterisation of surfaces	Wear of materials
Affatato et al, 2005[64]	MOP	Diamond stylus 35 µm tip used to create 3 scratches in a asterix shape	Pre-test, R_a 0.12–0.14 µm, no post-test roughness measurements	XLPE has superior (40x) wear resistance than conventional PE in this study, no control carried out
Al-Hajjar et al, 2018[86]	MOP	Scratches and scrapes created in metal heads to represent retrievals	See Kruger et al [27]	Severe scratches led to a higher wear rate of PE than severe scrapes
Barbour et al, 2000[50]	MOP	3 scratches created with a diamond stylus with 25 µm tip and 2.5 N load 3 scratches created with a CoCr bead 250 µm ø embedded in a polyethylene pin 80 N load applied	Stylus R_a 0.04 µm CoCr bead R_a 0.02 µm Scratches with stylus had a higher lip height, were deeper and narrower than with the bead	Scratching with a bead increased wear rate of PE compared to unscratched controls, scratching with a diamond stylus led to a further increase in wear
Bowsher and Shelton, 2001[53]	MOP	Metal heads roughened with 400 grit SiC paper to produce overlapping circular scratches	Mean R_a 0.4 µm, maximum R_p 3 µm	~8x increase in wear of roughened heads compared to smooth heads under gait conditions
Carli et al, 2018[88]	Oxidised zirconium-on-polyethylene and COP	Retrieved femoral heads. Heads classified into either severely damaged (dislocated) or mildly damage (non-dislocated)	Severe scratching on the oxidised zirconium heads which suffered recurrent dislocations, Sa 1.4-8.6 µm; mildly damaged heads with scratches >0.5 cm in length, Sa 0.4-0.7 µm; ceramic heads Sa 0.06-0.2 µm	High PE wear against oxidised zirconium heads which suffered recurrent dislocations; lower wear of PE against ceramic heads with recurrent dislocations similar to oxidised zirconium heads with mild damage
Endo et al, 2002[56]	MOP	3 scratches created on the pole of the femoral heads as Barbour et al [50]	Lip height of scratches, 2-3 µm	Wear rate of PE and XLPE UHMWPE increased 2-3-fold against scratched femoral heads
Good et al, 2005[65]	MOP	Tumbling in abrasive media	R_a of roughened CoCr heads similar to retrieved samples, R_{pm} of roughened higher than retrieves samples.	With conventional PE, wear rate against roughened heads twice that of smooth implants
Heiner et al, 2012[73]	MOP	5 CoCr beads (300-320 µm ø) embedded and glued in acetabular cup and run for 10,000 cycles under a gait cycle	Circular scratches on femoral heads and acetabular cup. P_p of scratches ~0.5 µm.	Wear test not carried out

Hembus et al, 2020[91]	COP	Retrieved ceramic heads with metallic transfer	Regions with metallic transfer had a significantly higher surface roughness (R_a ~0.35 µm compared to ~0.09 µm in the new components)	Higher wear of UHMWPE liners against heads with metallic transfer than new heads
Liao et al, 2008[68]	MOP MOXLPE COXLPE	Heads tumbled for 30 minutes with a bauxite/alumina abrasive media in a table top tumbler	For metal heads, pre tumbling R_a ~0.01 µm, R_p <0.1 µm, post tumbling R_a ~0.04 µm, R_p >1.5 µm For ceramic heads, pre tumbling R_a <0.01 µm, R_p, ~0.05 µm, post tumbling R_a <0.01 µm, R_p ~0.07 µm	Following scratching, wear of XLPE remained lower than PE, wear of scratched COP similar to smooth implants
McKellop et al, 1999[49]	MOP	Femoral heads polished with grit compound or emery paper	Moderately rough – R_a 0.4 µm, extremely rough – R_a 0.9 µm	Moderate roughening had no influence on PE wear rate compared to polished controls, significant increase in wear rate against extremely rough heads
Morrison et al, 2015[82]	MOP and oxidised zirconium on poly	Tumbled in a centrifugal barrel mass-finisher, ~30 s in a 25 µm alumina powder and plastic cone media	After tumbling CoCr implants, peaks formed leading to a positive R_{sk}; oxidised zirconium implants had a negative R_{sk} post tumbling.	Tumbling increased the wear rate against CoCr, no increase in wear against oxidised zirconium
Wang et al, 1998[48]	MOP	Multidirectional scratches created with SiC paper	R_a 0.85 µm	Linear relationship between R_a and wear
