Background and purpose — The incidence of knee replacements (KRs) has increased in the past decades. Previous studies have forecast a continuous and almost exponential rise in the use of KRs, but this rise must cease at some point. We estimated when and at what incidence the use of KRs will plateau in Denmark.

Patients and methods — We retrieved 138,223 primary KRs conducted from 1997 to 2019 from the Danish Knee Arthroplasty Registry. Censuses from 1997 to 2019 as well as population projections from 2020 through 2050 were collected from Statistics Denmark. We applied logistic and Gompertz regression analysis to the data to estimate the future incidence until 2050 with root mean squared error (RMSE) as a quantitative measurement of the models’ fit.

Results — The Danish incidence of KRs from 1997 to 2009 increased by more than 300%, but has stalled since 2009. Logistic and Gompertz regression had an RMSE of 14 and 15 indicating that these models fitted the data well. Logistic and Gompertz regressions estimated that the maximum incidence will be reached in 2030 at 250 (95% prediction interval [PI] 159–316) KRs per 10^5 or in 2035 at 260 (PI 182–336) KRs per 10^5, respectively.

Interpretation — The Danish incidence of KRs seems set to plateau within the coming decades. Countries experiencing a current exponential rise at a lower incidence may benefit from this study’s projection when forecasting their future demand for KRs.

Only few studies have attempted to project the future demand for knee replacements (KRs) (Kurtz et al. 2007, Culliford et al. 2015, Patel et al. 2015, Guerrero-Ludueña et al. 2016) with only 1 conducted in a recent Swedish population (Nemes et al. 2015). Most of these studies are based on historical data from a period when the countries experienced a rapid, almost exponential, growth in the incidence of KRs. Historically Denmark has experienced a similar growth, but within the last decade the increase in incidence has stalled. In all countries, a similar stagnation is to be expected. Yet, when a country is experiencing a rapid increase in the incidence of KRs it is difficult to reliably estimate at which timepoint and volume the incidence will stagnate. Therefore, we used the stagnating incidence in Denmark to make a more reliable estimation of when and at what volume the incidence of primary KRs will plateau during 2020 to 2050.
conducted at public and private hospitals since 1968 (Schmidt et al. 2015). This linkage was used to adjust for unregistered primary KRs in the DKR, and thus the total number of primary KRs was in accordance with the DNPR, whereas the reported subtypes of KRs (e.g., total knee arthroplasties or unicompartmental knee arthroplasties) were based solely on the registered KRs in the DKR.

Censuses from 1997 to 2019 and population projections from 2020 through 2050 were collected from Statistics Denmark. Statistics Denmark is the central Danish authority of collecting, processing, and publishing statistical information e.g., censuses in Denmark (Statistics Denmark; https://www.dst.dk/en). The data used in this study was collected on March 9, 2020.

Study cohort
From the DKR, we retrieved information on all primary KRs conducted from 1997 to 2019. Individuals younger than 30 or older than 99 were excluded as they do not represent the typical patient undergoing KR. After exclusion of these as well as duplicates, undefined implants, and condylar implants (e.g., hemicaps), 138,223 primary KRs were included in the study cohort (Figure 1).

Data analyses and modelling
The KRs were divided by type of arthroplasty to see the evolution in the use of different KRs from 1997 to 2019.

The censuses from Statistics Denmark were used to determine the incidence per 10^5 of primary KRs from 1997 through 2019.

From the incidence and population projections, we estimated the annual number of primary KRs to be conducted in Denmark from 2020 through 2050.

The annual incidence of KRs was regressed on each calendar year from 1997 throughout 2050 with the use of logistic and Gompertz regression analysis on the actual incidences between 1997 and 2019. Logistic regression assumes that the quantity of knee replacements increases in a similar fashion to an exponential curve but gradually slows to linear growth. Gompertz regression analysis assumes that the quantity of knee replacements increases similarly to the logistic model, but the upper asymptote is approached more gradually than in the logistic, where the curve is symmetric.

Statistics
Root mean squared error (RMSE) was used as a quality estimator of the models’ fit to the data points and used to pick the best-fitted models. All estimates were rounded to the nearest hundreds or thousands (when the projected numbers exceeded 1,000), and presented with their 95% prediction interval (PI).

