Medial bicompartamental arthroplasty patients display more normal gait and improved satisfaction, compared to matched total knee arthroplasty patients

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Abstract
Purpose Medial bicompartamental arthroplasty, the combination of ipsilateral medial unicompartmental and patellofemoral arthroplasty, is an alternative to total knee arthroplasty for patients with medial tibiofemoral and severe patellofemoral arthritis, when the lateral tibiofemoral compartment and anterior cruciate ligament are intact. This study reports the gait and subjective outcomes following medial bicompartamental arthroplasty.

Methods Fifty-five subjects were measured on the instrumented treadmill at top walking speeds, using standard metrics of gait. Modular, single-stage, medial bicompartamental arthroplasty subjects ($n=16$) were compared to age, body mass index, height- and sex-matched healthy ($n=19$) and total knee arthroplasty ($n=20$) subjects. Total knee arthroplasty subjects with pre-operative evidence of tricompartmental osteoarthritis or anterior cruciate ligament dysfunction were excluded. The vertical component of ground reaction force and temporospatial measurements were compared using Kruskal–Wallis, then Mann–Whitney test with Bonferroni correction ($\alpha=0.05$). Oxford Knee and EuroQoL EQ-5D scores were compared.

Results Objectively, the medial bicompartamental arthroplasty top walking speed of $6.7 \pm 0.8$ km/h was $0.5$ km/h (7%) slower than that of healthy controls ($p=0.2$), but $1.3$ km/h (24%) faster than that of total knee arthroplasty subjects ($5.4 \pm 0.6$ km/h, $p<0.001$). Medial bicompartamental arthroplasty recorded more normal maximum weight acceptance ($p<0.001$) and mid-stance forces ($p=0.03$) than total knee arthroplasty subjects, with $11$ cm (15%) longer steps ($p<0.001$) and $21$ cm (14%) longer strides ($p=0.006$). Subjectively, medial bicompartamental arthroplasty subjects reported Oxford Knee Scores of median $41$ (interquartile range $38.8–45.5$) compared to total knee arthroplasty Oxford Knee Scores of $38$ (interquartile range $30.5–41$, $p<0.02$). Medial bicompartamental arthroplasty subjects reported EQ-5D median $0.88$ (interquartile range $0.84–0.94$) compared to total knee arthroplasty median $0.81$ (interquartile range $0.73–0.89$, $p<0.02$).

Conclusion This study finds that, in the treatment of medial tibiofemoral osteoarthritis with severe patellofemoral arthritis, medial bicompartamental arthroplasty results in nearer-normal gait and improved patient-reported outcomes compared to total knee arthroplasty.

Level of evidence III.

Keywords Gait · Bicompartamental knee arthroplasty · Compartmental arthroplasty · Total knee arthroplasty · Walking speed · Satisfaction · Medial with patellofemoral arthroplasty

Introductions

Total knee arthroplasty (TKA) remains the gold-standard treatment for osteoarthritis (OA) of the knee, with widely reported success. Relative to TKA, unicompartmental knee arthroplasty (UKA) is associated with more normal gait [21, 35], higher satisfaction [26] and fewer peri- and post-operative serious complications [25], but significantly higher revision rates [1, 23]. There is limited evidence for multi-compartment PKA.

Of those undergoing primary knee arthroplasty, 23% have medial tibiofemoral and patellofemoral (PFJ) OA, with a spared lateral compartment [31]. Medial bicompartamental arthroplasty (BCA-M), the combination of ipsilateral medial UKA and patellofemoral arthroplasty (PFA), is a bone,
meniscus and anterior cruciate ligament (ACL)-preserving alternative to TKA (Fig. 1) [12, 14]. This study seeks to understand the gait characteristics and patient-reported outcomes of BCA-M compared to patients treated with a posterior-cruciate retaining TKA. The null hypothesis is that there are no differences between BCA-M and TKA in these parameters.

**Materials and methods**

A previous instrumented treadmill study compared the top walking speed of UKA-M \((n = 12)\) to healthy controls \((n = 121)\) and TKA \((n = 12)\) [21]. UKA TWS was 7.9 km/h, similar to healthy subjects (TWS 7.9 km/h) but 37% faster than TKA (5.76 km/h). We assumed that the TKA subjects in our study would not differ significantly from previous studies, but predicted that BCA-M may walk up to 15% faster (TWS 6.63 km/h, 15% faster). A power calculation indicated that a minimum of 14 subjects per implant group would be necessary to detect such differences with 80% power and 95% confidence.