Weisenburger et al 2018[76]	MOP	Femoral heads pressed into abrasive beads, loaded (body weight) then moved through 90° (x10), then repeated in perpendicular direction		~2.5X increase in wear rate compared to smooth controls for conventional PE, 4X increase in wear rate for XLPE

Table S2b: Summary of studies carrying out third body wear with simulation by creating discrete scratches on the counterfaces in the knee

Author and date	Materials	Method	Characterisation of surfaces	Wear of materials
Cowie et al, 2019[90]	MOP	Scratches created with a 200 µm radius stylus in a grid pattern	Scratches with a lip height of >3 µm, R_a ~1.3 µm	7-fold increase in wear rate of PE against scratched tibia components compared to smooth
DesJardins et al, 2008[67]	MOP and oxidised zirconium-on-PE	Components roughened by tumbling with 25 µm alumina powder and plastic cone media in a centrifugal finishing barrel for 30s	Following tumbling, increase in R_a of femoral components: CoCr – 0.17 µm Oxidised zirconia – 0.06 µm	Higher wear against scratched CoCr femoral components than oxidised zirconium
Muratoglu et al, 2004[63]	MOP	Explanted femoral components tested against new tibial inserts	Scratches on femoral components primarily orientated in an AP direction, initial R_a 0.1-0.2 µm, R_p 0.3-0.8 µm	Wear rate of PE ~3.5x higher with explanted femoral components compared to smooth implants
Widding et al, 2002[58]	MOP	Femoral components tumbled in a centrifugal mass finisher containing 25 µm alumina and abrasive-embedded plastic cones	Significant increase in R_a, R_{pm} and R_{pk} over non-tumbled implants	
Widding et al, 2003[60]	MOP	Femoral components tumbled in a centrifugal mass finisher containing 25 µm alumina and abrasive-embedded plastic cones	After tumbling, mean R_a 0.1 µm, mean R_{pm} 0.2 µm of femoral components	3-fold increase in wear rate conventional PE of scratched femoral components compared to smooth
Ries et al, 2002[57]	MOP OxZr-on-PE	Femoral components tumbled with 25 µm alumina powder and plastic cone media in a centrifugal finishing barrel	R_a of CoCr femoral components doubled after tumbling, R_{pm} increased 4-fold, no influence of tumbling on R_a or R_{pm} of OxZr	Wear of PE 8-fold lower against abraded OxZr compared To CoCr

Table S2c: Summary of studies carrying out third body wear with simulation by creating discrete scratches on the counterfaces in simple geometry pin-on-plate or pin-on-disc

Author and date	Materials	Method	Characterisation of surfaces	Wear of materials
Cowie et al, 2020[33]	PE-on-PEEK and PE-on-CoCr	CoCr and PEEK counterfaces scratched with a (200 µm conical tipped) diamond stylus	Lip height 1, 2 and 4 µm created in PEEK and CoCr	Behaviour of PE-on-PEEK different from PE-on-CoCr, against 4 µm lip height scratches in CoCr, wear of PE significantly higher than against PEEK
Dowson et al, 1987[46]	MOP (stainless steel)	Single scratch created either perpendicular to or parallel to wear test with a diamond stylus, plates then lapped to remove lips on scratches, single indentation also investigated	Scratch and indent depth up to 60 µm, lip height up to 36 µm. No change in geometry of scratches after wear simulation (>100 Km sliding distance)	Scratches perpendicular to the wear test have a greater influence (10 x wear rate) on wear than parallel scratches; lapping to remove lips reduced wear rate; single indentation did not influence PE wear
Fisher et al, 1995[47]	MOP (stainless steel)	Comparison of pin on plate and pin on disc	Lip height of scratches 1µm, Ra 0.013 µm	30-fold increase in wear for unidirectional motion tests 70-fold increase in wear for multidirectional motion tests
Galvin et al, 2006[66]	MOP	Scratched with a diamond stylus, 100 µm diameter perpendicular to the direction of the wear test	Mean lip height of scratches, 0.8 or 1.8 µm	Increased wear factor with increased lip height of scratches
Minakawa et al, 1998[31]	MOP COP	Scratches created with a diamond stylus, R_p 0.1-1 µm	R_p of scratches in stainless steel (R_p ~1.0 µm) larger than CoCr (R_p ~0.4 µm), in ceramic, R_a <0.1 µm	Dependence of PE wear on scratch R_p or R_{pm}
