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Joint kinematics following bi-compartmental knee replacement during daily life motor tasks

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ABSTRACT

In many cases knee osteoarthritis leads to total knee replacement surgery (TKR) even if the lateral compartment is not involved. More recently, a bicompartmental knee replacement system (BKR) (Journey Deuce, Smith & Nephew Inc., Memphis, TN, USA) has been developed that only replaces the medial tibiofemoral and the patellofemoral compartments, thus preserving both cruciate ligaments with its associated benefits. However information on the effect of BKR on in vivo knee joint kinematics is not widely available in the literature.

Therefore, this study analyzed full three-dimensional knee joint kinematics in 10 postoperative BKR-subjects for a broad spectrum of relevant daily life activities: walking, walking followed by a cross-over or sidestep turn, step ascent and descent, mild squatting and chair rise. We analyzed to what extent normal knee motion is regained through comparison with their non-involved limb as well as a group of matched controls. Furthermore, coefficients of multiple correlation were calculated to assess the consistency of knee joint kinematics both within and between subject groups.

This analysis demonstrated that, despite the presence of differences indicative for retention of pre-operative motion patterns and/or remaining compensations, knee joint kinematics in BKR limbs replicate, for a large range of daily-life motor tasks, the kinematics of the contra-lateral non-affected limbs and healthy controls to a similar extent as they are replicated within both these control groups.

1. Introduction

Knee osteoarthritis (KOA) is one of the most common degenerative joint diseases [1,2]. The gait pattern of KOA patients typically shows increased knee adduction moments leading to increased loading of the medial knee compartment [3–5] and therefore a higher prevalence of cartilage damage at the medial compartment, the patellofemoral compartment or a combination of both [1,6].

In many cases KOA leads to total knee replacement (TKR) surgery although the lateral compartment is not involved. In contrast, uni-compartmental knee replacement (UKR) only replaces the medial compartment while retaining the lateral compartment and the cruciate ligaments. In the literature, this is reported to lead to improved proprioception and more natural knee kinematics after surgery [7,8]. Nevertheless, when strictly adhering to selection criteria, only a low percentage of KOA patients would be eligible for UKA [9]. More recently, a bicompartmental knee replacement system (BKR) (Journey Deuce, Smith & Nephew Inc., Memphis, TN, USA) has been developed that only replaces the medial tibiofemoral and patellofemoral compartments. This system also preserves both cruciate ligaments with its associated benefits [10–13].

A recent study on knee joint mechanics in eight patients with BKR [14] showed that they still demonstrate some compensatory mechanisms but largely exhibit normal kinematics and kinetics. While knee mechanics of UKR and TKR patients have been extensively studied [5], more information on the effect of BKR on in vivo knee joint kinematics is, to the authors' knowledge, not yet available in the literature.

Therefore, the purpose of the presented study was to examine full three-dimensional knee joint kinematics in patients with BKR for a broader spectrum of relevant daily life activities: walking, walking followed by cross-over or sidestep turns, step ascent and descent, mild squatting and chair rise. Through comparison with their non-involved limb as well as a group of matched controls, we

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analyzed to what extent normal knee motion is regained following BKR in a group of 10 patients. We hypothesized to find similar results for walking as in the study of Wang et al. [14], but an increased presence of compensatory mechanisms and retention of the pathologic motion pattern for motor tasks associated with higher knee joint loading (e.g. squatting and chair rise). Furthermore, as knee replacement specifically aims at correcting knee alignment in the coronal and axial plane [15], we expected to also find effects on out-of-sagittal plane knee joint kinematics.

2. Materials and methods

2.1. Sample characteristics

Upon ethical approval, ten patients participated in this study after giving informed consent (Appendix 1). Following a diagnosis of localized osteoarthritis in the medial and the patello-femoral compartment with an intact lateral compartment and normal functioning cruciate ligaments, each patient received a Journey Deuce bicompartmental knee replacement (Smith & Nephew Inc., Memphis, TN, USA) at least one year prior to this study. Furthermore, in all patients the non-operated side was screened by the treating surgeon to exclude the presence of any comorbidity that might negatively affect their functional performance during the analyzed motor tasks. As a reference, side-matched kinematic data of a group of 10 control subjects was selected out of the gait lab's normal reference database aiming for subjects that best match each individual patients' sex, age, height and BMI. A physiotherapist performed an additional screening of the control subjects to exclude any condition that could affect their functional performance.