Potential subjects were retrospectively identified from the operative database of the senior author, between 2009 and 2019. Of 3090 knee arthroplasty procedures, 69 patients had undergone primary modular BCA-M. Subjects were excluded if they had a contralateral TKA (\(n = 4\), Fig. 2, Supplementary Table A); if they had undergone significant ipsilateral limb surgery pre- or post-BCA-M \((n = 8)\), which included two subjects who had been revised following BCA-M; were over 85 years \((n = 13)\); medically unfit \((n = 6)\) or deceased \((n = 10)\); or if they declined \((n = 4)\) or were uncontactable \((n = 6)\). After 53 exclusions (Fig. 2, Supplementary Table A), 16 BCA-M patients entered the study.

**Matching**

With institutional review board approval from NRES Committee South Central and the Academic Health Science Centre, Imperial College London and Imperial College Healthcare NHS Trust, UK, our group prospectively evaluated healthy subjects and the patients of three senior arthroplasty surgeons on an instrumented treadmill (Kistler Gaitway, Kistler Instrument Corporation, Amherst, NY), over the past 9 years. Data were collected by a research assistant blinded to arthroplasty status. For the current study, the database was searched to identify suitable control subjects for comparison to the BCA-M group. At the time of data analysis, 19 healthy subjects matched to the age, body mass index (BMI) and sex of the BCA-M group (Table 1, Fig. 2). Forty-nine posterior-cruciate retaining TKA subjects were identified in the database. Potential TKA subjects were excluded if they had been measured prior to scheduled revision surgery \((n = 5)\); had an ipsilateral hip replacement in situ \((n = 2)\); had significant OA of the contralateral knee \((n = 9)\); tricompartmental OA graded Kellgren and Lawrence (KL) ≥ 2 or evidence of ACL deficiency \((n = 5)\), defined by > 7 mm anterior tibial translation on pre-operative radiographs [9]. The remaining TKA subjects underwent age, sex and body mass index matching (IBM® SPSS® Version 27, Table 1) resulting in 22 potential posterior-cruciate retaining TKA subjects. Since all BCA-M subjects had undergone patellar resurfacing, a further two TKA subjects were excluded, since they had not undergone patellar resurfacing. Consequently, 20 posterior-cruciate retaining TKA subjects entered the study, of whom 11 had single-compartment disease (medial \(n = 8\), lateral \(n = 3\)). The remaining had two-compartment disease (medial and lateral \(n = 8\), lateral with patellofemoral \(n = 1\)). TKAs were mean 40.6 ± 43 months post-surgery, 19.6 months longer than primary BCA-M (21 ± 18) though this did not reach statistical significance \((p = 0.1)\). The median months post-surgery were BCA-M 12.5 months (range 6–65 months) compared to TKA, 19.5 months (range 6–147 months, \(p = 0.5\)).

**Treadmill testing**

All subjects walked at 4 km/h for 2 min to acclimatize to the treadmill, before increasing speed in 0.5 km/h increments to their ‘top walking speed’ (TWS) defined as their fastest comfortable speed, or the highest walking speed before
breaking into a run. Subjects walked, on average, for 12 min continuously, without the assistance of the hand safety rail. All subjects completed the test comfortably. Two tandem force plates, beneath the moving belt, recorded the vertical component of the ground reaction forces, temporospatial measurements and centre of pressure for both limbs, sampling at 100 Hz frequency over 10 s. To correct for differences in leg length and body mass, data were normalized post-collection using Hof scaling [20] and normalization of body weight (BW = ground reaction force/(body mass/gravity)) respectively.

**Patient-reported outcome measures**

Arthroplasty subjects were asked to complete the Oxford Knee Score (OKS) and EuroQoL EQ-5D 5L Score at the time of their treadmill assessment.

**Statistical analysis**

TKA and healthy subjects were matched to the BCA-M cohort in IBM® SPSS® Version 27 for age (p = 0.3), sex (p = 1), body mass index (p = 0.9) and height (p = 0.5) from the prospectively collected database (Table 1). Gait output data were averaged using a custom MathWorks® MatLab® script and analysed in IBM® SPSS® Version 27. The Shapiro–Wilk test demonstrated that a number of variables were not normally distributed; therefore, all variables were compared using Kruskal–Wallis, then Mann–Whitney test with Bonferroni correction where differences were detected. Significance was set at α = 0.05.

