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► **To cite this version:**

Sylvain Guy, Xavier Flecher, Akash Sharma, Jean-Noël Argenson, Matthieu Ollivier. Highly Crosslinked Polyethylene Can Reduce Wear Rate in THA for High-Demand Patients: A Matched-Paired Controlled Study.. *The Journal of Arthroplasty*, 2021, 36 (9), pp.3226–3232. 10.1016/j.arth.2021.04.036 . hal-03553750

**HAL Id: hal-03553750**

**<https://hal.science/hal-03553750>**

Submitted on 2 May 2022

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## Primary Hip

# Highly Crosslinked Polyethylene Can Reduce Wear Rate in THA for High-Demand Patients: A Matched-Paired Controlled Study

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## ARTICLE INFO

### Keywords:

total hip prosthesis  
total hip arthroplasty  
impact sport  
linear wear  
highly crosslinked polyethylene

## ABSTRACT

**Background:** The average age of patients benefiting from total hip arthroplasty (THA) has been declining. In addition to pain relief, patients seek to return to physical activity. However, the latter may increase polyethylene wear and therefore the potential risk of early aseptic loosening. The introduction of highly crosslinked polyethylene (HXLPE) has reduced wear rates in the general patient population. The objective of this study was to evaluate the influence of impact sports in patients operated with THA using ceramic-on-conventional polyethylene (cPE) versus ceramic-on-HXLPE, in terms of wear and function, with a minimum of five year follow-up.

**Methods:** Sixty-eight patients practicing an impact sport (University of California Los Angeles score  $\geq 8$ ) who underwent a primary THA were included: 34 with a ceramic-on-cPE versus 34 with a ceramic-on-HXLPE using the same cementless acetabular and femoral component. Patients were matched-paired by age, sex, BMI, and University of California Los Angeles score. The wear analysis was performed using the IMAGIKA software. The Harris hip score and hip and osteoarthritis outcome score were collected.

**Results:** The linear wear rate was statistically higher ( $P < .0001$ ) in the cPE group ( $0.13503 \pm 0.0630$  mm/year) than in the HXLPE group ( $0.03059 \pm 0.0084$  mm/year). Postoperatively, the increase in Harris hip score was calculated at 37.64 for the entire cohort and was comparable in both groups ( $P = .3674$ ). The hip and osteoarthritis outcome score for pain ( $P = .0009$ ), daily life activities ( $P = .0016$ ), and quality of life ( $P = .0179$ ) were significantly higher in the HXLPE group, with, between groups, a difference inferior to the reported minimal clinical important difference. Three patients exhibited signs of periprosthetic osteolysis in the cPE group, one on the femoral side and two on the acetabular side. None were observed in the HXLPE group. No revision for aseptic loosening was reported in both cohorts.

**Conclusion:** Patients partaking in impact sports and receiving a ceramic-on-HXLPE THA demonstrated lower wear and osteolysis rates than those having a ceramic-on-cPE THA, with similar functional results.

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One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work.

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Total hip arthroplasty (THA) is one of the leading success stories of modern day orthopedic surgery, it promotes a significant improvement in quality of life [1,2]. With the development of materials, techniques, an aging population, and the expansion of indications, an increase of 174% is anticipated in the practice of THA in the United States from 2005 to 2030 [3]. This evolution of practice has led to a positive health gain of the patient population. Patients' expectations have therefore changed, and the resumption of sporting activity is now a major objective within this younger population [4,5].

THA allows a significant increase in recreational sport practice [6], which in turn has a positive impact on the overall health of patients as well as their life expectancy [5,7,8]. The practice of