2.2. Motion capture

Kinematic data were obtained using a fourteen camera MX40 motion capture system (Vicon, Oxford, UK) tracking the 3D positions of 23 retro-reflective spherical markers. A single well-trained physiotherapist fixed the markers onto the skin of the lower limbs and trunk according to the Helen-Hayes marker protocol. Although alternative, functional or image-based methods exist for subject-specific joint axis calibration, a Knee Alignment Device (KAD) [16] was used to identify the axis about which tibiofemoral flexion/extension is calculated. As mal-alignment of the knee flexion axis results in crosstalk between sagittal and coronal knee motion [17], the KAD position producing minimal excursion of knee abduction-adduction during the swing phase of walking was selected out of three trials.

Foot contacts were detected with two forceplates collecting at 1000 Hz (Advanced Mechanical Technology, Inc, Watertown, MA, USA). Workstation and Polygon software (Vicon, Oxford, UK) were used to identify motor task events and to derive the kinematics from the acquired data [17–19].

2.3. Motor tasks

Each subject was asked to perform seven different motor tasks, with three repetitions each:

1. Walking: walk straight ahead on a level floor at self-selected speed.
2. Walk and crossover turn: while walking forward, perform a 90° crossover turn, with the pivoting leg over a forceplate, as in [20].
3. Walk and sidestep turn: while walking forward, perform a 90° sidestep turn, with the pivoting leg over a forceplate, as in [20].
4. Step Ascent: step onto and over a 20 cm high step placed over a forceplate, as in [21], and continue straight ahead. The step length and width were 30 cm × 45 cm. Subjects started with toes 20 cm away from the step.
5. Step descent: descend from the same step as in 4 onto the force plate, and continue walking straight ahead.
6. Chair rise: without assistance of the upper limbs, rise from a sitting position into an up-right, full standing position, with feet over separate force plates. Subjects adjusted their own seat height for comfort, starting with approximately 90° knee flexion.
7. Mild squat: squat down to less than 90° knee flexion with both feet over separate force plates, with minimal exertion, and rise back up. Heels can rise off the floor.

For the patient group, both the involved and the non-involved limb were analyzed, while for the control group only one out of both sides was analyzed.

2.4. Data analysis and reduction

Data was extracted using Workstation software (version 5.2.9, Vicon, Oxford, UK) and the Plug-in-Gait model (Vicon, Oxford, UK) [22] following Woltring filtering (MSE = 15). Cycles for gait related tasks (walking and ascent/descent tasks) were time-normalized from initial contact (IC) to IC. CR-cycles were time-normalized from the moment the upper body began to lean forward till maximal knee extension. Squat cycles were defined between times of maximal knee extension. Further processing of the data was performed in custom-build software (Matlab 7.12.0, The MathWorks, Natick, MA). For each task, corresponding kinematics curves were grouped together in three categories: patient – involved side, patient – non-involved side, controls. Furthermore a set of kinematic and spatio-temporal parameters was calculated [23].

A non-parametric Mann–Whitney U test was automatically performed at every percentage of the normalized motion cycles to detect systematic differences between the patients' involved sides and the control group. As a secondary control, non-parametric Wilcoxon signed rank tests were performed comparing between the patients' non-involved and involved sides. Significance level was set for both tests at 0.05, with a Bonferoni correction adjusting for the three repetitions of each motor task. Using the same setup, spatio-temporal parameters were analyzed statistically.

Finally, to analyze and interpret the kinematic consistency between the patient's operated side and their non-operated side as well as controls, both within- and between-group coefficients of multiple correlation (CMC) [18] were calculated. In case of poor kinematic consistency between the operated side and both reference groups, combining kinematic curves from both groups would decrease the homogeneity and therefore result in between-group CMC having lower values than the corresponding within-group CMC [24,25].