**Results**

**Top walking speeds**

Objectively, the medial bicompartamental arthroplasty top walking speed of 6.7 ± 0.8 km/h was 0.5 km/h (7%) slower than that of healthy controls (p = 0.16, Table 1, Fig. 3), but 1.3 km/h (24%) faster than that of total knee arthroplasty subjects (5.4 ± 0.6 km/h, p < 0.001). The TKA group walked 25% slower than healthy subjects (p < 0.001). The differences remained apparent after Hof scaling for leg length (Table 1).
Vertical ground reaction forces

At top walking speeds, compared to healthy subjects, both arthroplasty groups recorded reduced weight acceptance, though the differences did not reach significance ($p > 0.05$, Table 1, Fig. 4). BCA-M and healthy subjects recorded similar maximum weight acceptance force ($p = 0.051$), whilst in TKA subjects it was reduced ($p < 0.001$). During mid-stance, both groups recorded higher forces than the healthy cohort ($p < 0.03$); however, the BCA-M subjects were nearer normal, with a significant advantage over the TKA group ($p < 0.03$). All groups were similar in terms of push-off force and rate ($p = 1$). Compared to healthy and BCA-M subjects, TKA subjects recorded reduced cadence ($p < 0.003$, Table 1), increased double support time (Vs BCA-M $p = 0.03$) and increased contact time ($p < 0.003$).
BCA-M subjects displayed nearer-normal temporospatial characteristics, with differences failing to reach significance when compared to healthy controls.

**Step and stride lengths**

BCA-M subjects’ median step lengths were similar to those of healthy subjects (both 82 cm), whilst those of TKA subjects were median 12 cm (15%) shorter (Fig. 5). This reflected the differences in stride length, whereby median BCA-M stride lengths were 167 cm (IQR 149-175 cm), 3 cm (2%) longer than those of healthy subjects, while TKA stride lengths were median 142 cm, 22 cm (13%) shorter than those of healthy subjects (Fig. 5).

**Satisfaction and quality of life**

OKS and EQ-5D scores were completed by all arthroplasty subjects. For the OKS, median scores were significantly higher for BCA-M than TKA (41 vs 38, \( p = 0.02 \), Fig. 6, Table 1). Though not validated by individual question, it is noteworthy that BCA-M scored equal to or higher than TKA in all questions of the OKS, with significant differences seen in the use of transport, chair rising, kneeling, instability symptoms and stair descent (all \( p < 0.03 \), Table 2). Similarly, median EQ-5D values were higher for BCA-M compared to TKA (0.88 vs 0.81, \( p < 0.02 \), Fig. 6, Table 1). BCA-M subjects recorded scores closer to 1 in every domain, reaching significance in mobility, usual activities and pain (\( p < 0.02 \), Table 3).
Discussion

This study finds that BCA-M has advantages over TKA in terms of gait and patient-reported outcomes, leading to the null hypothesis being rejected.

Table 2  Oxford Knee Scores between BCA-M and TKA groups by overall score, where 48 is the best possible outcome and by individual question

| Item                                                                 | BCA-M       | TKA         | Difference | p value |
|----------------------------------------------------------------------|-------------|-------------|------------|---------|
| Overall OKS                                                          | 41.4 ± 5    | 36.0 ± 6.5  | 5.4        | 0.016   |
| Q1. How would you describe the pain you usually have on your knee? | 2.8 ± 1.1   | 2.8 ± 1.1   | 0          | 1       |
| Q2. Have you had any trouble with washing and drying yourself (all over) because of your knee? | 3.8 ± 0.5   | 3.8 ± 0.4   | 0.1        | 0.4     |
| Q3. Have you had any trouble getting in or out of a car or using public transport because of your knee? | 3.3 ± 0.8   | 2.6 ± 1.0   | 0.7        | 0.02    |
| Q4. For how long have you been able to walk before pain from your knee becomes severe? | 3.8 ± 0.5   | 3.4 ± 0.9   | 0.5        | 0.07    |
| Q5. How painful has it been for you to stand up from a chair because of your knee? | 3.4 ± 0.8   | 2.8 ± 0.7   | 0.6        | 0.01    |
| Q6. Have you been limping when walking because of your knee?         | 3.6 ± 0.6   | 3.1 ± 1.0   | 0.5        | 0.2     |
| Q7. Could you kneel down and get up again afterwards?                | 2.8 ± 1.2   | 1.6 ± 1.0   | 1.3        | 0.002   |
| Q8. Have you been troubled by pain from your knee in bed at night?   | 3.3 ± 0.8   | 3.2 ± 1.0   | 0.1        | 0.9     |
| Q9. How much has pain from your knee interfered with your usual work?| 3.6 ± 0.5   | 3.1 ± 0.8   | 0.3        | 0.8     |
| Q10. Have you felt that your knee may suddenly 'give way' or let you down? | 3.6 ± 0.5   | 3.1 ± 0.8   | 0.6        | 0.03    |
| Q11. Could you do household shopping on your own?                    | 3.9 ± 0.3   | 3.4 ± 1.3   | 0.5        | 0.3     |
| Q12. Could you walk down one flight of stairs?                       | 3.7 ± 0.8   | 3.1 ± 0.9   | 0.6        | 0.005   |