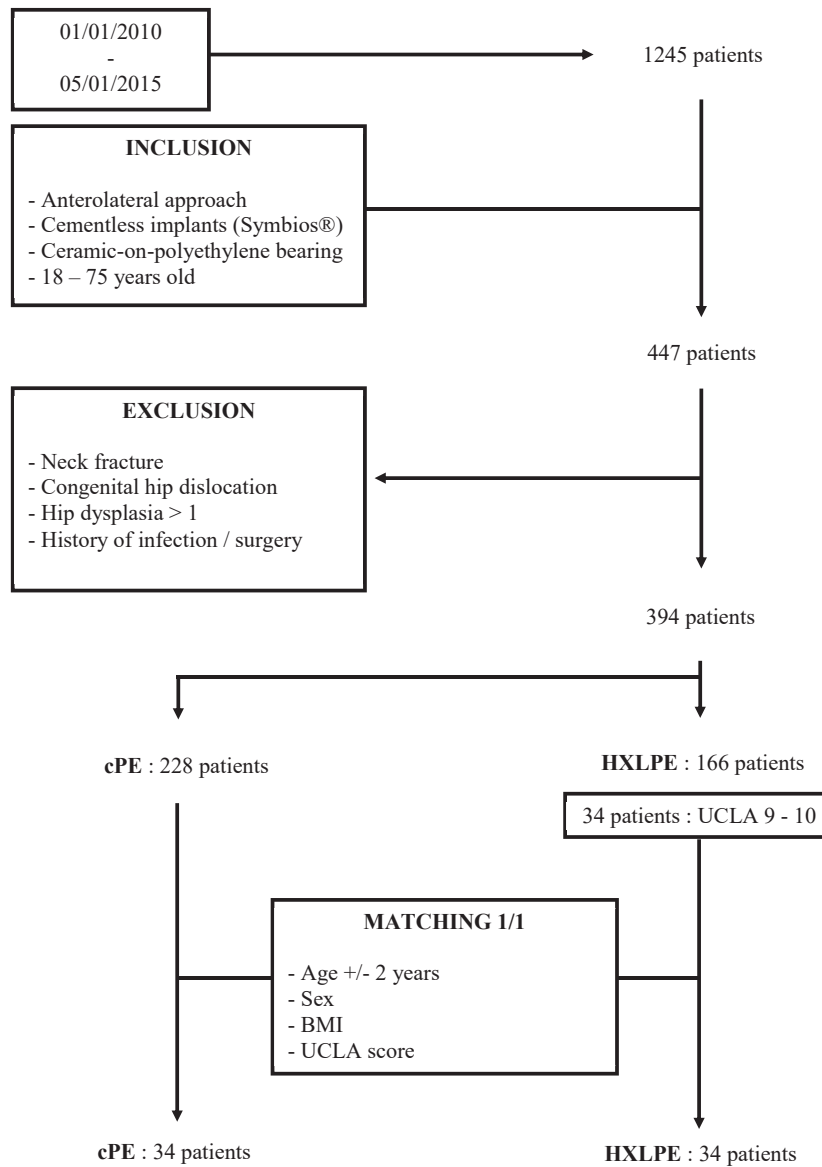


Fig. 1. Flow chart.

sustained physical activity is, however, associated with premature wear of the polyethylene [9–11], which is believed to be worsened by impact sports practice [12]. The inflammation generated by the wear debris causes a periprosthetic osteolysis, which leads to decreased implant survivorship by aseptic loosening [12–14]. Developed in the early 2000s, highly crosslinked polyethylene (HXLPE) has drastically reduced wear rates [15,16]. However, as no study has demonstrated its safety in terms of wear and survivorship, the contraindication for impact sports practice after THA has remained the rule [5,17].

Based on the current data in literature, our hypothesis was that the use of HXLPE significantly reduces polyethylene wear rates compared with cPE in patients involved in impact sports practice. The primary objective of this study was to evaluate the polyethylene wear rates in such high-demand patients, operated on with THA using ceramic-on-conventional polyethylene (cPE) versus ceramic-on-HXLPE with a minimum of five year follow-up. The secondary objectives were to evaluate 1) periprosthetic osteolysis, 2) aseptic loosening, and 3) function based on the type of polyethylene used.

## Material and Methods

### Patients

From a prospectively collected database in our center between January 1<sup>st</sup>, 2010 and May 1<sup>st</sup>, 2015, 1245 primary THAs were identified. Of this group, 447 patients met the inclusion criteria: the completion of a primary THA using the Watson-Jones anterolateral approach, the use of the same Symbios cementless acetabular and femoral implants, the use of a ceramic-on-polyethylene bearing, and patients aged between 18 and 75 years at the time of surgery and a minimum of five years follow-up. Patients who underwent surgery for the following indications were excluded: femoral neck fracture, congenital hip dislocation, and hip dysplasia worse than Crowe stage I. A history of infection or of surgery on the operated hip was also an exclusion criterion, and 53 patients were thus excluded.

Selected patients were divided into two groups as per the type of bearing involved, ceramic-on-cPE or ceramic-on-HXLPE. University of California Los Angeles (UCLA) score was used to assess the

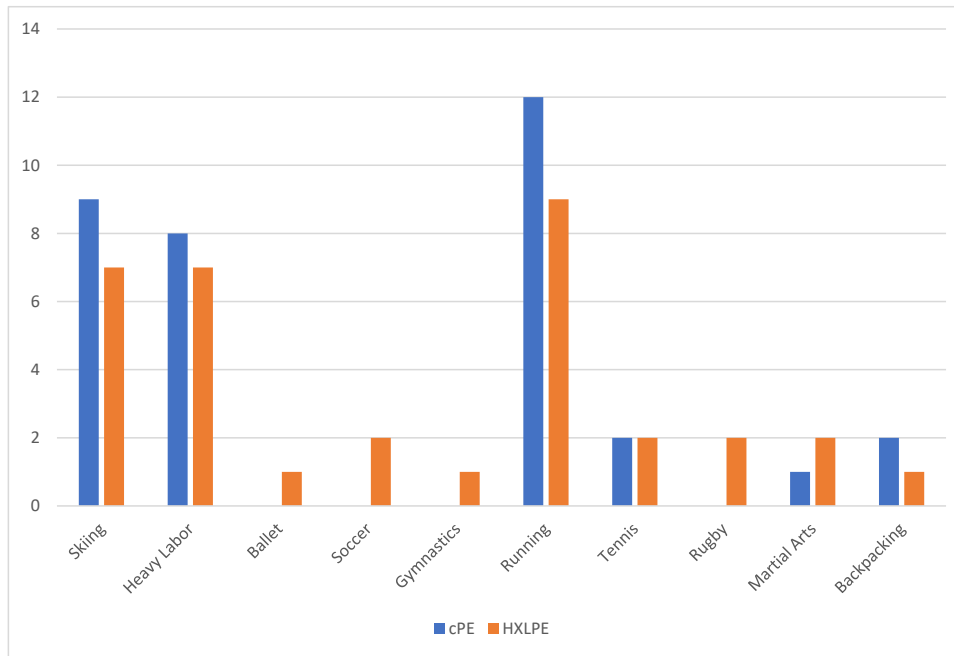


Fig. 2. Sport practice.

