Interest continues in hip resurfacing arthroplasty (HRA), despite concerns relating to metal ion release.1-6 HRA remains an alternative to total hip arthroplasty (THA) that preserves proximal femoral bone stock, decreases stress shielding, and increases bone mineral density, with a lower dislocation rate and easier femoral revision.7-11 Nevertheless, HRA remains little used today, with less than 1% of all hip arthroplasties as reported by the United Kingdom National Joint Registry (NJR), largely owing to fear of metal-on-metal (MoM) bearings following the withdrawal of several particular types of HRA.12-15 A recent biomechanical cadaveric study highlighted the functional advantage of retaining the femoral neck by maintaining more normal capsular tension.16 The Birmingham Hip Resurfacing (BHR) implant (Smith & Nephew, Memphis, Tennessee) has obtained an Orthopaedic Data Evaluation Panel (ODEP) 10A* rating, which signifies better than 95% survival at minimum ten years in more than three nondeveloping centres. Survivorship has been reported to rival conventional THA, even in nondesigner centres.17-19 Currently, the United Kingdom Medicines and Healthcare products Regulatory Agency (MHRA) guidelines require regular follow-up for patients and an HRA with measurement of blood metal ions.20 HRA is now only indicated in larger men who demand an active lifestyle.21,22 Even with this restricted indication, the impact of HRA on higher levels of physical activity is still debated. The majority of kinematic studies have reported on the function of devices that have since been withdrawn.23,24 There remains a serious debate regarding the extent to which HRA with a highly rated device restores normal hip function, something that conventional THA has never demonstrated.25-28 This prospective

Aims
The aim of this study was to assess the functional gain achieved following hip resurfacing arthroplasty (HRA).

Patients and Methods
A total of 28 patients (23 male, five female; mean age, 56 years (25 to 73)) awaiting Birmingham HRA volunteered for this prospective gait study, with an age-matched control group of 26 healthy adults (16 male, ten female; mean age, 56 years (33 to 84)). The Oxford Hip Score (OHS) and gait analysis using an instrumented treadmill were used preoperatively and more than two years postoperatively to measure the functional change attributable to the intervention.

Results
The mean OHS improved significantly from 27 to 46 points (p < 0.001) at a mean of 29 months (12 to 60) after HRA. The mean metal ion levels at a mean 32 months (13 to 60) postoperatively were 1.71 (0.77 to 4.83) µg/l (ppb) and 1.77 (0.68 to 4.16) µg/l (ppb) for cobalt and chromium, respectively. When compared with healthy controls, preoperative patients overloaded the contralateral good hip, limping significantly. After HRA, patients walked at high speeds, with symmetrical gait, statistically indistinguishable from healthy controls over almost all characteristics. The control group could only be distinguished by an increased push-off force at higher speeds, which may reflect the operative approach.

Conclusion
Patients undergoing HRA improved their preoperative gait pattern of a significant limp to a symmetrical gait at high speeds and on inclines, almost indistinguishable from normal controls. HRA with an approved device offers substantial functional gains, almost indistinguishable from healthy controls.

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gait study set out to determine the functional improvement attributed to HRA by testing patients to the limit of their ability by assessing higher walking speeds and negotiating steeper inclines. The primary objective was to: 1) assess the change in loading pattern following HRA; and 2) compare this function with the normal contralateral hip. The secondary objective was to compare these gait characteristics with a comparative healthy group, to determine the extent to which a normal gait pattern could be achieved.

**Patients and Methods**

**Participants.** In an ethically registered prospective comparative gait study (London-Camberwell St Giles Research Ethics Committee (10/H0807/101)), 28 self-selected patients awaiting
HRA were recruited between 2011 and 2016. HRA patients were only invited to participate in this gait study if the inclusion and exclusion criteria were met. Specifically, participants had to be cardiovascularly fit with no other conditions that would limit their gait at higher speeds. Patients were excluded from the study if they had any other joint disease or replacements. All of the patients were operated through a posterior approach with release of the external rotators and gluteus maximus tendon followed by repair by the senior author (JPC). All patients received a BHR (Smith & Nephew) inserted according to the manufacturer’s instructions, with a cemented femoral component oriented at 135° valgus with neutral version on the femoral neck, and an uncemented acetabular component with a preoperative plan of 40° of abduction and 20° of anteversion. All patients had a standardized postoperative rehabilitation programme involving range of movement and strengthening exercises. Patients were examined by the senior author (JPC) in clinic before and after surgery. Oxford Hip Scores (OHS) were taken at the time of the pre- and postoperative gait studies. The OHS is a validated 12-item questionnaire, which was reported to provide a commonly reported and identifiable metric. Whole blood levels of cobalt and chromium were taken after the first year postoperatively. An active and healthy asymptomatic group of subjects, consisting of staff of the institution, were recruited and analyzed for comparative purposes. Informed written consent was obtained prior to their involvement.