Glennon et al, 2008[69]	MOP	Scratched with 50 µm stylus compared to plates roughened with emery paper	Mean R_a 1.2 µm, mean lip height 1.3 µm of scratches. Scratches in different orientations	The direction of the scratches influences PE wear
Lancaster et al, 1997[32]	MOP COP	Lapping, different roughness's created by different duration of lapping	R_a from 0.003-0.010 µm, R_p 0.01-0.31 µm	Exponential relationship between surface topography and wear, R_a <0.05 µm, diminishing returns in improvement of surface topography reducing wear
McNie et al, 2000[51]	MOP	SS bead 10, 150 or 300 µm diameter embedded in polyethylene	Damage created similar to retrieved implants	
Wang et al, 1998[48]	MOP	Scratches created parallel to the direction of motion with SiC paper or alumina paste	R_a 0.1-0.7 µm	Exponential relationship between R_a and wear, when R_a < 0.05 µm, the wear factor is almost independent of surface roughness

Weightman and Light, 1986[44]	MOP COP	Fewer polishing stages adopted to create more rough surfaces	Alumina counterfaces R_a up to 0.1 µm, SS counterfaces R_a up to 0.75 µm	Exponential increase in wear with R_a, optimum R_a <0.15 µm

References

[1] National Joint Registry 16th Annual Report, 2019. https://reports.njrcentre.org.uk/Portals/0/PDFdownloads/NJR%2016th%20Annual%20Report%202019.pdf. (Accessed Accessed 12th May 2020 Access 2019).
[2] E. Ingham, J. Fisher, Biological reactions to wear debris in total joint replacement, Proceedings of the Institution of Mechanical Engineers, Part: H Journal of Engineering in Medicine 214(1) (2000) 21-37.
[3] L.M. Jennings, M. Al-Hajjar, C.L. Brockett, S. Williams, J.L. Tipper, E. Ingham, J. Fisher, (iv) Enhancing the safety and reliability of joint replacement implants, Orthopaedics and trauma 26(4) (2012) 246-252.
[4] J. Fisher, D. Dowson, Tribology of total artificial joints, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 205(2) (1991) 73-79.
[5] H.A. McKellop, The lexicon of polyethylene wear in artificial joints, Biomaterials 28(34) (2007) 5049-5057.
[6] ISO 14242-1:2014/AMD 1:2018 Implants for surgery — Wear of total hip-joint prostheses — Part 1: Loading and displacement parameters for wear-testing machines and corresponding environmental conditions for test — Amendment 1.
[7] ISO 14242-3:2009/AMD 1:2019 Implants for surgery — Wear of total hip-joint prostheses — Part 3: Loading and displacement parameters for orbital bearing type wear testing machines and corresponding environmental conditions for test — Amendment 1.
[8] ISO 14243-1:2009/AMD 1:2020 Implants for surgery — Wear of total knee-joint prostheses — Part 1: Loading and displacement parameters for wear-testing machines with load control and corresponding environmental conditions for test — Amendment 1.
[9] ISO 14243-3:2014/AMD 1:2020 Implants for surgery — Wear of total knee-joint prostheses — Part 3: Loading and displacement parameters for wear-testing machines with displacement control and corresponding environmental conditions for test — Amendment 1.
[10] ISO 22622:2019 Implants for surgery — Wear of total ankle-joint prostheses — Loading and displacement parameters for wear-testing machines with load or displacement control and corresponding environmental conditions for test.
[11] ISO 14242-4:2018 Implants for surgery — Wear of total hip-joint prostheses — Part 4: Testing hip prostheses under variations in component positioning which results in direct edge loading.
[12] ISO 14243-5:2019 Implants for surgery — Wear of total knee prostheses — Part 5: Durability performance of the patellofemoral joint.
[13] ASTM F3141 - 17 Standard Guide for Total Knee Replacement Loading Profiles.
[14] H.A. McKellop, P. Campbell, S.-H. Park, T.P. Schmalzried, P. Grigoris, H.C. Amstutz, A. Sarmiento, The origin of submicron polyethylene wear debris in total hip arthroplasty, Clinical Orthopaedics Related Research (311) (1995) 3-20.
[15] G. Isaac, J. Atkinson, D. Dowson, P. Kennedy, M. Smith, The causes of femoral head roughening in explanted Charnley hip prostheses, J Engineering in medicine 16(3) (1987) 167-173.