physical activity level of the participants [18]. We identified 34 patients involved in impact sports in the HXLPE group, characterized by a UCLA score of 9 or 10. To obtain homogeneous groups, each patient in the HXLPE group was computer-matched with one patient from the cPE group, based on sex, age ( $\pm 2$  years), body mass index (BMI,  $\text{kg}/\text{m}^2$ ), and UCLA score (Fig. 1). The type of sport practiced by the patients is shown within Figure 2.

The Watson-Jones anterolateral approach was used for the implantation of the total hip prosthesis. A preoperative three-dimensional implant-based low-dose CT scan of the lower limbs was used to determine ideal implant positioning, by taking into account the native offset, the native femoral neck version, and lower limb length. A titanium cementless acetabular implant and a cementless custom femoral stem, both covered with hydroxyapatite, were implanted in all patients (Symbios, Yverdon, Switzerland). The implanted polyethylene was either conventional (cPE) or highly crosslinked (HXLPE). The choice of polyethylene used was based on its availability in our center. The acquisition of HXLPE for Symbios implants dates back from the end of 2012. At the time of use, a number published series had already supported a reduction in terms of wear rates when HXLPE was used [15]. All patients operated on after this date benefited from it and the use of cPE stopped. Preoperative information was provided on the type of polyethylene to be used. Ceramic femoral heads were used, with a

28- or 32-millimeter diameter. The head size was chosen in relation to the acetabular implant diameter, and the largest possible diameter was selected for each case. The following demographic characteristics were collected for all patients: sex, age, weight, height, BMI, and American Society of Anesthesiologists score (Table 1).

#### Radiological Study

Radiographic analysis was performed based on frontal pelvic radiographs and on frontal and lateral radiographs of the operated hip. The radiographs taken at one-year checkup were used as a reference, to account for the bedding-in phenomenon. Further radiographs were taken at the last follow-up appointment, after which the patients answered the questionnaires. Most of these radiographs (45/68, 66.18%) were directly collected in digital JPEG format. The X-rays captured on radiographic films were digitized using a high-density scanner (SIERRA Advantage VIDAR Systems Corporation, Herndon, VA) and then converted into JPEG format.

Polyethylene wear was measured using the IMAGIKA software (GSI Medical, Neuilly sur Seine, France). The reproducibility and reliability of this software have already been validated [19]. Each measurement was performed by two experienced observers (blinded for review), twice, two days apart. The duration of follow-

Table 1  
Demographics.

Characteristics	cPE	HXLPE	P-Value
Sex (male) n (%)	24 (70.59)	25 (73.53)	.7869
Age mean $\pm$ SD (range), y	56.24 $\pm$ 9.96 (35-71)	55.74 $\pm$ 7.39 (34-65)	.8137
BMI mean $\pm$ SD (range), $\text{kg}/\text{m}^2$	24.82 $\pm$ 3.98 (17.52-33.12)	24.67 $\pm$ 3.62 (18.94-36.61)	.8677
Head size 32 n (%)	9 (26.47)	11 (32.35)	.601
Operated side (right) n (%)	19 (55.88)	15 (44.12)	.3314
Preoperative HHS mean $\pm$ SD (range)	54.09 $\pm$ 13.28 (22-78)	56.53 $\pm$ 7.46 (36-72)	.0938
UCLA score mean $\pm$ SD (range)	9.35 $\pm$ 0.49 (9-10)	9.41 $\pm$ 0.49 (9-10)	.6239
ASA score mean $\pm$ SD (range)	1.26 $\pm$ 0.45 (1-2)	1.15 $\pm$ 0.36 (1-2)	.2276
Follow-up mean $\pm$ SD (range), y	8.76 $\pm$ 0.83 (7.67-10.25)	6.39 $\pm$ 0.78 (5.25-7.75)	< .0001

BMI, body mass index; HHS, Harris hip score; UCLA, University of California Los Angeles; ASA, American Society of Anesthesiologists.

**Table 2**  
Results: Harris Hip Score (HHS).

Characteristics	cPE	HXLPE	P-Value
Preoperative HHS mean $\pm$ SD (range)	54.09 $\pm$ 13.28 (22-78)	56.53 $\pm$ 7.46 (36-72)	.0938
Postoperative HHS mean $\pm$ SD (range)	90.47 $\pm$ 9.52 (68-98)	97.44 $\pm$ 2.97 (89-100)	.0001
Delta mean $\pm$ SD (range)	36.38 $\pm$ 14.18 (2-63)	38.91 $\pm$ 7.94 (24-63)	.3674

up was significantly longer in the cPE group ( $P < .0001$ ): to standardize the results, wear was reported as wear rate per year, and expressed in millimeters per year.