All analyses were conducted in JMP Pro 15 by SAS (SAS Institute, Cary, NC, USA).

Ethics, funding, data sharing, and potential conflicts of interests
This study was approved by the North Denmark Region (ID: 2019-107) and by the Steering Committee of the Danish Knee Arthroplasty Registry (DKR-2019-10-16). The study was financed by Interdisciplinary Orthopedics at Aalborg University Hospital. All the data used in this study can be retrieved from the Danish Knee Arthroplasty Registry and Statistics Denmark. All data retrieved from these sources and used in this study can be seen in Table 1. None of the authors report any conflicts of interest.

Results
The annual number of primary KRs conducted in Denmark has increased exponentially, from 2,003 in 1997 to 7,651 in 2008. Since 2008, the increase has gradually stalled and in 2019, 10,184 primary knee replacements were inserted in Denmark.
had an RMSE of 13.9 and 15.5 respectively, which represent 22% of primary knee replacements in Denmark (Table 1).

The mean patient age at knee replacement surgery in 2019 was 68 years (30–99) and 57% were females. The proportion of unicompartmental knee arthroplasties (UKAs) has increased within the past 2 decades and currently constitutes 22% of primary knee replacements in Denmark (Table 1).

The logistic and Gompertz regression analysis (Figure 2) had an RMSE of 13.9 and 15.5 respectively, which represent an acceptable fit and thus these models were used for forecasting. The regressions forecast a maximal incidence at 250 (PI 159–316) per 10^5 in 2030 (logistic regression) or 260 (PI 182–336) per 10^5 in 2035 (Gompertz regression) (Table 2). However, as the population grows the annual number of primary KRs continues to increase until 2050 (Table 2) when between 10,379 (logistic regression) and 10,808 (Gompertz regression) are expected.

**Discussion**

We found that the incidence of primary knee replacement will plateau within the next 10–15 years with an expected maximal annual incidence between 250 and 260 per 10^5 Danes.

Comparable studies from the USA, United Kingdom, Spain, Australia, Germany, and Sweden have either found no maximal incidence within their projection, a higher maximal incidence per 10^5 citizens than presented in our study, a slowing incidence rate (Bini et al. 2011), or the nearing of what seems to be a maximal incidence. The higher maximal incidences in the aforementioned studies might be due to wider inclusion of KRs, such as revisions, or difficulties estimating the maximal incidence at the time of an exponential or linear rising incidence (Kurtz et al. 2007, Culliford et al. 2015, Nemes et al. 2015, Patel et al. 2015, Guerrero-Ludueña et al. 2016, Inacio et al. 2017a, 2017b, Niemeläinen et al. 2017) investigated the different incidences of knee arthroplasty in Denmark, Sweden, Norway, and Finland from 1997 through 2012. They found that the incidences of primary TKA and UKA per 10,000 inhabitants over the age of 30 increased in all 4 countries:

- Denmark (3.4–21), Sweden (9.0–21), Norway (3.6–14), and Finland (13–28). However, they assumed a 10–15% underestimation of the Danish data due to lower completion of the DKR in the first 10 years of the study period. At the end of their study period, Danish and Finnish incidences seemed more stable in nature than the Swedish and Norwegian incidences, which still showed signs of linear to exponential growth. This is the start of the bend in the Danish incidence curve observed from 2010 through 2017. This had