**Gait instrumentation.** A validated instrumented treadmill (Gaitway Kistler; Kistler Instrument Corporation, Amherst, New York) with a previously reported protocol was used to collect patient gait data. The treadmill has been shown to be reliable, reproducible, and able to assess higher-end function. The vertical components of the ground reaction forces (GRF) were collected on calibrated tandem Kistler force plates at a sample frequency of 100 Hz. All participants were weighed with the force plate prior to assessment, to allow normalization for body weight. Once acclimatized and free of aids, participants were tested through their entire range of speed during level walking at 0.5 km per hour increments. After a short rest period, the patient had their walking uphill assessment with trials at 4 km per hour for 5%, 10%, and 15% inclinations. Data were recorded at all trial intervals of speed and inclination.

**Gait variables.** The variables selected for analysis had been identified in two recent studies as being both reliable and able to discriminate between types of subjects. The peak GRF with the highest intraclass correlation coefficient (ICC) and area under the curve (AUC) were: weight acceptance, push-off, and midstance.
Table II. Inclination and speed parameter means with mean absolute symmetry indices (SIs) displayed as percentages

| Limb | 4 km/hr; 10% incline | 4 km/hr; 15% incline | 5.5 km/hr; flat | 6 km/hr; flat | 6.5 km/hr; flat | 7 km/hr; flat | SI, % |
|------|-----------------------|-----------------------|-----------------|--------------|----------------|--------------|--------|
| Preoperative HRA | | | | | | | |

| | Mean weight acceptance, BWN (range) | Postoperative HRA | | | | | |
| | | | | | | | |
| | | | | | | | |

| | | | | | | | |

| Mean midstance, BWN (range) | | | | | | | |
| | | | | | | | |
| | | | | | | | |

| Mean push-off, BWN (range) | | | | | | | |
| | | | | | | | |
| | | | | | | | |

and push-off along with their associated symmetry index (SI) (Fig. 1).

An absolute SI was used in order to remove the ‘averaging’ effect that could occur if not used. This has been validated in an earlier study. *34

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Absolute SI = \frac{|X1 - X2|}{0.5 \times (X1 + X2)} \times 100%  
X1 was the implanted limb result and X2 was the contralateral normal limb result. This gives a measure of percentage

\[ \text{Absolute SI} = \frac{|X1 - X2|}{0.5 \times (X1 + X2)} \times 100\% \]

**Statistically significant difference between patient and control**

†Statistically significant difference between patient limbs

‡Statistically significant difference from preoperative to postoperative

BWN, body weight normalized force; HRA, hip resurfacing arthroplasty
difference between limbs. For controls, X1 and X2 refer to right and left, respectively.

**Radiographs.** Plain orthogonal hip radiographs taken prior to surgery were assessed for disease aetiology, morphology, and severity. Postoperative plain radiographs were also assessed for any coronal malalignment of the components.

We recruited 26 subjects to the control group, who were compared with 28 patients who had undergone HRA and fulfilled our inclusion and exclusion criteria (Table I). Despite having a greater male:female ratio in the HRA group, with associated greater height and body mass index (BMI), no significant statistical differences for age, sex, BMI, height, and top walking speed were identified. All hip patients, except one, had osteoarthritis (OA). The single non-OA patient had steroid-induced osteonecrosis. Morphologically, six patients had acetabular dysplasia. In total, 18 patients had cam impingement and three patients had pincer femoroacetabular impingement. The most common disease severity was Tönnis grade 2, which represented moderately severe arthrosis. Hip patients preoperatively had a mean OHS of 27 points (9 to 37), which improved significantly to 46 (40 to 48) points after surgery (p < 0.001).

**Statistical analysis.** All trials were visually examined to ensure six consecutive strides were captured cleanly. Typically, ten or more strides were collected for multiple trials, so a MATLAB (MathWorks, Natick, Massachusetts) script was written to extract the data from the Kistler software in a formatted manner for analysis. Statistical analysis was completed with MATLAB. Kolmogorov–Smirnov testing showed data were normally distributed, therefore parametric tests were used. To determine differences between the demographics of the controls and hip patients, an unpaired Student’s t-test was undertaken for continuous data, while categorical data, such as sex, utilized a chi-squared test. To determine differences between group’s and limb’s ground reaction forces, a one-way analysis of variance (ANOVA) with Tukey post hoc test was used, with significance set at a p-value < 0.05 throughout. Paired Student’s t-tests were carried out to detect significant differences in OHS and GRF in the affected and unaffected limbs before and after HRA.

**Results**
The mean time to gait assessment after surgery was 29 months (12 to 60). The mean metal ion levels at a mean 32 months (13...
to 60) postoperatively were 1.71 µg/l (0.77 to 4.83) (ppb) and 1.77 µg/l (0.68 to 4.16) (ppb) for cobalt and chromium, respectively. One female patient with a 46 mm head had cobalt and chromium levels of 4.83 µg/l and 4.16 µg/l (ppb), respectively. A screening metal artefact reduction sequence (MARS) MRI scan did not demonstrate any adverse features at five years after surgery.

Gait analysis. Healthy controls exhibited symmetrical gait at all speeds and inclines (Fig. 2).