Periprosthetic osteolysis was investigated for on each X-ray. Femoral osteolysis was defined by the appearance of a radiolucent edging greater than 2 millimeters in width, in one of the seven zones described by Gruen et al [20]. The stability of the femoral implant was evaluated as per the criteria of Engh et al [21]. The implant was considered loose in the event of a collapse greater than 2 millimeters or of a change in axis greater than 2 degrees. The stability of the acetabular implant was evaluated as per the Massin et al method [22]. The migration of the implant was characterized by a difference in orientation of greater than 3 degrees between the two baseline radiographs.

### Clinical Study

A questionnaire was posted to each patient or carried out by telephone when they were unreachable. UCLA score, Harris hip score (HHS) [23] and the hip and osteoarthritis outcome score (HOOS) were conducted [24,25]. The HHS score was also collected preoperatively (Table 1) and used to assess the functional capabilities after THA. The HOOS score was used to assess the quality of life associated with having a total hip prosthesis. This score is divided into five sections: pain, symptoms, daily life activities, sport participation, and quality of life. An online calculator was used to estimate each section separately, with values estimated on a scale of 1 to 100 ([www.orthotoolkit.com/hoos/](http://www.orthotoolkit.com/hoos/)).

### Statistics

Before initiating the study, a sample size analysis was performed to estimate the number of patients necessary to obtain a 90% statistical power. 30 patients by groups were needed to distinguish a difference in linear polyethylene wear  $>0.03 \pm 0.05$  mm/y between groups. A post hoc analysis also confirmed that 34 patients by group were sufficient to distinguish a difference between groups superior to the published minimal clinical important difference (MCID) of the HOOS and HSS scores [26,27]. Data were represented as mean values with ranges. Chi-squared tests were used to compare binary variables (demographic data) in the two groups. After verification of Gaussian distribution, parametric or nonparametric tests were used to compare continuous parameters between groups. To estimate the effect of demographic factors on wear rates, a multivariate model was constructed including parameters associated with linear wear in the univariate analysis ( $P < .2$ ).

Statistical analysis was performed with the use of SSPS software (IBM; Armonk, New York).

## Results

### Radiological Study

The linear wear rate of the cPE group (0.13503 mm/year  $\pm 0.0630$ , range 0.05226-0.26976) was significantly greater ( $P < .0001$ ) than that of the HXLPE group (0.03059 mm/year  $\pm 0.0084$ ,

range 0.01553-0.04588). The mean difference between the two groups was  $0.10445 \pm 0.01090$ . No evidence of periprosthetic osteolysis was found on the radiographs of the patients belonging to the HXLPE group. Three patients in the cPE group presented with radiological signs of osteolysis, one patient on the femoral side and two on the acetabular side. However, no radiological sign of implant loosening was noted. All reported no clinical symptoms, and no revision for aseptic loosening was performed in the cohort. No prosthetic dislocations or periprosthetic fractures occurred in either group.

Once all parameters were included, the multivariate analysis identified two independent risk factors for polyethylene wear: whether it was highly crosslinked polyethylene or not ( $P < .0001$ ) and BMI ( $P = .04131$ ).

### Clinical Study

No significant differences were found between the two groups concerning preoperative HHS ( $P = .0938$ ). The postoperative score was significantly higher in the HXLPE group ( $P = .0001$ ) with an average difference between the two groups of  $6.9706 \pm 1.7116$  (Table 2). The difference between preoperative and postoperative HHS was comparable between the two groups ( $P = .3674$ ).

The sections of the HOOS describing symptoms and sports practice were comparable between the two groups ( $P = .0626$  and  $P = .8562$ , Table 3). Concerning the pain section, the score was significantly better in the HXLPE group than in the cPE group ( $P = .0009$ ), with an average difference of  $6.25 \pm 1.79$ . Similar results were found for the sections describing daily life activities and quality of life ( $P = .0016$  and  $P = .0179$ ), with respective mean differences of  $5.89 \pm 1.79$  and  $3.96 \pm 0.95$ . The averages of the five sections were all superior to 90 points.

## Discussion

The main finding of this study is the reduced wear by the use of HXLPE compared with cPE in patients practicing impact sports after THA. This is in keeping with our initial hypothesis and supports its validation. The correlation between polyethylene wear and physical activity has been established for almost 30 years [9,10]. It is known that wear rate increases with the intensity of the practiced sport [12]. The critical linear wear threshold has been estimated between 0.1 mm and 0.2 mm/y [13,14], above which osteolysis is feared. With an average linear wear rate of  $0.03059$  mm/y  $\pm 0.0084$ , along with the absence of periprosthetic osteolysis, the present study demonstrates that the use of HXLPE could support the practice of impact sports after THA without adverse consequences on implant survivorship.

