Reduction in rate of implant waste associated with robotic-assisted total hip arthroplasty

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Aims
Implant waste during total hip arthroplasty (THA) represents a significant cost to the USA healthcare system. While studies have explored methods to improve THA cost-effectiveness, the literature comparing the proportions of implant waste by intraoperative technology used during THA is limited. The aims of this study were to: 1) examine whether the use of enabling technologies during THA results in a smaller proportion of wasted implants compared to navigation-guided and conventional manual THA; 2) determine the proportion of wasted implants by implant type; and 3) examine the effects of surgeon experience on rates of implant waste by technology used.

Methods
We identified 104,420 implants either implanted or wasted during 18,329 primary THAs performed on 16,724 patients between January 2018 and June 2022 at our institution. THAs were separated by technology used: robotic-assisted (n = 4,171), imageless navigation (n = 6,887), and manual (n = 7,721). The primary outcome of interest was the rate of implant waste during primary THA.

Results
Robotic-assisted THA resulted in a lower proportion (1.5%) of implant waste compared to navigation-guided THA (2.0%) and manual THA (1.9%) (all $p < 0.001$). Both navigated and manual THA were more likely to waste acetabular shells (odds ratio (OR) 4.5 vs 3.1) and polyethylene liners (OR 2.2 vs 2.0) compared to robotic-assisted THA after adjusting for demographic and perioperative factors, such as surgeon experience ($p < 0.001$). While implant waste decreased with increasing experience for procedures performed manually ($p < 0.001$) or with navigation ($p < 0.001$), waste rates for robotic-assisted THA did not differ based on surgical experience.

Conclusion
Robotic-assisted THAs wasted a smaller proportion of acetabular shells and polyethylene liners than navigation-guided and manual THAs. Individual implant waste rates vary depending on the type of technology used intraoperatively. Future studies on implant waste during THA should examine reasons for non-implantation in order to better understand and develop methods for cost-saving.

Take home message
- Robotic-assisted total hip arthroplasties (THAs) wasted a smaller proportion of acetabular shells and polyethylene liners than navigation-guided and manual THAs.
- Individual implant waste rates vary depending on the type of technology used intraoperatively.

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Introduction
Implant waste during total hip arthroplasty (THA) represents a significant cost and burden to the USA healthcare system.[1,2] The annual cost of wasted hip arthroplasty implants to hospitals across the USA was estimated to be USD $36,019,000 in a study published in 2010.[1] Taking into account a rapidly ageing population and the rising

demand for primary THA,[3–6] this cost is only expected to continue increasing over the next few decades.[1]

Robotic-assisted techniques are becoming increasingly popular among surgeons performing THA.[7-9] Some studies have shown that, compared to navigation-guided and conventional manual procedures, robotic-assisted THA facilitates increased precision with component positioning.[7-11] In turn, these technical advantages can lead to smaller leg-length discrepancies,[9,12] greater bone stock preservation,[13,14] fewer postoperative complications,[15-17] and, in some series, better patient-reported outcomes and fewer revision surgeries.[7,17-19]

While prior literature has compared the clinical benefits of robotic-assisted, navigation-guided, and manual THA, studies examining these three techniques from an implant waste standpoint are limited. The few studies that have reported on orthopaedic implant waste have typically focused on waste from orthopaedic trauma procedures or total knee arthroplasty, and have reported the average volume and weight of implant waste per surgical case as opposed to rates and types of implants wasted.[20–22] Therefore, the primary aim of this study was to determine the rate of implant waste associated with robotic-assisted, navigation-guided, and manual THA. The secondary aims were to determine the effect of surgeon experience on the rate of implant waste, to compare the odds of implant waste by technology used while adjusting for demographic and perioperative factors, and to determine the effect of acetabular shell size on the rate of implant waste.