3. Results

3.1. Temporal findings

Except for mild squat, post-op subjects systematically performed all motor tasks at a lower cadence when compared to healthy controls, leading to 18.0 ± 6.9% longer cycle times (Table 1). Furthermore, a shortened stance phase was found at the patients' involved side for walking and step ascent when compared to their non-involved side. Contrastingly, it was prolonged for walking followed by a sidestep when compared to controls (Table 1).

3.2. Kinematic findings

3.2.1. Sagittal plane

When compared to controls (Fig. 1), we found a decreased range of motion (ROM) at the involved side for the stance phases of walking, walking followed by a sidestep and step descent. Although knee flexion during initial contact and loading response was in general very similar with only step descent showing a statistically significant reduction, the change in ROM was mainly caused by decreased (peak) knee extension at mid stance. For walking these effects resulted in a statistically significant increase of the average flexion angle during stance of 2.68° (Table 2).

Table 1
Overview for the different groups of motion cycle times (in s) (top) and timing of foot off, expressed as a percentage of the gait cycle. Significant differences are marked in black text ($p < 0.05/3$).

	Cycle time (s)			% diff
	Controls		Involved side	
Walking	1.00 ± 0.08	<	1.12 ± 0.07	12.0
Walking + cross over	1.50 ± 0.27	<	1.81 ± 0.35	20.7
Walking + sidestep	1.36 ± 0.22	<	1.63 ± 0.25	19.9
Step ascent	1.56 ± 0.28	<	1.74 ± 0.16	11.5
Step descent	1.11 ± 0.12	<	1.22 ± 0.11	10.0
Chair rise	1.30 ± 0.32	<	1.65 ± 0.35	26.9
Mild squat	2.38 ± 0.73		2.98 ± 1.12	25.2

	% cycle at foot off				
	Controls		Involved side		Non-involved side
Walking	59.83% ± 1.64		60.37% ± 1.63	<	61.17% ± 1.49
Walking + cross over	66.07% ± 4.38		68.37% ± 5.20		69.87% ± 4.13
Walking + sidestep	60.87% ± 2.91	<	64.93% ± 3.86		65.37% ± 3.78
Step ascent	70.60% ± 3.15		69.80% ± 2.37	<	71.83% ± 2.66
Step descent	60.83% ± 2.93		62.40% ± 2.94		62.10% ± 3.20