The resumption of a sporting activity after THA is a major objective for young and active patients [4,5]. Such patients are more likely to resume impact sports, usually against their surgeons' advice [28–30]. However, Ollivier et al showed a drastic increase in cPE wear with impact sports practice with an average linear wear rate of 0.14 mm/y [12]. Implant survivorship was thus significantly reduced, 80% after 15 years of follow-up versus 93.5% for less active patients. Gschwend et al study focused his report on the practice of

**Table 3**  
Results: Hip and Osteoarthritis Outcome Score (HOOS).

Characteristics	cPE	HXLPE	P-Value
Pain mean ± SD (range)	91.84 ± 9.89 (65-100)	98.09 ± 3.37 (87.5-100)	.0009
Symptoms mean ± SD (range)	92.79 ± 8,18 (75-100)	96.10 ± 6.07 (75-100)	.0626
Daily life activities mean ± SD (range)	91.52 ± 9.75 (68,8-100)	97.48 ± 3.58 (89,7-100)	.0016
Sport practice mean ± SD (range)	92.17 ± 11.67 (62,5-100)	91.74 ± 7,64 (75-100)	.8562
Quality of life mean ± SD (range)	93.11 ± 7.76 (75-100)	97.07 ± 5.15 (81,3-100)	.0179

off-track skiing after THA, and this further supports these results [31]: the cPE wear rate was calculated at 0.21 mm/y, with 26.6% of periprosthetic osteolysis at 10 year follow-up. This present study demonstrates patients practicing high-impact sports with cPE show a lower wear rate calculated at 0.13503 mm/y ± 0.0630, with 3 patients demonstrating periprosthetic osteolysis (8.8%), but rely on a relatively shorter follow-up. These values are still greater than the critical threshold of 0.1 mm/y estimated by Dumbleton et al [13]. Reducing wear rates thus emerges as a key issue for high-demand patients.

Developed in the early 2000s, HXLPE has led to a reduction in wear rates [32,33]. This has been evidenced by two randomized, double-blind clinical trials comparing wear rate of cPE and HXLPE [15,16], demonstrating a 5- to 9-fold reduction of wear rates in the general population. A decrease in the infection rate was even reported by Vertullo et al [34]. The clinical results, periprosthetic osteolysis, and implant survivorships are comparable with those found with ceramic-on-ceramic bearings [35,36]. As for impact sports, Abe et al did not notice an increase in wear rate with the practice of jogging [37]. In their 15-year follow-up retrospective study, Rames et al found a HXLPE linear wear rate of 0.0297 mm/y among impact sports participants, with no significant difference when less active patients were involved [38]. Gaudiani et al found similar results, with a linear wear of 0.032 mm/y and a survivorship rate of 100% with a 14 year follow-up among a young and athletic patient cohort [39]. With a HXLPE linear wear of 0.03059 mm/year ± 0.0084 mm/y without periprosthetic osteolysis, the results of this present study comparing two groups of patients implanted by the same surgeon with the same approach and using the same implants, only differing by the type of polyethylene are consistent with the literature. Impact sports practice after THA therefore appears to be safe as long as HXLPE is used.

Furthermore, sport practice after THA is a source of satisfaction for patients. The literature shows significant increased clinical scores after THA in young and athletic patients, with HHS exceeding 90 points [15,33,38,39]. The present study results corroborate those findings, the mean postoperative clinical scores of the patients being greater than 90/100 for all studied parameters. The post-operative HHS as well as the HOOS sections on pain, daily activities, and quality of life, were significantly higher in the HXLPE group. However, the average difference between the two groups did not exceed the MCID for each of them [26,27]; the clinical results can therefore be considered as comparable. The health benefits of physical activities are also well documented [7]. Low-impact sports practice after THA is therefore usually recommended by most surgeons [5,17,40,41].

The rate of return to sport is estimated at 61.4% after total knee or hip arthroplasty, particularly in young patients and when low-impact sports are involved [42]. The resumption of sport after THA depends more on the patient than on the implant [43,44]. Those individuals not resuming sport practice is therefore rarely attributed to implant-related pain: some of the most common cited examples are the fear of premature wear, (now drastically reduced with HXLPE), the fear of injury, and the operating surgeons' recommendations [37,44,45]. The fear of a periprosthetic

fracture is often invoked as a barrier for resuming sports activities after THA. However, no study has established an increased risk of fracture in patients with THA participating in impact sport compared with the general population [46–49]. Similar conclusions have been drawn regarding the prosthetic dislocation rate, however, reported rates are either equivalent or even reduced when patients practice intense physical activities [46,47]. Regarding surgeons' recommendations, young and active patients are less susceptible to follow them. It is also observed that clinical satisfaction does not correlate with decreased implant survivorship when cPE is used. Mont et al highlighted an excellent satisfaction rate in patients who returned to tennis after THA, despite an increased reintervention rate [29]. All patients returned to singles tennis, although 86% of surgeons were in opposition. The same trend can be found in the studies by Ollivier et al and Gschwend et al [12,31] who showed a higher satisfaction rate despite lower implant survivorship in active patients. Athletic and motivated patients are therefore willing to resume impact sports practice after THA, despite their surgeon's objection [5,17,40,41], rather than the capability of the THA implants [46,47,50]. With the contribution of HXLPE, this practice could be carried out without risk of premature wear.