Methods

Patient population

We identified all patients who underwent a primary THA at our institution (Hospital for Special Surgery, New York, USA) between 1 January 2018 and 30 June 2022 and the implants used during these procedures. Partial hip arthroplasty and revision surgeries were excluded. Patients who underwent one primary THA on each side were included in our study and both surgeries were included in the analyses. The study was approved by the Institutional Review Board and conducted in accordance with the ethical standards in the 1964 Declaration of Helsinki.[23]

Demographic, perioperative, and surgical data

Demographic data and patient-level characteristics, including sex, age, and BMI, were obtained from electronic health records. Perioperative and surgical data such as American Society of Anesthesiologists (ASA) grade,[24] date of surgery, surgeon experience at the time of surgery, procedure type (unilateral or bilateral), surgical approach (anterior or posterior), type of technology used intraoperatively (robotics, navigation, or manual), name and units of implants used, and implant status (implanted or wasted) were also retrieved from medical records. All robotic-assisted THAs performed at our institution during the study period used a CT-based robotic arm-assisted system (Mako; Stryker, USA). Navigation technologies used included HipAlign (OrthAlign, USA), Intellijoint HIP (Intellijoint Surgical, Canada), Naviswiss (Naviswiss, Switzerland), and OrthoSensor (OrthoSensor, USA). Implants were manually reviewed and categorized as femoral heads, femoral components, acetabular shells, polyethylene liners, acetabular screws, dome hole covers, dual-mobility (DM) polyethylene-bearing centralizers, cement restrictors, DM liners, cables/wires, or other. Other implants included femoral head sleeve adapters, bone substitutes, and cones. Acetabular shells were further subcategorized by implant size. Surgeon experience was defined as the time between a surgeon's fellowship graduation date and the date of surgery.

Table I. Total hip arthroplasty patient-level characteristics.*†

Variable	Robotic-assisted (n = 4,171), n (%)	Navigation-guided (n = 6,887), n (%)	Manual (n = 7,271), n (%)
Age, yrs			
< 50	376 (9)	520 (8)	615 (8)
50 to 59	926 (22)	1,652 (24)	1,509 (21)
60 to 69	1,565 (38)	2,734 (40)	2,527 (35)
70 to 79	1,029 (25)	1,594 (23)	1,929 (27)
80+	275	387	691
BMI, kg/m²			
< 18.5	44 (1)	101 (1)	87 (1)
18.5 to 24.9	1,038 (25)	2,259 (33)	1,641 (23)
25 to 29.9	1,504 (36)	2,452 (36)	2,466 (34)
30 to 39.9	1,408 (34)	1,843 (27)	2,581 (35)
40+	177 (4)	232 (3)	496 (7)
Sex			
Male	1,880 (45)	2,748 (40)	3,165 (44)
Female	2,291 (55)	4,139 (60)	4,106 (56)
ASA grade			
0	7 (0.2)	29 (0.4)	33 (0.5)
1	174 (4.2)	334 (4.8)	238 (3.3)
2	3,325 (79.7)	5,672 (82.4)	5,615 (77.2)
3	655 (15.7)	846 (12.3)	1,381 (19)
4	10 (0.2)	6 (0.1)	4 (0.1)
THA procedure			
Unilateral	4,144 (99)	6,714 (97)	7,080 (97)
Bilateral	27 (1)	173 (3)	191 (3)

*Bilateral total hip arthroplasties (THAs) were counted as one case for all patient-level characteristics.
†Patients who underwent one primary THA on each hip were counted twice.
ASA, American Society of Anesthesiologists; THA, total hip arthroplasty.

Outcome measures

The primary outcome of interest of this study was the proportion of surgical implant waste during primary THA. The secondary outcome of interest was the proportion of wasted implants by implant type and size.

Patient characteristics and surgical data

We identified 104,420 implants either implanted or wasted during 18,329 primary THAs performed on 16,724 patients by 43 orthopaedic surgeons at a single institution (Hospital for Special Surgery) between 1 January 2018 and 30 June 2022. Of these procedures, 17,938 were unilateral THAs and 391 were simultaneous bilateral THAs (Table I). Navigation guidance and robotic assistance were used in 6,887 and 4,171

Table II. Implant waste for primary total hip arthroplasty components by technology used.