[16] H. McKellop, S.-H. Park, R. Chiesa, P. Doorn, B. Lu, P. Normand, P. Grigoris, H. Amstutz, In vivo wear of 3 types of metal on metal hip prostheses during 2 decades of use, Clinical Orthopaedics Related Research 329 (1996) S128-S140.
[17] E. Morscher, A. Hefti, U. Aebi, Severe osteolysis after third-body wear due to hydroxyapatite particles from acetabular cup coating, The Journal of bone joint surgery. British volume 80(2) (1998) 267-272.
[18] H.J. Lundberg, S.S. Liu, J.J. Callaghan, D.R. Pedersen, M.R. O'Rourke, D.D. Goetz, D.A. Vittetoe, J.C. Clohisy, T.D. Brown, Association of third body embedment with rim damage in retrieved acetabular liners, Clinical Orthopaedics Related Research 465 (2007) 133-139.
[19] G.A. Engh, K.A. Dwyer, C.K. Hanes, Polyethylene wear of metal-backed tibial components in total and unicompartmental knee prostheses, The Journal of bone joint surgery. British volume 74(1) (1992) 9-17.

[20] V. Jones, I. Williams, D. Auger, W. Walsh, D. Barton, M. Stone, J. Fisher, Quantification of third body damage to the tibial counterface in mobile bearing knees, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 215(2) (2001) 171-179.
[21] S.C. Scholes, E. Kennard, R. Gangadharan, D. Weir, J. Holland, D. Deehan, T.J. Joyce, Topographical analysis of the femoral components of ex vivo total knee replacements, Journal of Materials Science: Materials in Medicine 24(2) (2013) 547-554.
[22] R. Malikian, K. Maruthainar, J. Stammers, S.R. Cannon, R. Carrington, J.A. Skinner, N. Maruthainar, G. Dowd, T.W. Briggs, G.W. Blunn, In vivo roughening of retrieved total knee arthroplasty femoral components, The Knee 21(1) (2014) 278-282.
[23] J. Cooper, D. Dowson, J. Fisher, B. Jobbins, Ceramic bearing surfaces in total artificial joints: resistance to third body wear damage from bone cement particles, Journal of medical engineering technology 15(2) (1991) 63-67.
[24] J. Atkinson, D. Dowson, G. Isaac, B. Wroblewski, Laboratory wear tests and clinical observations of the penetration of femoral heads into acetabular cups in total replacement hip joints: II: a microscopical study of the surfaces of Charnley polyethylene acetabular sockets, Wear 104(3) (1985) 217-224.
[25] T.W. Bauer, J. Schils, The pathology of total joint arthroplasty, Skeletal radiology 28(9) (1999) 483-497.
[26] H. Spece, E.S. Ouellette, O.L. Jones, D.W. MacDonald, N.S. Piuzzi, G.-C. Lee, M.A. Mont, G.R. Klein, S.M. Kurtz, Fretting Corrosion, Third-Body Polyethylene Damage, and Cup Positioning in Primary vs Revision Dual Mobility Total Hip Arthroplasty, The Journal of Arthroplasty (2021).
[27] K.M. Kruger, N.M. Tikekar, A.D. Heiner, T.E. Baer, J.J. Lannutti, J.J. Callaghan, T.D. Brown, Encoding scratch and scrape features for wear modeling of total joint replacements, Computational mathematical methods in medicine 2013 (2013).
[28] T. Halim, M. Burgett, T.K. Donaldson, C. Savisaar, J. Bowsher, I.C. Clarke, Profiling the third-body wear damage produced in CoCr surfaces by bone cement, CoCr, and Ti6Al4V debris: a 10-cycle metal-on-metal simulator test, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 228(7) (2014) 703-713.
[29] R. Poggie, A. Mishra, J. Davidson, Three-body abrasive wear behaviour of orthopaedic implant bearing surfaces from titanium debris, Journal of Materials Science: Materials in Medicine 5(6-7) (1994) 387-392.
[30] T.H. Ltd, Exploring Surface Texture: A fundamental guide to the measurement of surface finish, 4th ed.2003.
[31] H. Minakawa, M. Stone, B. Wroblewski, J. Lancaster, E. Ingham, J. Fisher, Quantification of third-body damage and its effect on UHMWPE wear with different types of femoral head, The Journal of bone joint surgery. British volume 80(5) (1998) 894-899.