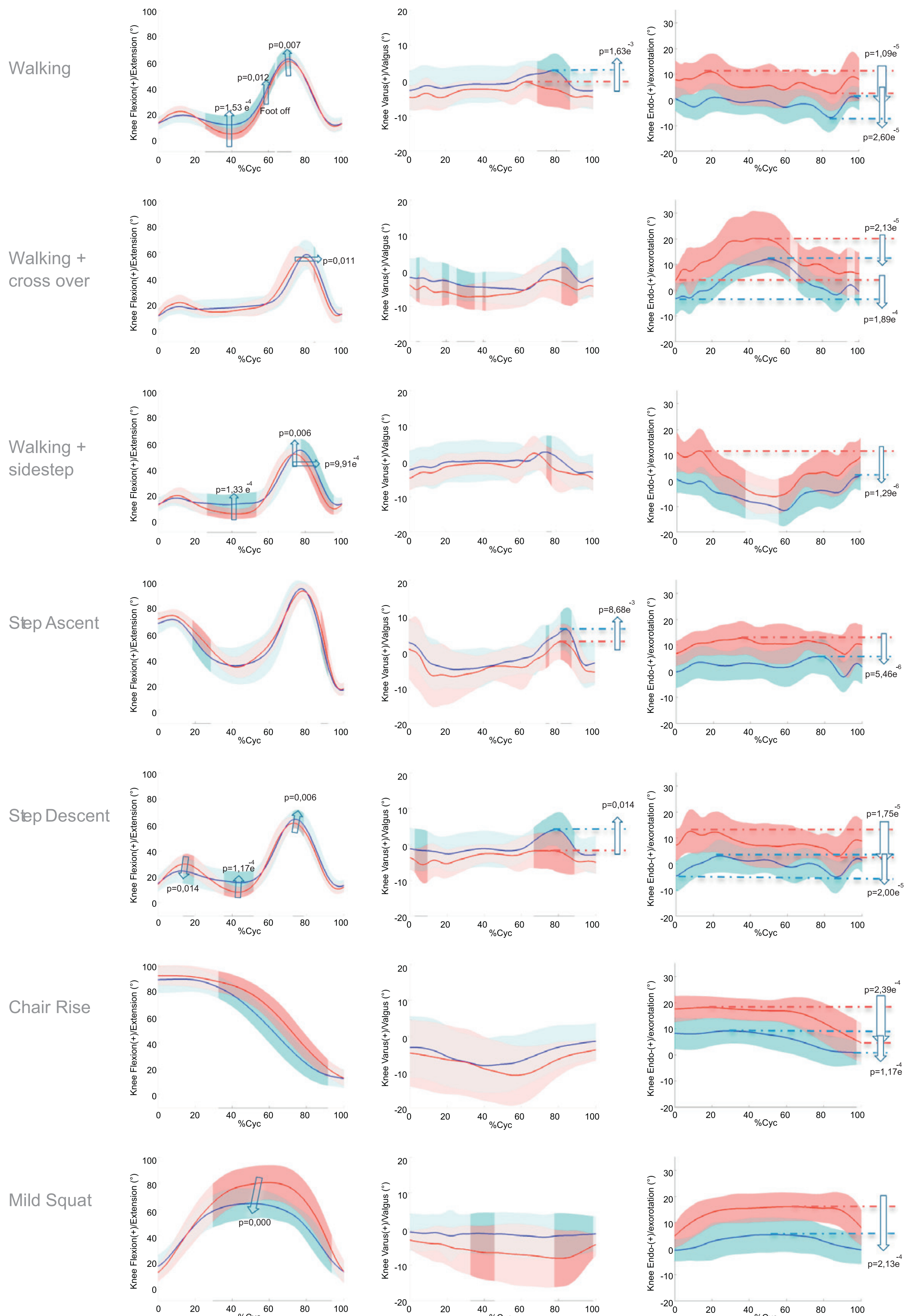

Fig. 1. Comparison of the knee joint kinematics (mean ± standard deviation) in all three planes of motion between the patient's involved side (shown in blue) and controls (shown in red). In areas with faded out standard deviation, the difference in the corresponding knee joint angle is not significant at the faded out percentages of the gait cycle (Mann–Whitney *U* test, $p > 0.05/3$). Systematically increased minima or maxima during stance or swing for gait related motor tasks, or over the full motion cycle for non-gait related tasks are indicated by vertical arrows and the associated *p*-value. Also potential differences in knee flexion/extension at initial contact and foot-off for gait related motor tasks are indicated likewise. Finally, significant timing differences of specific peak joint angles are indicated using horizontal arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 2
Mean difference in knee joint angles during the full motion cycle, the stance and the swing phase between the patients' involved side and controls (top) as well as the patients' involved side and the contralateral non-involved side (bottom), measured in degrees. Positive values indicate increased flexion, varus or endorotation at the patients' involved side. Significant differences are marked in black text ($p < 0.05/3$).

Versus	Flexion/extension			Varus/valgus			Endo-/exorotation		
	Overall	Stance	Swing	Overall	Stance	Swing	Overall	Stance	Swing
Controls									
Walking	1.77	2.68	0.72	2.40	1.92	3.09	−7.83	−7.73	−8.01
Walking + cross over	0.28	0.45	0.99	2.31	2.32	2.49	−8.55	−9.28	−7.52
Walking + sidestep	2.86	3.58	3.73	1.26	1.23	1.34	−7.02	−7.27	−6.34
Step ascent	−2.57	−3.20	−1.20	1.95	1.72	2.51	−7.96	−8.50	−6.72
Step descent	1.20	1.14	2.18	2.71	2.12	3.65	−8.28	−8.67	−7.61
Non-involved side									
Walking	−0.94	−2.23	0.61	2.14	2.04	2.25	−3.02	−3.62	−2.00
Walking + cross over	−0.41	−0.98	−0.40	2.21	2.14	2.31	−2.87	−3.54	−1.24
Walking + sidestep	−0.47	−2.17	2.20	1.86	1.82	1.79	−3.28	−4.53	−0.91
Step ascent	−5.82	−8.17	−0.68	3.05	2.86	3.29	−2.94	−3.93	−0.63
Step descent	−3.58	−5.56	−0.17	2.57	2.31	3.07	−3.99	−4.73	−2.73