Implant	Robotic-assisted (n = 4,171)			Navigation-guided (n = 6,887)			Manual (n = 7,271)			Total (n = 18,329)		
	Implanted, n	Wasted, n	Waste, %	Implanted, n	Wasted, n	Waste, %	Implanted, n	Wasted, n	Waste, %	Implanted, n	Wasted, n	Waste, %
Femoral head	4,198	52	1.2	7,060	187	2.6	7,462	114	1.5	18,720	353	1.9
Femoral component	4,198	44	1.0	7,060	111	1.5	7,462	113	1.5	18,720	268	1.4
Acetabular shell	4,198	19	0.5	7,060	89	1.2	7,462	90	1.2	18,720	198	1.0
Polyethylene liner	3,923	63	1.6	6,331	208	3.2	6,069	201	3.2	16,323	472	2.8
Acetabular screw	5,252	104	1.9	3,377	51	1.5	2,254	112	4.7	10,883	267	2.4
Dome hole covers	1,624	72	4.2	2,783	44	1.6	3,112	64	2.0	7,519	180	2.3
DM poly bearing	275	3	1.1	729	12	1.6	1,393	19	1.3	2,397	34	1.4
Centralizer	217	4	1.8	780	7	0.9	819	11	1.3	1,816	22	1.2
Cement restrictor	428	14	3.2	817	10	1.2	519	13	2.4	1,764	37	2.1
DM liners	271	-	0.0	494	5	1.0%	871	5	0.6	1,636	10	0.6
Cables/wires	132	6	4.3	77	7	8.3	113	5	4.2	322	18	5.3
Other	1,370	18	1.3	1,483	28	1.9	831	11	1.3	3,684	57	1.5
Total	26,086	399	1.5	38,051	759	2.0	38,367	758	1.9	102,504	1,916	1.8

DM, dual-mobility.

Table III. Proportion of implant waste by surgeon experience and technology used.

Experience, yrs	Robotic-assisted			Navigation-guided			Manual		
	Implanted, n	Wasted, n	Waste, %	Implanted, n	Wasted, n	Waste, %	Implanted, n	Wasted, n	Waste, %
Less than 5	8,521	158	1.8	3,012	97	3.1	1,593	53	3.2
5 to 10	13,317	189	1.4	2,256	68	2.9	6,304	144	2.2
10 to 20	3,750	42	1.1	18,626	386	2.0	10,271	196	1.9
20 or more	498	10	2.0	14,157	208	1.4	20,199	365	1.8

procedures, respectively. The remaining 7,271 THAs were performed manually. Mean age at the time of surgery was 63.4 years (12 to 97). Mean BMI was 28.7 kg/m^2 (15 to 63). More robotic-assisted, navigation-guided, and manual THAs were performed in females than males. Most patients were white (86%) and were ASA grade II (79%) at the time of surgery. Over 97% of all THAs were unilateral procedures.

Statistical analysis
Descriptive statistics were reported with frequencies and percentages for categorical variables including patient age in ten-year bins, sex, race, BMI with World Health Orginazation (WHO) categories, ASA grades from 0 to IV, surgical procedure (unilateral or bilateral), surgeon experience (< five years, five to ten years, ten to 20 years, and 20+ years), and shell size. Chi-squared test and Fisher's exact test were used to compare categorical variables between/within three groups (robotics, navigation, or manual) and implant status (implanted or wasted). Multivariate logistic regression analyses were performed to determine if a specific technology assistant was significantly associated with a type of component waste (femoral head, femoral component, acetabular shell, or polyethylene liner), after adjusting for patient BMI, weight, height, age, race, sex, ASA grade, surgeon experience, and surgical approach (anterior or posterior). A p-value ≤ 0.05 was considered statistically significant. All odds ratios (ORs) are reported with 95% CIs. All tests were two-tailed. Statistical analyses were performed using SAS v. 9.4 (SAS Institute, USA) and RStudio v. 1.4.1717 (RStudio, USA).

Results
Proportion of implant waste
The overall rate of implant waste for any component was significantly higher for navigation-guided (2.0%) and manual (1.9%) THAs compared to robotic-assisted (1.5%) THAs (both $p < 0.001$) (Table II). Specifically, robotic-assisted THAs wasted a smaller proportion of femoral components, acetabular shells, and polyethylene liners than navigation-guided and manual THAs (all $p < 0.05$). In particular, acetabular shell waste was 0.5% in the robotic-assisted group compared to 1.2% in both

Table IV. Odds of implant waste by technology used adjusted for demographic and perioperative factors.