| Year | Population age 30–99 | Primary KR in the DKR | Partial KR | Complete- ness (%) | Absolute number of primary KR | Incidence per 10^5 Danes |
|------|----------------------|------------------------|------------|--------------------|------------------------------|--------------------------|
| 1997 | 3,274,026            | 1,386                  | 29         | 69                 | 2,003                        | 61                       |
| 1998 | 3,302,439            | 1,869                  | 40         | 83                 | 2,242                        | 68                       |
| 1999 | 3,325,149            | 1,816                  | 46         | 77                 | 2,373                        | 71                       |
| 2000 | 3,343,867            | 2,235                  | 92         | 89                 | 2,522                        | 75                       |
| 2001 | 3,363,911            | 2,690                  | 98         | 87                 | 3,105                        | 92                       |
| 2002 | 3,386,844            | 3,599                  | 220        | 83                 | 4,339                        | 128                      |
| 2003 | 3,409,437            | 3,940                  | 333        | 87                 | 4,549                        | 133                      |
| 2004 | 3,428,946            | 4,209                  | 381        | 84                 | 5,009                        | 146                      |
| 2005 | 3,449,794            | 4,686                  | 414        | 83                 | 5,616                        | 163                      |
| 2006 | 3,471,898            | 5,445                  | 479        | 88                 | 6,204                        | 179                      |
| 2007 | 3,489,318            | 7,003                  | 594        | 93                 | 7,504                        | 215                      |
| 2008 | 3,507,360            | 6,987                  | 707        | 91                 | 7,651                        | 218                      |
| 2009 | 3,528,810            | 8,219                  | 788        | 97                 | 8,430                        | 239                      |
| 2010 | 3,544,098            | 8,309                  | 901        | 96                 | 8,670                        | 245                      |
| 2011 | 3,559,168            | 8,030                  | 888        | 97                 | 8,278                        | 233                      |
| 2012 | 3,570,344            | 8,042                  | 784        | 99                 | 8,299                        | 232                      |
| 2013 | 3,583,952            | 7,994                  | 806        | 97                 | 8,209                        | 229                      |
| 2014 | 3,598,842            | 8,240                  | 897        | 98                 | 8,394                        | 233                      |
| 2015 | 3,619,744            | 8,180                  | 1,214      | 98                 | 8,307                        | 229                      |
| 2016 | 3,646,223            | 8,067                  | 1,462      | 98                 | 8,264                        | 227                      |
| 2017 | 3,671,269            | 8,159                  | 1,727      | 97                 | 8,384                        | 228                      |
| 2018 | 3,695,198            | 9,240                  | 1,823      | 97                 | 9,535                        | 258                      |
| 2019 | 3,719,214            | 9,878                  | 2,263      | 97                 | 10,184                       | 274                      |

KR, knee replacement
DKR, the Danish Knee Arthroplasty Registry
a Assumed completeness due to a lack of data.

| Year | Logistic regression | Gompertz regression |
|------|---------------------|---------------------|
|      | Predicted number of primary KRs | Incidence (PI) | Predicted number of primary KRs | Incidence (PI) |
| 2000 | 3,343,867           | 86 (79–239)        | 2,878        | 90 (80–236)        | 3,009          |
| 2005 | 3,449,794           | 172 (93–252)       | 5,947        | 172 (95–250)       | 5,937          |
| 2010 | 3,549,044           | 226 (106–264)      | 8,004        | 221 (109–264)      | 7,850          |
| 2015 | 3,619,744           | 244 (120–277)      | 8,819        | 244 (124–278)      | 8,844          |
| 2020 | 3,745,142           | 248 (133–290)      | 9,298        | 254 (139–293)      | 9,506          |
| 2025 | 3,881,337           | 249 (146–303)      | 9,679        | 258 (153–307)      | 9,999          |
| 2030 | 3,990,028           | 250 (159–316)      | 9,961        | 259 (168–322)      | 10,339         |
| 2035 | 4,061,503           | 250 (172–329)      | 10,142       | 260 (182–336)      | 10,548         |
| 2040 | 4,116,730           | 250 (184–343)      | 10,280       | 260 (196–351)      | 10,700         |
| 2045 | 4,135,043           | 250 (197–356)      | 10,326       | 260 (210–366)      | 10,752         |
| 2050 | 4,156,132           | 250 (209–370)      | 10,379       | 260 (223–381)      | 10,808         |
In conclusion, the incidence in Denmark of primary knee replacements seems to be nearing its plateau, but in spite of this the absolute number of primary KRs will continue to increase as the population gets older. The Danish healthcare system ought to prepare for an increase in primary knee replacements as well as revisions in the future.

All authors were involved in planning the study. LD and AEG retrieved and analyzed the data. LD and TJ wrote the initial manuscript, and all authors accepted the final manuscript before submission.

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