Also when comparing the involved side to the contralateral non-involved side we found this reduction in ROM, although now caused by a statistically significant reduced peak knee flexion angle at loading response for walking, walking followed by a sidestep and step ascent and descent. In contrast with the comparison with controls, we found increased peak knee extension at mid stance (Fig. 2). For both ascent and descent these findings resulted in a statistically significant decrease of the average flexion angle during stance of 8.17° and 5.56°, respectively (Table 2).

During swing, kinematic differences were less pronounced mainly showing a small increase in peak flexion angle at the involved side compared to both controls and their non-involved side. Furthermore, this peak was systematically delayed for turning tasks when compared to healthy controls.

For non-gait related motor tasks, larger parts of the motion cycle were found to differ significantly. Furthermore, the involved side showed a statistically significant reduction in peak knee flexion for mild squat when compared to controls.

3.2.2. Coronal plane

In comparison with both controls and the patients' contralateral, non-involved side (Figs. 1 and 2), their involved side showed fairly similar knee varus valgus motion patterns despite a systematic shift towards increased varus/decreased valgus for all motor tasks. Nevertheless this shift was only found to be statistically significant at certain parts of the motion cycles, mainly during swing (Figs. 1 and 2, Table 2). Only for chair rise and mild squat, this shift was statistically significant for approximately the full motion cycle when compared to the non-involved side.

3.2.3. Axial plane

As for the coronal plane, similar axial plane kinematic patterns were found again showing an offset (shift towards increased external/decreased internal rotation) for all motor tasks (Figs. 1 and 2). Contrasting with findings for coronal plane knee kinematics, this shift versus both controls and the non-operated side was now found to be statistically significant during the major parts of all motion cycles. Consequentially also the overall peak values (Figs. 1 and 2) as well as the knee rotation angles averaged during stance, swing or over the full gait cycle (Table 2) differed in most cases.

3.3. Repeatability analysis

Confirming previous studies [6,18], CMC values show a higher repeatability of sagittal plane kinematics both within and between subject groups when compared to the coronal and axial planes of motion (Table 3). Furthermore, turning tasks show a higher repeatability for axial knee motion. More interestingly however, CMC values show, for all joint angles and motor tasks, a consistency of the kinematic curves between the patients' involved side and their non-involved side as well as controls, respectively, very similar to the consistency within each of these groups.

4. Discussion

This study reported on kinematic findings during a large set of relevant daily-life motor tasks between the operated limbs of patients who received a bi-compartmental knee replacement system and their contralateral, non-involved limb as well as a group of matched control subjects.

Results showed that BKR patients performed all motor tasks at a slower cadence when compared to controls (Table 1). For level walking, this finding contrasts with the study of Wang et al. who found no differences in self-selected walking speed between controls and patients with the same prosthesis design, i.e. the Journey Deuce bicompartmental knee replacement (Smith & Nephew Inc., Memphis, TN, USA) [14]. We believe this to be associated with the higher post-operative functional and knee society scores reported in their study. Nevertheless, also in TKR patients, reduced preferred walking speeds have been reported despite an improved functionality and reduced pain following surgery [26–28]. This finding has been hypothesized to be correlated with a loss in quadriceps strength [29]. Unfortunately, this could not be confirmed in this study as quadriceps strength data was not collected.