The present study presents some limitations. First, there is a noticeable difference in the follow-up duration between the two groups. This can be explained by the fact that the acquisition of HXLPE in our center dates back from the end of 2012: all patients operated on after this date benefited from it. Because it was impossible to avoid this bias, we studied the results focusing on linear wear only. This may also explain the lower values of certain clinical scores in the cPE group, although the difference did not exceed the MCID. Second, the overall average follow-up of 7.25 years may appear low in the context of a study on the longevity of prosthetic implants. For this reason, we have chosen not to use implant survivorship as the main end point. Based on previous published literature, we are however able to estimate the risk for osteolysis and aseptic loosening in accordance with polyethylene wear values: those pertaining to the HXLPE group remain below the critical threshold of 0.1 mm/y defined by Dumbleton and al [13]. Finally, the low number of patients in our cohort could be criticized. However, it remains sufficient in light of the calculation of statistical power that we carried out before the completion of the study. Furthermore, the present study is the first to directly compare wear of conventional and highly crosslinked polyethylene in patients participating in impact sports using the same implants with the same approach. It should be noted that in comparison only a smaller proportion of patients is concerned by impact sports practice, and it is therefore difficult to obtain larger numbers of patients with a sufficient follow-up within this niche group. However, with populations matched by age, sex, BMI, UCLA score, our results are comparable on all parameters studied, and our results remain relevant.

In conclusion, the evolution of techniques and equipment has made it possible to reduce polyethylene wear rates and increase prosthetic implant survivorship. The present study is the first to compare cPE and HXLPE wear rate in patients participating in

impact sports. The contraindication of these activities after THA is mainly supported by the results obtained with cPE. The results of our study bring a new perspective that may challenge current practices.