[32] J. Lancaster, D. Dowson, G. Isaac, J. Fisher, The wear of ultra-high molecular weight polyethylene sliding on metallic and ceramic counterfaces representative of current femoral surfaces in joint replacement, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 211(1) (1997) 17-24.
[33] R.M. Cowie, N.M. Pallem, A. Briscoe, L.M. Jennings, Third Body Wear of UHMWPE-on-PEEK-OPTIMA™, Materials 13(6) (2020) 1264.
[34] https://www.predev.com/pdffiles/surface_roughness_terminology_and_parameters.pdf. (Accessed 7th February 2021.
[35] Y. Niki, H. Matsumoto, T. Otani, T. Tomatsu, Y. Toyama, How much sterile saline should be used for efficient lavage during total knee arthroplasty? Effects of pulse lavage irrigation on removal of bone and cement debris, The Journal of arthroplasty 22(1) (2007) 95-99.
[36] T. De Baets, W. Waelput, J. Bellemans, Analysis of third body particles generated during total knee arthroplasty: is metal debris an issue?, The Knee 15(2) (2008) 95-97.

[37] E. McPherson, M. Dipane, S. Sherif, Dissolvable antibiotic beads in treatment of periprosthetic joint infection and revision arthroplasty-the use of synthetic pure calcium sulfate (Stimulan®) impregnated with vancomycin & tobramycin, Reconstructive Review 3(1) (2013).
[38] M.A. McGee, D.W. Howie, K. Costi, D.R. Haynes, C.I. Wildenauer, M.J. Pearcy, J.D. McLean, Implant retrieval studies of the wear and loosening of prosthetic joints: a review, Wear 241(2) (2000) 158-165.
[39] C.R. Bragdon, M. Jasty, O.K. Muratoglu, D.O. O'Connor, W.H. Harris, Third-body wear of highly cross-linked polyethylene in a hip simulator, The Journal of arthroplasty 18(5) (2003) 553-561.
[40] J.B. Medley, Highly cross-linked polyethylene is the new 'gold standard'bearing material for total hip arthroplasty, Biosurface Biotribology (2021).
[41] Australian Orthopaedic Association National Joint Replacement Registry Annual Report 2020, 2020.
https://aoanjrr.sahmri.com/documents/10180/689619/Hip%2C+Knee+%26+Shoulder+Arthroplasty+New/6a07a3b8-8767-06cf-9069-d165dc9baca7. (Accessed Accessed 11th August 2021 Access 2020).
[42] C.R. Bragdon, M. Jasty, O.K. Muratoglu, W.H. Harris, Third-body wear testing of a highly cross-linked acetabular liner: the effect of large femoral head size in the presence of particulate poly (methyl-methacrylate) debris, The Journal of arthroplasty 20(3) (2005) 379-385.
[43] Author, Data associated with "Third Body Damage and Wear in Arthroplasty Bearing Materials: A Review of Laboratory Methods", 2021. [Dataset] https://doi.org/10.5518/1036. Access 2021).
[44] B. Weightman, D. Light, The effect of the surface finish of alumina and stainless steel on the wear rate of UHMW polyethylene, Biomaterials 7(1) (1986) 20-24.
[45] L. Caravia, D. Dowson, J. Fisher, B. Jobbins, The influence of bone and bone cement debris on counterface roughness in sliding wear tests of ultra-high molecular weight polyethylene on stainless steel, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 204(1) (1990) 65-70.
[46] D. Dowson, S. Taheri, N. Wallbridge, The role of counterface imperfections in the wear of polyethylene, Wear 119(3) (1987) 277-293.
[47] J. Fisher, P. Firkins, E. Reeves, J. Hailey, G. Isaac, The influence of scratches to metallic counterfaces on the wear of ultra-high molecular weight polyethylene, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 209(4) (1995) 263-264.
[48] A. Wang, V. Polineni, C. Stark, J. Dumbleton, Effect of femoral head surface roughness on the wear of ultrahigh molecular weight polyethylene acetabular cups, The Journal of arthroplasty 13(6) (1998) 615-620.
[49] H. McKellop, F.-w. Shen, W. DiMaio, J.G. Lancaster, Wear of gamma-crosslinked polyethylene acetabular cups against roughened femoral balls, Clinical Orthopaedics Related Research 369 (1999) 73-82.
[50] P. Barbour, M. Stone, J. Fisher, A hip joint simulator study using new and physiologically scratched femoral heads with ultra-high molecular weight polyethylene acetabular cups, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 214(6) (2000) 569-576.