Looking at knee joint kinematics, we reported several findings in all three planes of motion. In the sagittal plane, a first finding for gait related motor tasks was a flattening of the flexion–extension curve during stance when compared to control subjects. To a smaller extent, the associated statistically significant decrease of peak knee extension during the second half of stance during walking has also been reported by Wang et al. [14]. As similar effects have recently been observed in typically developing children as a consequence of reduced walking speeds (Fig. 4 in [30]), this finding might be a consequence of post-op subjects in this study walking most comfortably at slower speed. Nevertheless, many possible alternative causes have been reported in the TKA-literature, including lack of muscular control and flexion deformities [31]. However, as sufficient knee extension has been identified as an important stabilizing factor for power generation during propulsion [31,32], further research is necessary to thoroughly explain this finding.

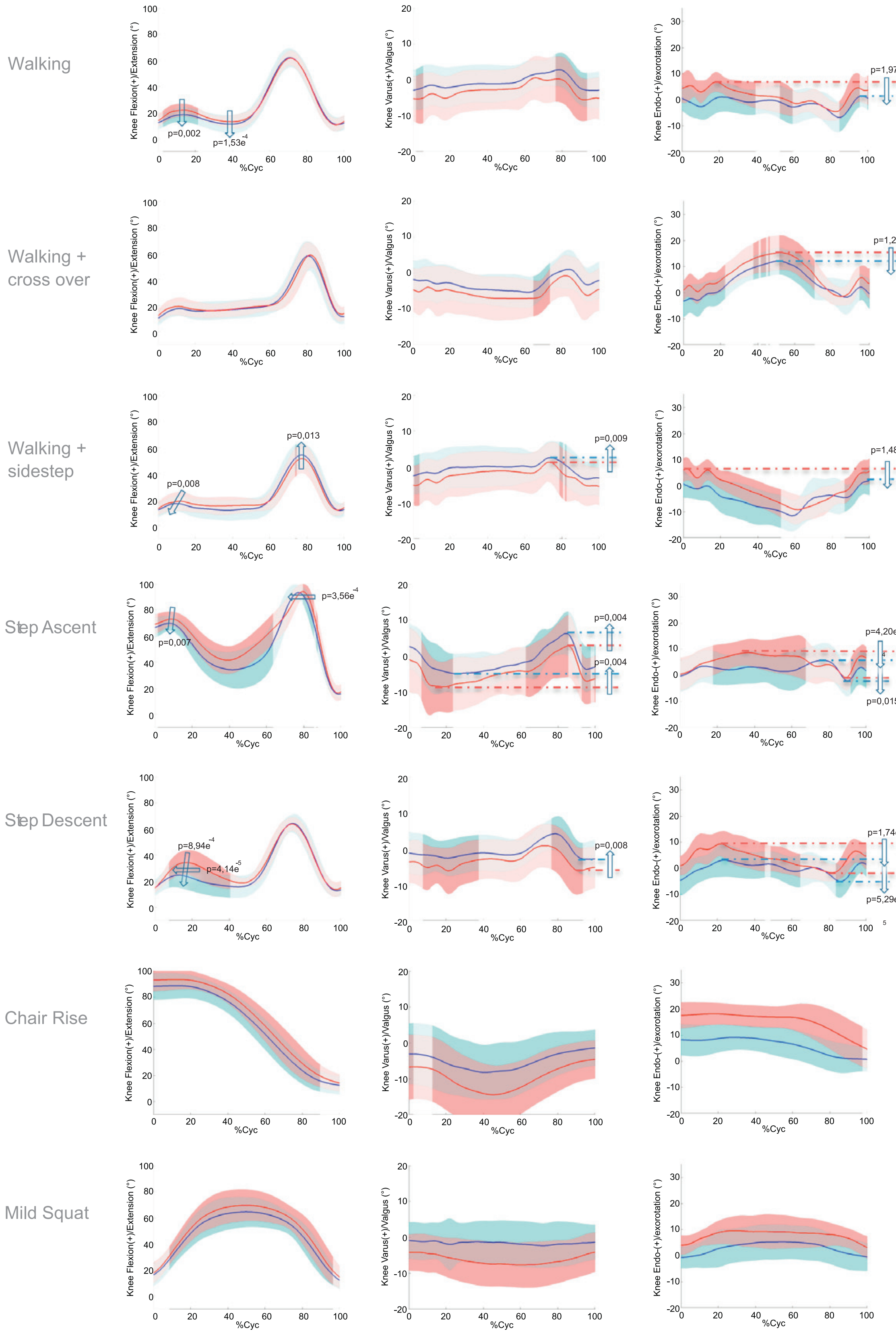

Fig. 2. Comparison of the knee joint kinematics (mean ± standard deviation) in all three planes of motion between the patient's involved side (shown in blue) and their contralateral non-involved side (shown in red). In areas with faded out standard deviation, the difference in the corresponding knee joint angle is not significant at the faded out percentages of the gait cycle (Wilcoxon signed rank test, $p > 0.05/3$). Systematically increased minima or maxima during stance or swing for gait related motor tasks, or over the full motion cycle for non-gait related tasks are indicated by vertical arrows and the associated p-value. Also potential differences in knee flexion/extension at initial contact and foot-off for gait related motor tasks are indicated likewise. Finally, significant timing differences of specific peak joint angles are indicated using horizontal arrows. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 3
Overview of the within- (grey text) and between group (black text) CMC values, quantifying the kinematic consistency between the patients' involved side and controls (top) as well as the patients' involved side and the contralateral non-involved side (bottom).

Versus	Flexion/extension		Varus/valgus		Endo-/exorotation	
	Within (CMC_i)	Between (CMC)	Within (CMC_i)	Between (CMC)	Within (CMC_i)	Between (CMC)
