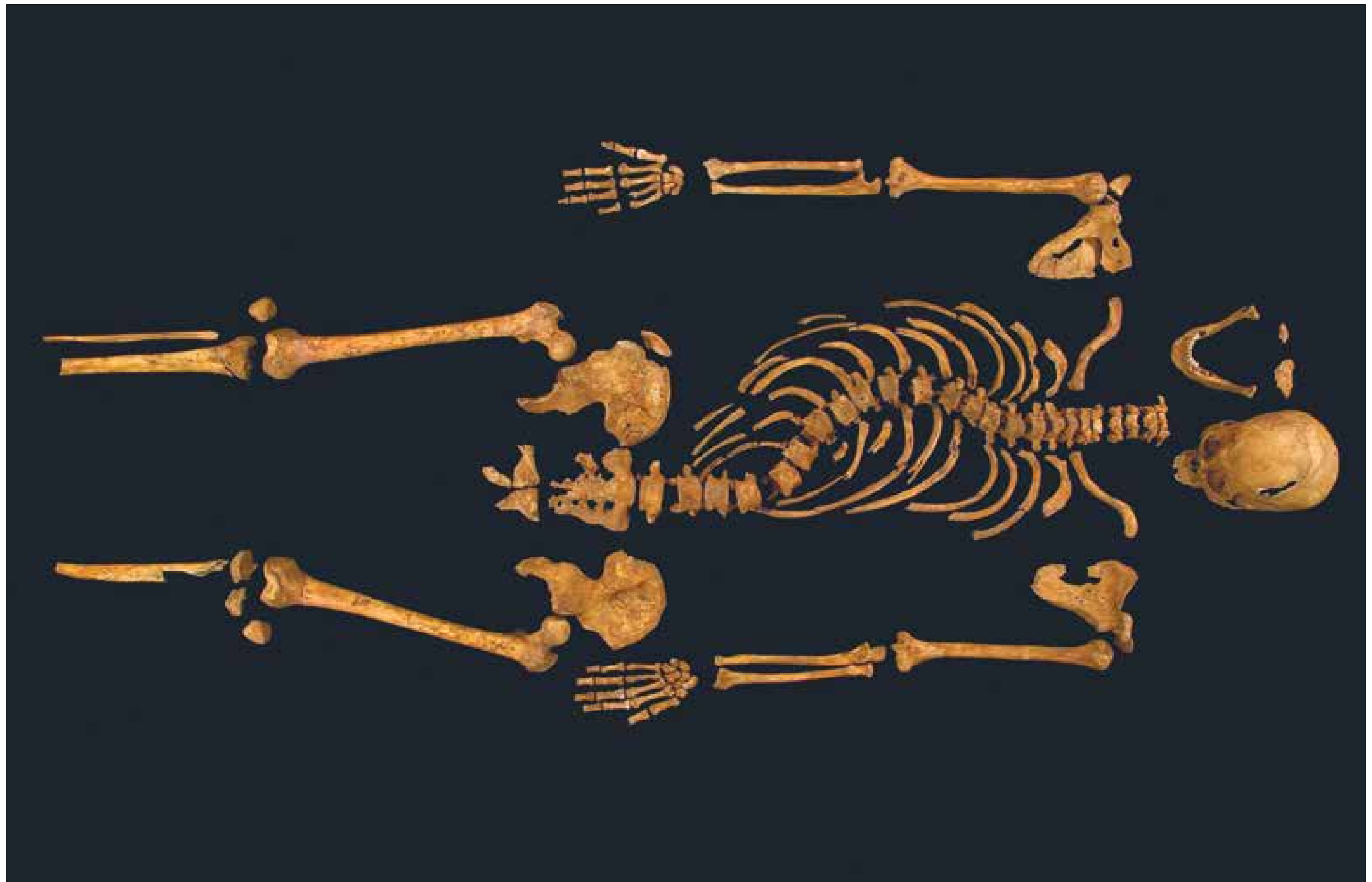

The skeleton found buried at the site of the former Grey Friars Abbey in Leicester displayed signs of trauma and the effect of the scoliosis on the spine, a condition that is generally associated with the traditional depiction of Richard III © University of Leicester

SOLVING A HISTORICAL MYSTERY

Following defeat at the Battle of Bosworth Field in 1485, Richard III's body was lost for almost 530 years, until it was sensationally rediscovered beneath a Leicester car park in September 2012. Science and technology journalist Sarah Griffiths spoke to Professor Sarah Hainsworth FREng, Professor of Materials and Forensic Engineering at the University of Leicester, about how modern forensic engineering science helped to discover what happened on the battlefield.