Prior to surgery, patients limped with an asymmetrical gait pattern (Table II and Fig. 3), favouring the contralateral normal side by up to 12% (p = 0.001) at weight acceptance with higher speeds. The affected limb was spared from peak loads at weight acceptance and push-off, when compared with healthy controls at all speeds and gradients (Fig. 2).

After hip resurfacing, the mean walking speed of the patients was marginally faster than controls (7.5 km vs 7.3 km per hour). This difference disappeared when speed was normalized for leg length, as the controls were slightly shorter than the patients (mean 172 cm vs mean 176 cm; Table I).

After HRA surgery, a marked improvement was seen in patients’ gait pattern, returning towards symmetry (Figs 1 and 4). Symmetry was achieved by both the unloading of the contralateral normal hip and the near-normal loading of the operated hip during weight acceptance and push-off (Fig. 4). All variables became more symmetrical following surgery. This improvement reached statistical significance for every variable (Table II). When compared with healthy controls, gait symmetry and hip loading was restored, and were found to be indistinguishable except for weight acceptance SI at some speeds (p = 0.008, 5.5 km per hour; p = 0.04, 6 km per hour; p = 0.02, 6.5 km per hour) and in push-off force during uphill walking (p = 0.02 at 10% inclination and p = 0.03 at 15% inclination).

Discussion

This small prospective gait study set out to determine the impact of HRA on a patient’s gait. It was found that patients who underwent HRA with a BHR had significant improvements in their gait pattern, rendering them almost indistinguishable from healthy controls. Our findings contradict published functional studies with different HRA devices, where significant asymmetries persisted in the affected limb when one device was used that is now the subject of class action litigation. A randomized gait study with another product (Durom, Zimmer, Warsaw, Indiana) that has since been withdrawn failed to detect any superiority over THA. The current study is supported by a
recently published gait analysis of a randomized controlled trial of HRA versus THA using the BHR device.38

Despite the near-physiological findings in this study, statistically significant weakened push-off forces were still noted during uphill walking, which was not seen during level walking. This observation may relate to the posterior approach including gluteus maximus tendon release and repair. This may have weakened power in terminal extension, which is better tested on uphill walking. Interestingly, this finding was also noted in another study comparing differing stem lengths in conventional THAs with the posterior approach.28 Another equivocal finding was the weight acceptance SI. Despite significant improvement after surgery, weight acceptance was still statistically less symmetrical than in healthy controls. Previous studies have demonstrated that while implant choice can affect load transfer through the hip, skeletal changes cannot be completely undone.39 The small single treatment arm design of the study is a major limitation. This was purposeful, however, as it is well known that patients seeking hip resurfacing tend to have higher physical demands, and bias would eventually arise if another treatment arm was introduced without randomization.40 While the HRA group walked faster than the control group, this was not surprising given the greater number of male patients with a predictable height advantage. When taking height into consideration, there was no difference in normalized walking speed, which provides reassurance in this regard. Furthermore, sex and age analysis while walking on an instrumented treadmill have shown no difference in terms of gait pattern and capacity.41 A second limitation is that despite having a robust metric with the treadmill, 80% of hip resurfacing patients achieved the top walking speed of 8 km per hour, substantially faster than any previously published study of hip arthroplasty. At speeds beyond 8 km per hour, healthy adults will break into a run, so the use of walking as a continuous variable is seriously limited in this regard. While running after HRA is widely reported,42 it is not regularly undertaken by patients following THA.43 For the purposes of this study, we chose to limit our metrics to walking.

The strength of the study is that the entire range of walking gait during an everyday activity has been reported prospectively both before and after surgery and compared with healthy controls. The prospective design has allowed us to observe the extent to which HRA restores normal gait. The follow-up of a mean 29-month period after surgery gives the reassurance that this is indeed the functional gain in the longer term. This finding is in keeping with the pragmatic randomized control trial comparing HRA versus THA, which showed HRA patients experiencing a substantial enhancement in quality of life (> 20% EuroQol five-dimension three-level questionnaire (EQ-5D-3L)) three years after surgery over THA.45

The objective metrics of gait correlate well with the significant improvement in the patient-reported outcome measure at last follow-up, consistent with previous studies of HRA.2 The largely low metal ion levels are reassuring even with these high-performing hips and probably reflect the implant used. There were no cardiovascular events seen with our patients, in keeping with the evidence that higher walking speed is associated with enhanced life expectancy;44 and the recent United Kingdom NJR analysis that showed that HRA offered some protective effect against heart failure when compared with other forms of hip arthroplasty.45

In conclusion, the current gait study demonstrated that BHR is effective at improving function significantly, restoring a gait pattern that is hard to distinguish from healthy controls. The continued use of certain HRA in active people with appropriate bone stock is validated by this study, although this conclusion may not be generalizable to other devices.

Take home message
- Birmingham Hip Resurfacing markedly improves patients’ gait and performance.
- Hip resurfacing using an approved device offers an alternative option for patients requiring higher function.
- All hip resurfacing devices are not the same.

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