Controls						
Walking	0.9490	0.9447	0.2644	0.2566	0.2628	0.2158
Walking + cross over	0.8644	0.8597	0.3087	0.2974	0.5724	0.5030
Walking + sidestep	0.8868	0.8754	0.2757	0.2787	0.5577	0.4998
Step ascent	0.8973	0.8956	0.4470	0.4517	0.1765	0.1483
Step descent	0.9083	0.9034	0.3106	0.2834	0.2868	0.2208
Chair rise	0.9478	0.9360	0.2194	0.2360	0.5123	0.4109
Mild squat	0.8588	0.8247	0.0000	0.0237	0.3424	0.2469
Non-involved side						
Walking	0.9383	0.9378	0.2577	0.2768	0.4211	0.3864
Walking + cross over	0.8547	0.8555	0.2676	0.2860	0.6991	0.6854
Walking + sidestep	0.8441	0.8427	0.2146	0.2407	0.6102	0.5692
Step ascent	0.8830	0.8711	0.4296	0.4301	0.2941	0.2374
Step descent	0.8833	0.8730	0.3048	0.3068	0.4390	0.3817
Chair rise	0.9465	0.9437	0.3016	0.3043	0.4224	0.3746
Mild squat	0.8487	0.8461	0.0000	0.0000	0.2756	0.2654

Although peak knee flexion in the first half of swing is reduced for the majority of motor tasks when comparing the patients' involved to their non-involved sides, we contrastingly found better knee extension at push-off during walking in the operated limb. Although not significant, our results also show this effect for walking followed by a sidestep, step ascent and descent. It is thought to result from retention at the non-involved side of the pre-operative 'stiff knee' gait pattern [4,14]. Although pre-operative motion analysis data is not available to support this hypothesis, the better knee extension might additionally indicate a significant improvement and stabilization of the gait pattern following BKR [31,32].

For chair rise and mild squat, larger areas of the flexion/extension curve show a significant decrease in knee flexion angle at the involved side. This is thought to result from the higher knee loads and contact forces induced during these motor tasks [1,6]. Increased loading can increase pain, lead to more adaptation of the motion pattern and therefore heavier reliance on the contralateral limb as a pain avoiding strategy. Furthermore, this assumption also corresponds with our finding of shortened stance phases at the patients' involved side for walking and step ascent, when compared to their non-involved side. Two patients reported anterior knee paint (1 moderate, 1 mild) just prior to motion analysis. Quadriceps weakness and the consequential reduced knee extension moment generating capacity [3,5,14,27] could have been an additional contributing factor.