[51] C. McNie, D. Barton, J. Fisher, M. Stone, Modeling of damage to articulating surfaces by third body particles in total joint replacements, Journal of Materials Science: Materials in Medicine 11(9) (2000) 569-578.
[52] L. Que, L.T. Topoleski, Third-body wear of cobalt-chromium-molybdenum implant alloys initiated by bone and poly (methyl methacrylate) particles, Journal of Biomedical Materials Research 50(3) (2000) 322-330.
[53] J. Bowsher, J. Shelton, A hip simulator study of the influence of patient activity level on the wear of crosslinked polyethylene under smooth and roughened femoral conditions, Wear 250(1-12) (2001) 167-179.
[54] A. Wang, A. Essner, Three-body wear of UHMWPE acetabular cups by PMMA particles against CoCr, alumina and zirconia heads in a hip joint simulator, Wear 250(1-12) (2001) 212-216.

[55] S. Affatato, G. Bersaglia, I. Foltran, P. Taddei, G. Fini, A. Toni, The performance of gamma-and EtO-sterilised UHWMPE acetabular cups tested under severe simulator conditions. Part 1: role of the third-body wear process, Biomaterials 23(24) (2002) 4839-4846.
[56] M. Endo, J. Tipper, D. Barton, M. Stone, E. Ingham, J. Fisher, Comparison of wear, wear debris and functional biological activity of moderately crosslinked and non-crosslinked polyethylenes in hip prostheses, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 216(2) (2002) 111-122.
[57] M.D. Ries, A. Salehi, K. Widding, G. Hunter, Polyethylene wear performance of oxidized zirconium and cobalt-chromium knee components under abrasive conditions, JBJS 84(suppl_2) (2002) S129-S135.
[58] K. Widding, G. Hines, G. Hunter, A. Salehi, Knee Simulator Protocol for Testing of Oxidize Zirconium and Cobalt Chrome Femoral Components Under Abrasive Conditions, Transactiona fo the annual meeting - Orthopadic research society, 2002, p. 1009.
[59] A. Wang, G. Schmidig, Ceramic femoral heads prevent runaway wear for highly crosslinked polyethylene acetabular cups by third-body bone cement particles, Wear 255(7-12) (2003) 1057-1063.
[60] K. Widding, M. Scott, S. Jani, V. Good, Crosslinked UHMWPE in total knees: clean versus abrasive conditions, The proceedings of the 49th Annual Meeting of the Orthopaedic Research Society, 2003, p. 1427.
[61] C.R. Bragdon, D. O'Connor, O.K. Muratoglu, W.H. Harris, Development of a model for testing third body wear of UHMWPE acetabular components, Journal of ASTM International 1(1) (2004) 1-7.
[62] J. Manero, F. Gil, M. Ginebra, J. Planell, A. Artola, I. Goñ, M. Gurruchaga, Wear Behaviour of the Pair Ti–6Al–4V–UHMWPE of Acrylic Bone Cements Containing Different Radiopaque Agents, Journal of biomaterials applications 18(4) (2004) 305-319.
[63] O.K. Muratoglu, B.R. Burroughs, C.R. Bragdon, S. Christensen, A. Lozynsky, W.H. Harris, Knee simulator wear of polyethylene tibias articulating against explanted rough femoral components, Clinical Orthopaedics Related Research 428 (2004) 108-113.
[64] S. Affatato, G. Bersaglia, M. Rocchi, P. Taddei, C. Fagnano, A. Toni, Wear behaviour of cross-linked polyethylene assessed in vitro under severe conditions, Biomaterials 26(16) (2005) 3259-3267.
[65] V. Good, K. Widding, G. Hunter, D. Heuer, Oxidized zirconium: a potentially longer lasting hip implant, Materials design 26(7) (2005) 618-622.
[66] A. Galvin, L. Kang, J. Tipper, M. Stone, E. Ingham, Z. Jin, J. Fisher, Wear of crosslinked polyethylene under different tribological conditions, Journal of Materials Science: Materials in Medicine 17(3) (2006) 235-243.
[67] J.D. DesJardins, B. Burnikel, M. LaBerge, UHMWPE wear against roughened oxidized zirconium and CoCr femoral knee components during force-controlled simulation, Wear 264(3-4) (2008) 245-256.
[68] Y.-S. Liao, K. Greer, A. Alberts, Effect of head material and roughness on the wear of 7.5 Mrad crosslinked–remelted UHMWPE acetabular inserts, Trans. Orthopaedic Research Society (2008).