Richard III remains one of Britain's most divisive and controversial monarchs. William Shakespeare painted him as a cruel hunchback, but in fact he promoted legal fairness by instigating a court for poor people, regulated weights and measures, and banned restrictions on printing and sale of books. He died valiantly leading his men in battle, and was the last English king to do so on home soil. Despite his reputation, the discovery of a skeleton with a distinctly curved spine in an unmarked grave in Leicester in what was once Grey Friars – a grand friary that was dissolved during the Reformation in 1538 – captured the public's imagination.

Led by the University of Leicester, the 2012 project to excavate the Grey Friars site, which is now partly covered by a Leicester City Council car park, was the first search for the grave of an anointed king. As luck would have it, remains that were suspected to be Richard III were revealed on the first day of the dig in August, in the first trench to be dug. Less than a week later, the completed skeleton was uncovered and the bones were removed and carbon dated almost immediately. DNA was extracted and compared to that of the king's descendants, and in February 2013 the remains were confirmed as Richard III.

THE ENGINEERING BEHIND THE DISCOVERY

The bones were imaged to allow anthropologists, pathologists and engineers to analyse the skeleton's injuries in greater detail. To shed some light on just how Richard III died, the investigation looked at the trauma to the skeleton using modern forensic techniques, including CT (computed tomography) and micro-CT scanning – 3D imaging on a small scale with increased resolution – in order to characterise the injuries.

CT scanning and doughnut-shaped 'CAT scanners' have been routinely used in medicine since the early 1970s. An X-ray source is located on one side of the ring with an X-ray detector on the other and the machine rotates around the patient to gather information from all angles. Sophisticated software is then used to turn the array of radiographs into a 3D image.

The complete skeleton was first laid out in an anatomical position, displaying considerable curvature of the spine, and underwent post-mortem CT scanning. The aim of the first CT scan was to create a 3D record of the bones that experts could work from, as well as the skeleton's spinal abnormality and the injuries upon the bones.

Each time a part of the skull was scanned, it generated 3,600 radiographs and this mass of data had to be reconstructed. As there was no quick fix for this challenge, selecting the most useful views took a great deal of care and time © University of Leicester

The bones were then scanned using an Aquilion 64-slice scanner and the pelvis, spine and head were separately scanned once more to carefully gather important details that could help prove the identity of the remains. Bones that were identified as displaying injuries underwent high-resolution micro-computer X-ray tomography (micro-CT) imaging with a Nikon Metrology XTH 225 scanner and a PaxScan detector. This was one of the first times that micro-CT had been applied to analysing battle injuries on bone in an archaeological investigation.

Micro-CT is a much higher-resolution technique than conventional CT in which the X-ray source (an electron gun in a vacuum tube, not dissimilar to the cathode ray tube in an old television) and the detector remains static while the sample rotates. The resolution depends on the size of the pixel matrix employed and the spacing of volume elements or 'voxels', as well as the resolution of the detector, focal spot size, magnification, and how close the sample is to the X-ray emitter and the detector.

To improve the signal-to-noise ratio (which compares the level of a desired signal to background noise), the researchers chose to scan each bone of the skeleton for between six and eight hours, in order to give the highest possible resolutions. Micro-CT radiograph data was then reconstructed using proprietary Nikon Metrology software. This technique allowed the team to study the battle injuries in great detail.

One of the biggest challenges for the engineers was to avoid damaging the historically important skeleton while examining it. A polystyrene mould was used to hold the bones to ensure that they were securely mounted in the CT-scanner and could not move while the stage rotated.

WHAT THE SCANS REVEALED

The CT scans were used to assess the structure of the rib ends and cranial sutures (a fibrous joint) among other features, to deduce that the man was 30 to 34 years old when he died. This discovery was consistent with accounts of Richard III, who was said to have been 32 years old when he fell in battle.

The experts found 11 injuries that had been inflicted at or near the time of death, as no evidence of healing was noted. Nine of the injuries were on the skull and clearly inflicted in battle, which hinted at the final moments leading to the king's death, as well as another two injuries to a rib and the pelvis. As no wounds overlapped, the team was not able to establish a specific order of injuries. However, it is believed that the most likely fatal injuries were two to the inferior cranium, which could have caused subarachnoid haemorrhage (injury to the brain) or an air embolus and killed the victim 'within a short time'.

Micro-CT images of the skull of Richard III. The image on the left shows the skull seen from the base. A is where the spine joins the skull and B and C are injuries that were likely to have been created with a short sword and halberd respectively. The image on the right shows a knife mark to the jaw, probably inflicted as the leather strap on Richard III's helmet was cut to allow his other injuries to be inflicted © University of Leicester

The injuries on the skull are consistent with near-contemporary accounts of the battle, which suggest that Richard abandoned his horse after it became stuck in a mire and perished at the hands of his enemies. The number of cuts to the skull suggest a sustained attack. Interestingly, the location of the cuts as revealed by the CT-scan indicate that Richard III had lost his helmet, but a lack of defensive wounds to the arms and hands implies that he was still wearing other armour when he died.