Each question has a maximum score of 4 for the best outcome. Values shown are means with standard deviation. Significant differences Mann–Whitney test p < 0.05 highlighted in bold.

Table 3  EuroQol 5D Scores between BCA-M and TKA groups by overall score and by individual domain

| Domain | BCA-M       | TKA         | Difference | p Value |
|--------|-------------|-------------|------------|---------|
| Overall EQ5D | 0.89 ± 0.07 | 0.77 ± 0.16 | 0.12       | 0.012   |
| Mobility | 1.5 ± 0.7   | 2.5 ± 1.0   | 0.95       | 0.004   |
| Self-care| 1.1 ± 0.3   | 1.4 ± 0.7   | 0.34       | 0.07    |
| Usual activities | 1.6 ± 0.7   | 2.6 ± 1.1   | 0.99       | 0.005   |
| Pain    | 1.9 ± 0.6   | 2.4 ± 0.7   | 0.53       | 0.02    |
| Anxiety | 1.2 ± 0.4   | 1.3 ± 0.7   | 0.11       | 0.8     |

The best possible outcome for the overall score is 1. Each domain is graded 1–5 where 1 is the best overall outcome. Values shown are means with standard deviation. Significant differences Mann–Whitney test p < 0.05 highlighted in bold.

Table 4  Indications and contraindications for primary medial bicompartmental arthroplasty

| Indications | Contraindications |
|-------------|-------------------|
| Medial with patellofemoral arthrosis Kellgren and Lawrence Score ≥ 2 | Lateral tibiofemoral arthrosis Kellgren and Lawrence Score ≥ 2 |
| Spared lateral compartment (Kellgren and Lawrence Score < 2) | Medial collateral ligament disruption/ dysfunction/significant laxity |
| Functional anterior cruciate ligament* | Anterior cruciate ligament dysfunction* |
| Correctable varus | Inflammatory arthropathy |

*ACL dysfunction in the elderly is a relative contraindication, provided that the knee is otherwise stable.

Severe lateral facet PFJ OA is considered by many to be a relative contraindication to medial UKA [4, 5], leading to TKA in the majority of these patients [1, 23]. In those with isolated medial with patellofemoral wear, TKA necessitates resection of healthy lateral bone, menisci, and a functional ACL. BCA-M may be considered appropriate for those with medial tibiofemoral and severe patellofemoral arthrosis (KL ≥ 2), with correctable varus, anterior–posterior sagittal stability and medial collateral ligament sufficiency (Table 4).

BCA-M has documented clinical success in the short and medium term [11, 19, 30] and is thought to restore isokinetic quadriceps function [33], whilst preserving near-native extensor efficiency [13]. There is some evidence that BCA-M results in higher function during strenuous activity [28], but no studies to our knowledge have compared BCA-M to healthy controls and TKA at top walking speeds. Arthroplasty performance can be objectively assessed using gait analysis on the instrumented treadmill. Previous studies have reported an advantage of UKA-M over TKA at top walking speeds [18, 21, 35] which the current study suggests is preserved following primary modular BCA-M.
most notably in top walking speeds and stride length [21, 35]. Previous BCA-M gait studies have focused on historic monolithic BCA-M designs, some of which were blighted by high revision rates. These studies included fewer BCA-M subjects walking at slower walking speeds to those investigated here [24, 34].

The marked difference in top walking speed between BCA-M and TKA is particularly important. For every 0.1 m per second increase in top walking speed, life expectancy improves significantly and may be considered a proxy measure for a subject’s global post-operative health [32]. BCA-M is more anterior–posterior stable than TKA [15] where ACL resection can result in paradoxical anterior–posterior tibial translation, limiting mid-swing flexion and impacting stride length and walking speed [22]. Unlike TKA, BCA-M preserves extensor efficiency at the low flexion angles associated with gait [13], which may in part explain why differences are seen during maximum weight acceptance and mid-stance when the quadriceps are active.