[69] L.P. Glennon, T.E. Baer, J.A. Martin, W.D. Lack, T.D. Brown, Sliding direction dependence of polyethylene wear for metal counterface traverse of severe scratches, Journal of biomechanical engineering 130(5) (2008).
[70] K. Kubo, I. Clarke, T. Sorimachi, P. Williams, T. Donaldson, K. Yamamoto, Aggressive 3rd-body wear challenge to highly crosslinked polyethylene: A hip simulator model, Wear 267(5-8) (2009) 734-742.
[71] T. Sorimachi, I. Clarke, P. Williams, A. Gustafson, K. Yamamoto, Third-body abrasive wear challenge of 32 mm conventional and 44 mm highly crosslinked polyethylene liners in a hip simulator model, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 223(5) (2009) 607-623.
[72] Y. Liao, S. Swope, D. Whitaker, S. Vass, M. Reimink, T. Render 3rd, Effects of 3rd body hydroxylapatite (HA) particles on the wear performance of 36 mm ceramic-on-metal (COM) and

metal-on-metal (MOM) hip joint components in a wear simulation study, 56th Annual meeting ORS, 2010, p. 2325.
[73] A.D. Heiner, A.L. Galvin, J. Fisher, J.J. Callaghan, T.D. Brown, Scratching vulnerability of conventional vs highly cross-linked polyethylene liners because of large embedded third-body particles, The Journal of arthroplasty 27(5) (2012) 742-749.
[74] A. Metcalfe, M. Dressler, C. Hardaker, Recreating Third Body Damage on RP Knee Inserts, Orthopedic Research Society, San Antonio, TX, USA., 2013.
[75] C. Schroeder, T.M. Grupp, B. Fritz, C. Schilling, Y. Chevalier, S. Utzschneider, V. Jansson, The influence of third-body particles on wear rate in unicondylar knee arthroplasty: a wear simulator study with bone and cement debris, Journal of Materials Science: Materials in Medicine 24(5) (2013) 1319-1325.
[76] J. Weisenburger, K. Garvin, H. Haider, A Novel Method to Produce Scratches on Metallic Orthopaedic Implants Similar to Those Seen on Retrievals, Orthopaedic Proceedings, The British Editorial Society of Bone & Joint Surgery, 2013, p. 583.
[77] C. Zietz, P. Bergschmidt, R. Lange, W. Mittelmeier, R. Bader, Third-body abrasive wear of tibial polyethylene inserts combined with metallic and ceramic femoral components in a knee simulator study, The International journal of artificial organs 36(1) (2013) 47-55.
[78] R. Heuberger, P. Wahl, J. Krieg, E. Gautier, Low in vitro third-body wear on total hip prostheses induced by calcium sulphate used for local antibiotic therapy, Eur Cell Mat 28 (2014) 246-257.
[79] D. de Villiers, A. Traynor, S.N. Collins, J.C. Shelton, The increase in cobalt release in metal-on-polyethylene hip bearings in tests with third body abrasives, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 229(9) (2015) 611-618.
[80] D. de Villiers, A. Traynor, S.N. Collins, S. Banfield, J. Housden, J.C. Shelton, Chromium nitride coating for large diameter metal-on-polyethylene hip bearings under extreme adverse hip simulator conditions, Wear 328 (2015) 363-368.
[81] T. Halim, I. Clarke, M. Burgett-Moreno, T. Donaldson, C. Savisaar, J. Bowsher, A simulator study of adverse wear with metal and cement debris contamination in metal-on-metal hip bearings, J Bone joint research 4(3) (2015) 29-37.
[82] M.L. Morrison, S. Jani, A. Parikh, Design of an advanced bearing system for total knee arthroplasty, Lubricants 3(2) (2015) 475-492.
[83] A.C. Paulus, M. Franke, M. Kraxenberger, C. Schröder, V. Jansson, S. Utzschneider, PMMA third-body wear after unicondylar knee arthroplasty decuples the UHMWPE wear particle generation in vitro, BioMed research international 2015 (2015).
[84] R.M. Cowie, S. Carbone, S. Aiken, J.J. Cooper, L.M. Jennings, Influence of third-body particles originating from bone void fillers on the wear of ultra-high-molecular-weight polyethylene, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 230(8) (2016) 775-783.