As well as analysing the injuries, the university's forensic engineering expertise ('Forensics of knife crime', *Ingenia* 37) was used to identify the weapons that were potentially responsible for causing the injuries by analysing tool marks on the bones. One of the injuries, a puncture wound, was likely made by a rondel dagger that had a strong blade made for piercing; another would have appeared instantly more dramatic and was likely inflicted with a halberd, or axe blade, that cut through the skull and exposed the brain. Such a wound would likely be fatal, even today.

Upon closer inspection of the micro CT-scans, all 11 near-death injuries were found to be consistent with the types of weapons used in the late medieval period. For example, the researchers found a 10 millimetre v-shaped wound on the right side of the jaw. This was probably made by a dagger or knife, as the marks produced by swords typically have an uneven cross-section with one roughened wall and measure more than 20 millimetres. The team identified what weapons had likely been used to inflict the injuries by examining the striations, which are produced by marks present on the edge of a tool. These marks result from both the manufacture of the blade and damage that occurs during its use, meaning that the striations are unique to the tool that created them. This can make them difficult to identify; however, the engineers took macro-photographs of the striations to examine them closely and the use of micro-CT imagery to produce high-resolution images also helped. The team used a CT-processing software package called Osirex and an app called Bullit to produce the estimated wound tract on the pelvis, which demonstrated that of all the injuries, this was likely to have been inflicted post-mortem while the skeleton was over the back of a horse.

The team also used previous data from other medieval battlefields to identify the weapons, with help from Bob Woosnam-Savage, curator of European-edged weapons at the Royal Armouries in Leeds. They examined reports of battle injuries to skeletons that were involved in an earlier battle in the Wars of the Roses at Towton and also the Battle at Dornach in 1499. By comparison, Richard III appeared to suffer few injuries to the face. Medieval warfare was brutal and the skeletal remains often show considerable damage to the skulls.

It would be fascinating to compare the DNA of Richard III with the DNA of the two boys' skeletons that were found at the Tower of London and believed to be Richard's nephews

A CLOSED CASE

The mystery of Richard III's death is now as resolved as it ever can be and the king's remains have now been formally laid to rest. Professor Hainsworth thinks that it would be fascinating to compare the DNA of Richard III with the DNA of the two boys' skeletons that were found at the Tower of London and believed to be Richard's nephews. However, the bones now rest in Westminster Abbey and it would require the permission of HM The Queen Elizabeth to access these.

In the future, working on other remains with battle injuries will allow experts to understand the different ways in which engineering and archaeology can combine and would like to solve other royal mysteries. For example, it could help decipher whether the last Anglo Saxon king of England, Harold Godwinson, really did die from an arrow thorough the eye at the Battle of Hastings in 1066, as depicted in the Bayeux Tapestry. The combination of history and forensic engineering science is fascinating because it brings the subject to life.

BIOGRAPHY

Professor Sarah Hainsworth FREng is Professor of Materials and Forensic Engineering at the University of Leicester. She has become the international engineering forensic expert on skeletal contact damage, uniquely establishing the sequence of injuries leading to the death of King Richard III.

RECREATING THE KING'S SKELETON AND GRAVE

After more than five centuries, Richard III was finally given a burial fit for a king in March 2015, when his remains were reinterred at Leicester Cathedral.

However, a year before the regal event, experts from Loughborough University's School of Mechanical and Manufacturing Engineering were invited to make a replica of the curiously-shaped skeleton, using 3D printing techniques. They created a 3D computer model from the CT scans of the remains, which were cleaned up using Materialise's Mimics Innovation Suite software. Laser sintering was then used to create a replica of the skeleton. This technique used a high-power laser to fuse small particles of plastic into realistic bones, building them up layer by layer. As the skull emerged from the powder of the laser-sintering machine, a number of the injuries on it were clear to see.

Researchers also made a 3D reconstruction of the king's original grave for posterity. During the 2012 dig, archaeologists made detailed drawings of the grave in which Richard III was, they think, hastily buried, and experts from the University of Leicester used laser scanning and digital photogrammetric techniques to create a detailed 3D reconstruction.

Researchers from the Leicester LiDAR Research Unit in the Department of Geology mapped the exact shape of the grave using a terrestrial laser scanner. They placed the instrument at different points around the grave from where it fired laser pulses in a 360-degree arc to record the length of time taken to bounce off a surface and return to the scanner.

The information gathered at each point combined to create a 20-million-point cloud of the site, which recorded the excavated grave walls and even soil textures. This data was then amalgamated with a survey using more than 80 digital photographs of the grave, shot from different angles, which were used to build a 3D model of the void beneath the now-famous car park.

The 3D interactive digital reconstruction of King Richard III's grave allows it to be explored from all angles. It can be viewed at sketchfab.com/leicester-archaeology