## References

- [1] Learmonth ID, Young C, Rorabeck C. The operation of the century: total hip replacement. *Lancet* 2007;370:1508–19. [https://doi.org/10.1016/S0140-6736\(07\)60457-7](https://doi.org/10.1016/S0140-6736(07)60457-7).
- [2] Laupacis A, Bourne R, Rorabeck C, Feeny D, Wong C, Tugwell P, et al. The effect of elective total hip replacement on health-related quality of life. *J Bone Joint Surg Am* 1993;75:1619–26. <https://doi.org/10.2106/00004623-199311000-00006>.
- [3] Kurtz S, Ong K, Lau E, Mowat F, Halpern M. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. *J Bone Joint Surg Am* 2007;89:780–5. <https://doi.org/10.2106/JBJS.F.00222>.
- [4] Trousdale RT, McGrory BJ, Berry DJ, Becker MW, Harmsen WS. Patients' concerns prior to undergoing total hip and total knee arthroplasty. *Mayo Clin Proc* 1999;74:978–82. <https://doi.org/10.4065/74.10.978>.
- [5] Healy WL, Sharma S, Schwartz B, Iorio R. Athletic activity after total joint arthroplasty. *J Bone Joint Surg Am* 2008;90:2245–52. <https://doi.org/10.2106/JBJS.H.00274>.
- [6] Visuri T, Honkanen R. Total hip replacement: its influence on spontaneous recreation exercise habits. *Arch Phys Med Rehabil* 1980;61:325–8.
- [7] Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee I-M, et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Med Sci Sports Exerc* 2011;43:1334–59. <https://doi.org/10.1249/MSS.0b013e318213febf>.
- [8] Ries MD, Philbin EF, Groff GD, Sheesley KA, Richman JA, Lynch F. Effect of total hip arthroplasty on cardiovascular fitness. *J Arthroplasty* 1997;12:84–90. [https://doi.org/10.1016/s0883-5403\(97\)90052-8](https://doi.org/10.1016/s0883-5403(97)90052-8).
- [9] Schmalzried TP, Shepherd EF, Dorey FJ, Jackson WO, dela Rosa M, Fa'vae F, et al. The John Charnley Award. Wear is a function of use, not time. *Clin Orthop Relat Res* 2000;36–46. <https://doi.org/10.1097/00003086-200012000-00005>.
- [10] Kilgus DJ, Dorey FJ, Finerman GA, Amstutz HC. Patient activity, sports participation, and impact loading on the durability of cemented total hip replacements. *Clin Orthop Relat Res* 1991;25–31.
- [11] Maloney WJ, Galante JO, Anderson M, Goldberg V, Harris WH, Jacobs J, et al. Fixation, polyethylene wear, and pelvic osteolysis in primary total hip replacement. *Clin Orthop Relat Res* 1999;157–64. <https://doi.org/10.1097/00003086-199912000-00016>.
- [12] Ollivier M, Frey S, Parratte S, Flecher X, Argenson J-N. Does impact sport activity influence total hip arthroplasty durability? *Clin Orthop Relat Res* 2012;470:3060–6. <https://doi.org/10.1007/s11999-012-2362-z>.
- [13] Dumbleton JH, Manley MT, Edidin AA. A literature review of the association between wear rate and osteolysis in total hip arthroplasty. *J Arthroplasty* 2002;17:649–61. <https://doi.org/10.1054/arth.2002.33664>.
- [14] Orishimo KF, Claus AM, Sychterz CJ, Engh CA. Relationship between polyethylene wear and osteolysis in hips with a second-generation porous-coated cementless cup after seven years of follow-up. *J Bone Joint Surg Am* 2003;85:1095–9. <https://doi.org/10.2106/00004623-200306000-00018>.
- [15] Calvert GT, Devane PA, Fielden J, Adams K, Horne JG. A double-blind, prospective, randomized controlled trial comparing highly cross-linked and conventional polyethylene in primary total hip arthroplasty. *J Arthroplasty* 2009;24:505–10. <https://doi.org/10.1016/j.arth.2008.02.011>.
- [16] Devane PA, Horne JG, Ashmore A, Mutimer J, Kim W, Stanley J. Highly cross-linked polyethylene reduces wear and revision rates in total hip arthroplasty: a 10-year double-blinded randomized controlled trial. *J Bone Joint Surg Am* 2017;99:1703–14. <https://doi.org/10.2106/JBJS.16.00878>.
- [17] Laursen MK, Andersen JB, Andersen MM, Simonsen OH, Laursen MB. Danish surgeons allow the most athletic activities after total hip and knee replacement. *Eur J Orthop Surg Traumatol* 2014;24:1571–7. <https://doi.org/10.1007/s00590-014-1442-z>.
- [18] Zahiri CA, Schmalzried TP, Szuszczewicz ES, Amstutz HC. Assessing activity in joint replacement patients. *J Arthroplasty* 1998;13:890–5. [https://doi.org/10.1016/s0883-5403\(98\)90195-4](https://doi.org/10.1016/s0883-5403(98)90195-4).
- [19] Girard J, Touraine D, Soenen M, Massin P, Laffargue P, Migaud H. [Measurement of head penetration on digitalized radiographs: reproducibility and accuracy]. *Rev Chir Orthop Reparatrice Appar Mot* 2005;91:137–42. [https://doi.org/10.1016/s0035-1040\(05\)84291-6](https://doi.org/10.1016/s0035-1040(05)84291-6).
- [20] Gruen TA, McNeice GM, Amstutz HC. "Modes of failure" of cemented stem-type femoral components: a radiographic analysis of loosening. *Clin Orthop Relat Res* 1979:17–27.
- [21] Engh CA, Bobyn JD, Glassman AH. Porous-coated hip replacement. The factors governing bone ingrowth, stress shielding, and clinical results. *J Bone Joint Surg Br* 1987;69:45–55.
- [22] Massin P, Schmidt L, Engh CA. Evaluation of cementless acetabular component migration. An experimental study. *J Arthroplasty* 1989;4:245–51. [https://doi.org/10.1016/s0883-5403\(89\)80020-8](https://doi.org/10.1016/s0883-5403(89)80020-8).
- [23] Harris WH. Traumatic arthritis of the hip after dislocation and acetabular fractures: treatment by mold arthroplasty. An end-result study using a new method of result evaluation. *J Bone Joint Surg Am* 1969;51:737–55.
- [24] Nilsson AK, Lohmander LS, Klässbo M, Roos EM. Hip disability and osteoarthritis outcome score (HOOS)-validity and responsiveness in total hip replacement. *BMC Musculoskelet Disord* 2003;4:10. <https://doi.org/10.1186/1471-2474-4-10>.
- [25] Ornetti P, Parratte S, Gossec L, Tavernier C, Argenson J-N, Roos EM, et al. Cross-cultural adaptation and validation of the French version of the Hip disability and Osteoarthritis Outcome Score (HOOS) in hip osteoarthritis patients. *Osteoarthr Cartil* 2010;18:522–9. <https://doi.org/10.1016/j.joca.2009.12.007>.