[85] B. Sagbas, M.N. Durakbasa, Third-body wear behavior of orthopedic biopolymers, International Journal of Mining, Materials, Metallurgical Engineering 2 (2016) 1-7.
[86] M. Al-Hajjar, K. Vasiljeva, A. Heiner, K. Kruger, T. Baer, T. Brown, J. Fisher, L. Jennings, The Wear of Polyethylene Liners Articulating against Damaged Femoral Heads for the purpose of Validating an Computational Wear Prediction Model, Orthopaedic Proceedings, The British Editorial Society of Bone & Joint Surgery, 2017, p. 8.
[87] K. Lewicki, B. Prioreschi, K. Koenig, B. Keeney, M. Bartelstein, C. Moucha, D. Van Citters, The Effect of Absorbable Calcium Sulfate on Wear Rates in Ultra-high–Molecular-weight Polyethylene: Potential Implications for Its Use in Treating Arthroplasty Infections, JAAOS-Journal of the American Academy of Orthopaedic Surgeons 25(6) (2017) e114-e120.
[88] A. Carli, C.N. Koch, C.I. Esposito, T.M. Wright, D.E. Padgett, Polyethylene wear increases in liners articulating with scratched oxidized zirconium femoral heads, Clinical orthopaedics related research 476(2) (2018) 182.

[89] J. Hembus, L. Lux, M. Jackszis, R. Bader, C. Zietz, Wear analysis of cross-linked polyethylene inserts articulating with alumina and ion-treated cobalt-chromium femoral heads under third-body conditions, Wear 402 (2018) 216-223.
[90] R. Cowie, S. Aiken, J. Cooper, L. Jennings, The influence of a calcium sulphate bone void filler on the third-body damage and polyethylene wear of total knee arthroplasty, J Bone joint research 8(2) (2019) 65-72.
[91] J. Hembus, L. Rößler, M. Jackszis, A. Klinder, R. Bader, C. Zietz, Influence of Metallic Deposition on Ceramic Femoral Heads on the Wear Behavior of Artificial Hip Joints: A Simulator Study, Materials 13(16) (2020) 3569.
[92] M. De Fine, S. Terrando, M. Hintner, A.A. Porporati, G. Pignatti, Pushing Ceramic-on-Ceramic in the most extreme wear conditions: A hip simulator study, Orthopaedics Traumatology: Surgery Research 107(1) (2021) 102643.
[93] H. Minakawa, M. Stone, B. Wroblewski, M. Porter, E. Ingham, J. Fisher, Comparison of Third Body Damage on the Femoral Head Caused by Bone and Bone Cement, 44th Annual Meeting of the ORS, 1998.
[94] M.T. Raimondi, P. Vena, R. Pietrabissa, Quantitative evaluation of the prosthetic head damage induced by microscopic third-body particles in total hip replacement, Journal of Biomedical Materials Research 58(4) (2001) 436-448.
[95] L. De Ruiter, R.M. Cowie, L.M. Jennings, A. Briscoe, D. Janssen, N.J.M. Verdonschot, The Effects of Cyclic Loading and Motion on the Implant–Cement Interface and Cement Mantle of PEEK and Cobalt–Chromium Femoral Total Knee Arthroplasty Implants: A Preliminary Study, 13(15) (2020) 3323.
[96] H. Minakawa, Quantification and simulation of third body damage to femoral heads and its effect on polyethylene wear in artificial hip joints, School of Mechanical Engineering, University of Leeds, 1998.
[97] A. Lakdawala, S. Todo, G. Scott, The significance of surface changes on retrieved femoral components after total knee replacement, The Journal of bone joint surgery. British volume 87(6) (2005) 796-799.
[98] ISO 14242-2:2016 Implants for surgery — Wear of total hip-joint prostheses — Part 2: Methods of measurement.
[99] O.K. Muratoglu, R.S. Perinchief, C.R. Bragdon, D.O. O'Connor, R. Konrad, W.H. Harris, Metrology to quantify wear and creep of polyethylene tibial knee inserts, Clinical Orthopaedics Related Research® 410 (2003) 155-164.
[100] M.G. Teeter, A. Parikh, M. Taylor, J. Sprague, D.D. Naudie, Wear and creep behavior of total knee implants undergoing wear testing, The Journal of arthroplasty 30(1) (2015) 130-134.
[101] S. Affatato, M.C. Valigi, S. Logozzo, Knee Wear Assessment: 3D Scanners Used as a Consolidated Procedure, Materials 13(10) (2020) 2349.