Survivorship of primary BCA-M is largely unknown. The National Joint Registry has reported that primary multi-compartmental arthroplasty has a similar revision rate to primary patellofemoral arthroplasty, though the numbers are small and include all compartmental combinations, not just BCA-M [2]. Of the 69 primary BCA-M subjects considered for this study, two knees (3%) had been revised (Fig. 2, Supplemental Table A), one to a tricompartmental arthroplasty through the addition of a lateral UKA (Revision Partial Knee Classification PR2b [17]), 7 years after primary BCA-M, and one to a posterior-cruciate retaining TKA (Revision Partial Knee Classification PR3), performed at another hospital for unexplained pain after 4 years. Of the subjects included in the study, no subjects have since been revised.

Progressive arthritis remains a common mode of failure following single-compartment PFA [2, 6, 7]. The ‘compartmental approach’ (Revision Partial Knee Classification PR2b [17]) advocates the addition of a second PKA to the newly degenerate compartment, while retaining the primary PKA and ACL [14, 18]. It has been shown to preserve healthy gait characteristics, despite second surgery [16], reflecting the results of the present study.

The study was powered for gait analysis, with OKS and EQ-5D 5L scores collected as secondary outcome measures, though the study was underpowered for PROMs. Overall satisfaction and quality of life was good after both BCA-M and TKA, but a statistical advantage was reported following BCA-M. The difference in mean OKS exceeded the reported minimal important clinical difference of five points [3], though the difference in median OKS scores did not (Table 1). This suggests that there may be an advantage in PROMs with BCA-M, compared to this relatively satisfied cohort of TKAs. The recorded OKS and EQ-5D scores are similar to widely reported literature values for UKA and TKA [8, 26, 36], with no apparent adverse effect as a consequence of the additional PFA in BCA-M subjects when compared to medial UKA, supporting the findings of others [29]. Higher satisfaction is also reported in those revised through a compartmental approach [16]. The significant differences observed on the OKS in relation to rising from a chair, kneeling down, stair descent and instability symptoms support the theory that BCA-M preserves isokinetic quadriceps strength and anterior–posterior stability, known to be compromised following TKA [13, 15, 27].

This study would have benefited from pre-operative data to determine the extent of improvement each subject experienced as a consequence of surgery. However, attempts were made to mitigate its absence by only selecting TKA patients who underwent surgery for single- or two-compartment disease, did not have pre-operative evidence of ACL dysfunction, and would have been eligible for PKA or CPKA under the senior author’s current clinical practice. The inclusion of patients with single-compartmental disease in the TKA group was necessary to power the study, but may have acted to the detriment of the BCA-M group, who all had bicompartamental disease pre-operatively.

**Clinical relevance**

The retention of the lateral compartment and the cruciate ligament complex may play an important role in allowing patients with a BCA-M to retain near normal stride length and speed following surgery. The data may help clinicians and their patients when deciding on alternatives to TKA where once the benefits may have been considered unsubstantiated [10].

**Conclusions**

This study finds that, in the treatment of medial tibiofemoral osteoarthritis with severe patellofemoral arthritis, medial bicompartamental arthroplasty results in nearer-normal gait and improved patient-reported outcomes compared to total knee arthroplasty.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s00167-021-06773-8.

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Declarations

Conflict of interest A. Garner also reports research grants from Dunhill Medical Trust, RCS England, and the Sir Michael Uren Foundation for this study. R. van Arkel reports a research support grant from DePuy Synthes. J. Cobb reports board membership on Orthonika, consultancy payments from JRI, an institutional grant from DePuy Synthes, payment for lectures from Ceramicx, a patent and stocks from Embody, and royalties from Matortho, all unrelated to this study.

Ethical approval This study was conducted with full ethical approval. Data were collected in the gait laboratory with Institutional Review Board approval from NRES Committee South Central - Oxford B. Study title: 3D and 2D Motion Capture Gait Analysis of Lower Limb Orthopaedic Patients. REC reference: 14/SC/1243. IRAS project ID: 136430 and from the Academic Health Science Centre, Imperial College London and Imperial College Healthcare NHS Trust. Project Title: Gait Analysis Using An Instrumented Treadmill. Joint Research Office Reference number: JROHH0208. Ethics Reference number: 10/H0807/101.

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