In both the coronal and the axial plane very similar kinematic patterns were found, however shifted to increased knee varus and exorotation respectively. This corresponds with our original hypothesis that the knee alignment in BKR in the coronal and axial plane [15] also affects out-of-sagittal plane knee joint kinematics. For the coronal plane, this finding contrasts with results published by Wang et al. who found a return to normal knee mechanics during walking after BKR surgery [14] and previous studies on coronal plane post-operative knee alignment using the same prosthesis design [15]. Nevertheless, also post-operative X-ray based varus/valgus angle measurements still showed remaining varus compared to a normal anatomical valgus angle typically ranging between 5° and 7° [33–35] (Appendix 1). Probably, retention of the pre-operative gait pattern and pain avoidance additionally contributed to these remaining differences, as increased peak adduction angles are typically associated with medial knee osteoarthritis [36].

The kinematic shift was most pronounced in the axial plane. Unfortunately only very few motion-analysis studies report knee kinematics in this plane as they are known to be more error-sensitive. To the authors' knowledge only the study by McClelland et al. compared axial plane knee kinematics during walking between post-TKA subjects and healthy controls and found very comparable differences [31]. McClelland et al. hypothesized this bias into external rotation to be related to component misalignment [31]. Importantly, also in our study, these differences were greater than previously reported errors attributable to marker-placement [31,37]. In addition our result supports a recent in vitro study using a knee simulator to compare rotational tibiofemoral kinematics in the same prosthesis design with native knees [38]: they explained the decreased internal rotation by the influence of the surgery on the soft tissue [38]. However for the first time, this study reports this offset for motor tasks other than gait [31] or squat [38]. As additional data on the axial plane post-operative knee alignment is not available to correlate with the reported offsets and there is no consensus in the literature on the possible causes of this offset into more external rotation, future research is clearly necessary.

Finally, our CMC analysis (Table 3) revealed that kinematic curves of patients who received a BKR demonstrate a consistency with the kinematic curves from control subjects or their contralateral non-involved side, very similar to the consistency measured within each group individually and this for all motor tasks. In other words, compared to the variability within groups, grouping kinematic curves originating from post-operative limbs with healthy limbs did only introduce very small amounts of additional variability.

In his/her interpretation of the results, the reader should be aware of some limitations to this study: despite limiting the body mass index (BMI) when recruiting, most of the subjects included in this study were overweight (BMI > 25, Appendix 1) with a consequential negative effect on the accuracy of the calculated joint angles due to more difficult marker placement and larger soft tissue artifacts. This effect can be clearly seen when comparing the repeatability reported in Table 3 to previously reported repeatability measurements from the same gait lab [6]. However, increasing the range of motion by introducing additional motor tasks over walking partially compensates for this decreased accuracy. Furthermore, potential high-BMI artifacts are equally present in both patients' sides and are therefore unlikely to have introduced additional differences in this secondary control. A second limitation to this study is that it lacked pre-operative kinematic data or data on the performance of matched patients following total knee replacement. In upcoming studies, we want to assess both these flaws allowing, respectively, a quantitative analysis of the improvement of the gait pattern following BKR and a comparison with the corresponding improvement in TKR patients. Also, we want to perform a similar in-depth analysis of knee joint kinetics. Furthermore, the reader should be aware that reported results included the effect of the surgical technique applied during BKR. Finally, although our study resulted in some clear trends and statistically significant results, we believe straightforward extension of the reported findings to the general BKR-population requires further research and larger sample sizes.

Nevertheless, this study demonstrated that, despite the presence of differences indicative for a retention of pre-operative motion patterns and/or remaining compensations, knee joint kinematics following bicondylar knee replacement replicate the kinematics of the contra-lateral non-involved limbs and healthy controls to a similar extent as they are replicated within both these control groups in a large range of motor task with high relevance during daily life. Furthermore this study presented a framework for an objective and detailed analysis of the post-operative performance of knee replacement patients.

Conflict of interest statement

All authors have contributed to and reviewed the material in this report. L. Scheys and L. Labey are both employees of Smith & Nephew, Memphis, TN. J. Bellemans and A. Franz are both consultants of Smith & Nephew, Memphis, TN.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2012.04.008.

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