Outcome	Comparison	Odds ratio	95% CI	p-value*
Acetabular shell wasted	Navigation vs robotics	4.5	2.4 to 8.7	**< 0.001**
	Manual vs robotics	3.1	1.7 to 5.8	**< 0.001**
	Navigation vs manual	1.5	1.0 to 2.1	**0.047**
Polyethylene liner wasted	Navigation vs robotics	2.2	1.5 to 3.1)	**< 0.001**
	Manual vs robotics	2.0	1.4 to 2.7	**< 0.001**
	Navigation vs manual	1.1	0.8 to 1.5	0.999
Femoral head wasted	Navigation vs robotics	1.9	1.2 to 2.9	**0.002**
	Navigation vs manual	1.4	1.0 to 2.0	0.093
	Manual vs robotics	1.3	0.9 to 2.0	0.291
Femoral component wasted	Navigation vs robotics	1.7	1.2 to 2.6	**0.004**
	Navigation vs manual	1.3	0.9 to 1.9	0.195
	Manual vs robotics	1.3	0.9 to 2.0	0.340

*Multiple comparisons with Bonferroni correction. All models are adjusted for BMI, age, race, sex, American Society of Anesthesiologists grade, surgeon experience, and surgical approach (anterior or posterior). Bold indicates statistical significance.

the navigation-guided and manual groups, respectively. No statistically significant differences were seen in DM polyethylene bearing, centralizer, DM liner, or cables/wires waste.

Effects of surgeon experience on implant waste

Implant waste decreased significantly with increasing surgical experience for navigation-guided ($p < 0.001$) and manual ($p < 0.001$) THAs, but not for robotic-assisted THAs ($p = 0.420$) (Table III). For surgeons with less than 20 years of experience, the use of robotics resulted in lower implant waste rates compared to navigation-guided and manual procedures (all $p < 0.001$). However, robotic assistance did not result in reductions in implant waste for surgeons who had 20 or more years of experience. The rate of waste did not exceed 2.0% for all experience levels in the robotic-assisted group.

Multivariate analyses

After adjusting for demographic and perioperative factors including BMI, age, race, sex, ASA grade, surgeon experience, and surgical approach, the odds of acetabular shell and polyethylene liner waste were significantly greater for navigation-guided (OR 4.5, 95% CI 2.4 to 8.7 for acetabular shells; OR 2.2, 95% CI 1.5 to 3.1 for polyethylene liners) and manual (OR 3.1, 95% CI 1.7 to 5.8 for acetabular shells; OR 2.0, 95% CI 1.4 to 2.7 for polyethylene liners) THAs compared to robotic-assisted THAs (Table IV). Navigation-guided THAs wasted more femoral heads (OR 1.9, 95% CI 1.2 to 2.9) and femoral components (OR 1.7, 95% CI 1.2 to 2.6) compared to robotic-assisted THAs, but no other significant differences in femoral head and femoral component waste were observed.

Acetabular shell waste by shell size

Further analyses of acetabular shell waste demonstrated that implant waste differed significantly depending on shell size (Table V). Acetabular shell waste for shells 56 mm and larger was greater for navigation-guided and manual THAs compared to robotic-assisted procedures (navigation (1.9%) vs robotic (0.6%); $p = 0.005$; manual (1.2%) vs robotic (0.6%); $p = 0.048$). Waste rates for shells 52 mm and smaller did not differ significantly by technology used (all $p > 0.05$). No significant difference in acetabular shell waste by shell size was observed within groups for robotic-assisted, navigation-guided, and manual procedures.

Discussion

Understanding the factors that affect orthopaedic implant waste in primary THA may help reduce operating theatre expenditure and eliminate unnecessary costs to our healthcare system, especially as the demand for THA in the USA continues to increase. Though the use of robotics and navigation in THA has become more and more common,[15,25] no studies, to the best of our knowledge, have examined and compared the proportion of implant waste during THA by intraoperative technology use and implant type. This study included a large sample of robotic-assisted, navigation-guided, and manual THAs, and identified significant differences in waste rates depending on technology used, implant type, implant size, and surgeon experience. These findings suggest that the use of robotics during primary THA is associated with reduced rates of overall implant waste.