- [26] Lyman S, Lee Y-Y, McLawhorn AS, Islam W, MacLean CH. What are the minimal and substantial improvements in the HOOS and KOOS and JR versions after total joint replacement? *Clin Orthop Relat Res* 2018;476:2432–41. <https://doi.org/10.1097/CORR.0000000000000456>.
- [27] Singh JA, Schleck C, Harmsen S, Lewallen D. Clinically important improvement thresholds for Harris Hip Score and its ability to predict revision risk after primary total hip arthroplasty. *BMC Musculoskelet Disord* 2016;17:256. <https://doi.org/10.1186/s12891-016-1106-8>.
- [28] Huch K, Müller KaC, Stürmer T, Brenner H, Puhl W, Günther K-P. Sports activities 5 years after total knee or hip arthroplasty: the Ulm Osteoarthritis Study. *Ann Rheum Dis* 2005;64:1715–20. <https://doi.org/10.1136/ard.2004.033266>.
- [29] Mont MA, LaPorte DM, Mullick T, Silberstein CE, Hungerford DS. Tennis after total hip arthroplasty. *Am J Sports Med* 1999;27:60–4. <https://doi.org/10.1177/03635465990270011801>.
- [30] Lefevre N, Rousseau D, Bohu Y, Klouche S, Herman S. Return to judo after joint replacement. *Knee Surg Sports Traumatol Arthrosc* 2013;21:2889–94. <https://doi.org/10.1007/s00167-012-2064-9>.
- [31] Gschwend N, Frei T, Morscher E, Nigg B, Loehr J. Alpine and cross-country skiing after total hip replacement: 2 cohorts of 50 patients each, one active, the other inactive in skiing, followed for 5–10 years. *Acta Orthop Scand* 2000;71:243–9. <https://doi.org/10.1080/000164700317411825>.
- [32] Ranawat AS, Tsailis P, Meftah M, Koob TW, Rodriguez JA, Ranawat CS. Minimum 5-year wear analysis of first-generation highly cross-linked polyethylene in patients 65 years and younger. *J Arthroplasty* 2012;27:354–7. <https://doi.org/10.1016/j.arth.2011.07.003>.
- [33] Shia DS, Clohisy JC, Schinsky MF, Martell JM, Maloney WJ. THA with highly cross-linked polyethylene in patients 50 years or younger. *Clin Orthop Relat Res* 2009;467:2059–65. <https://doi.org/10.1007/s11999-008-0697-2>.
- [34] Vertullo CJ, Lewis PL, Peng Y, Graves SE, de Steiger RN. The effect of alternative bearing surfaces on the risk of revision due to infection in minimally stabilized total knee replacement: an analysis of 326,603 prostheses from the Australian orthopaedic association national joint replacement registry. *J Bone Joint Surg Am* 2018;100:115–23. <https://doi.org/10.2106/JBJS.17.00269>.
- [35] Beaupre LA, Al-Houkail A, Johnston DWC. A randomized trial comparing ceramic-on-ceramic bearing vs ceramic-on-crossfire-polyethylene bearing surfaces in total hip arthroplasty. *J Arthroplasty* 2016;31:1240–5. <https://doi.org/10.1016/j.arth.2015.11.043>.
- [36] Kim Y-H, Park J-W. Eighteen-year follow-up study of 2 alternative bearing surfaces used in total hip arthroplasty in the same young patients. *J Arthroplasty* 2020;35:824–30. <https://doi.org/10.1016/j.arth.2019.09.051>.
- [37] Abe H, Sakai T, Nishii T, Takao M, Nakamura N, Sugano N. Jogging after total hip arthroplasty. *Am J Sports Med* 2014;42:131–7. <https://doi.org/10.1177/0363546513506866>.
- [38] Rames RD, Stambough JB, Pashos GE, Maloney WJ, Martell JM, Clohisy JC. Fifteen-year results of total hip arthroplasty with cobalt-chromium femoral heads on highly cross-linked polyethylene in patients 50 Years and less. *J Arthroplasty* 2019;34:1143–9. <https://doi.org/10.1016/j.arth.2019.01.071>.
- [39] Gaudiani MA, Ranawat AS, Ranawat CS. Wear analysis of highly cross-linked polyethylene in young and active patients at average fourteen years: a concise follow-up of a previous report. *J Arthroplasty* 2018;33:586–9. <https://doi.org/10.1016/j.arth.2017.09.007>.
- [40] Klein GR, Levine BR, Hozack WJ, Strauss EJ, D'Antonio JA, Macaulay W, et al. Return to athletic activity after total hip arthroplasty. Consensus guidelines based on a survey of the Hip Society and American Association of Hip and Knee Surgeons. *J Arthroplasty* 2007;22:171–5. <https://doi.org/10.1016/j.arth.2006.09.001>.
- [41] Swanson EA, Schmalzried TP, Dorey FJ. Activity recommendations after total hip and knee arthroplasty: a survey of the American Association for Hip and Knee Surgeons. *J Arthroplasty* 2009;24:120–6. <https://doi.org/10.1016/j.arth.2009.05.014>.
- [42] Wylde V, Blom A, Dieppe P, Hewlett S, Learmonth I. Return to sport after joint replacement. *J Bone Joint Surg Br* 2008;90:920–3. <https://doi.org/10.1302/0301-620X.90B7.20614>.
- [43] Williams DH, Greidanus NV, Masri BA, Duncan CP, Garbus DS. Predictors of participation in sports after hip and knee arthroplasty. *Clin Orthop Relat Res* 2012;470:555–61. <https://doi.org/10.1007/s11999-011-2198-y>.
- [44] Ollivier M, Frey S, Parratte S, Flecher X, Argenson JN. Pre-operative function, motivation and duration of symptoms predict sporting participation after total hip replacement. *Bone Joint J* 2014;96-B:1041–6. <https://doi.org/10.1302/0301-620X.96B8.32813>.
- [45] Delasotta LA, Rangavajjala AV, Porat MD, Frank ML, Orozco FR, Ong AC. What are young patients doing after hip reconstruction? *J Arthroplasty* 2012;27:1518–1525.e2. <https://doi.org/10.1016/j.arth.2012.02.001>.

- [46] Meek RMD, Treacy R, Manktelow A, Timperley JA, Haddad FS. Sport after total hip arthroplasty: undoubted progress but still some unknowns. *Bone Joint J* 2020;102-B:661–3. <https://doi.org/10.1302/0301-620X.102B6.Bjj-2020-0208>.
- [47] Krismer M. Sports activities after total hip arthroplasty. *EFORT Open Rev* 2017;2:189–94. <https://doi.org/10.1302/2058-5241.2.160059>.
- [48] McGrory BJ. Periprosthetic fracture of the femur after total hip arthroplasty occurring in winter activities: report of two cases. *J Surg Orthop Adv* 2004;13:119–23.
- [49] Meek RMD, Norwood T, Smith R, Brenkel IJ, Howie CR. The risk of periprosthetic fracture after primary and revision total hip and knee replacement. *J Bone Joint Surg Br* 2011;93:96–101. <https://doi.org/10.1302/0301-620X.93B1.25087>.
- [50] Seyler TM, Mont MA, Ragland PS, Kachwala MM, Delanois RE. Sports activity after total hip and knee arthroplasty: specific recommendations concerning tennis. *Sports Med* 2006;36:571–83. <https://doi.org/10.2165/00007256-200636070-00003>.