There have been few studies that have reported on overall implant waste rates and costs in hip arthroplasty. Payne et al,[2] for instance, analyzed 1,076 THAs performed between June 2012 and May 2013 at a single institution and reported an estimated waste cost of USD$118 per THA. Laurut et al[26] examined all hip arthroplasties performed at a French teaching hospital in 2016 and reported higher rates of acetabular shell (6.1%) and polyethylene liner (6.6%) waste compared to our study. It should be noted, however, that both these studies included revision THAs.

Prior studies have also examined the variance in THA implant waste by years of surgical experience and found no significant differences in waste between surgeons with less than ten years of experience, ten to 19 years of experience, and more than 20 years of experience.[2] However, these researchers did not stratify THAs by technology used and reported the percentage of cases with implant waste without taking into account how many implants were used in each case. In our study, implant waste decreased with increasing experience for THAs performed manually and with navigation guidance, but not for robotic-assisted THAs. Furthermore, surgeons with less than 20 years of experience who performed robotic-assisted procedures wasted significantly fewer implants compared to those who performed navigation-guided and manual procedures. These findings suggest that the technical features of robotic-assisted surgery may aid less experienced surgeons to more consistently prepare and implant an acetabular component.

We observed a decreased rate of waste for larger acetabular shells 56 mm or greater using robotic assistance compared to navigation or manual technique. We speculate that this observation may be due to the use of a single- or two-stage reaming technique using a robotic arm that is able to maintain trajectory and centre of rotation throughout the reaming process. Conventionally, larger acetabular sizes are prepared with sequential reaming, with each step

Table V. Acetabular shell sizes wasted by technology.

	Robotic-assisted			Navigation-guided			Manual		
Acetabular shell size, mm	Implanted	Wasted	Wasted, %	Implanted	Wasted	Wasted, %	Implanted	Wasted	Wasted, %
46 or lower	167	-	0	358	4	1.1	264	4	1.5
48	775	5	0.6	1,296	13	1	1,014	12	1.2
50	450	3	0.7	1,336	20	1.5	1,305	21	1.8
52	1,149	4	0.3	1,571	19	1.2	1,705	14	0.8
54	600	1	0.2	1,138	7	0.6	1,252	15	1.2
56 or higher	1,057	6	0.6	1,361	26	1.9	1,922	24	1.2
Total	4,198	19	0.5	7,060	89	1.3	7,462	90	1.2

introducing the possibility of eccentric reaming and suboptimal fit of the acetabular component, which may lead to waste. Taken together with our observations regarding surgeon experience, we suggest that it is the unique technical features of the robotic arm that result in more consistent acetabular preparation, and by extension, decreased acetabular component waste.

This study has limitations. All data were obtained from a single teaching institution and therefore may not be generalizable to all orthopaedic departments across the USA. Nonetheless, our study is impactful in that it incorporates a large sample of robotic-assisted, navigation-guided, and manual THAs and is one of the first studies, to the best of our knowledge, to demonstrate that the use of robotic assistance during primary THAs can effectively reduce implant waste rates. We were not able to fully account for all surgeon-related and technical factors that may result in implant waste. The current study also included a smaller sample of surgeons with 20 or more years of experience who performed robotic-assisted THAs, which may have contributed to the differences in implant waste observed between robotic-assisted and conventional procedures performed by this cohort. Additionally, we did not track the reason for each wasted implant, which could have included unpackaging errors, failed implantation due to patient anatomy, loss of sterility, or incorrect surgical use, among others. Understanding the reason for non-implantation can be helpful for future cost-containment efforts.

Robotic-assisted THAs wasted a smaller proportion of acetabular shells and polyethylene liners than navigation-guided and manual THAs. Individual implant waste rates vary depending on the type of technology used intraoperatively. Future studies on implant waste during THA should examine reasons for non-implantation in order to better understand and develop methods for cost-saving.

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Data sharing

The data that support the findings for this study are available to other researchers from the corresponding author upon reasonable request.

Ethical review statement

The study was approved by the Institutional Review Board and conducted in accordance with the ethical standards in the 1964 Declaration of Helsinki.

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