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How symmetric are metal-on-metal hip resurfacing patients during gait? Insights for the rehabilitation

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ABSTRACT

Metal-on-metal hip resurfacing patients demonstrate hip biomechanics closer to normal in comparison to total hip arthroplasty during gait. However, it is not clear how symmetric is the gait of hip resurfacing patients. Biomechanical data of 12 unilateral metal-on-metal hip resurfacing participants were collected during gait at a mean time of 45 months (SD 24) after surgery. Ankle, knee, hip, pelvis and trunk kinematics and kinetics of both sides were measured with a motion and force-capture system. Principal component analysis and mean hypothesis' tests were used to compare the operated and healthy sides. The operated side had prolonged ankle eversion angle during late stance and delayed increased ankle inversion angle during early swing ($p = 0.008$; effect size = 0.70), increased ankle inversion moment during late stance ($p = 0.001$; effect size = 0.78), increased knee adduction angle during swing ($p = 0.044$; effect size = 0.57), decreased knee abduction moment during stance ($p = 0.05$; effect size = 0.40), decreased hip range of motion in the sagittal plane ($p = 0.046$; effect size = 0.56), decreased range of hip abduction moment during stance ($p = 0.02$; effect size = 0.63), increased hip range of motion in the transverse plane ($p = 0.02$; effect size = 0.62), decreased hip internal rotation moment during the transition from loading response to midstance ($p = 0.001$; effect size = 0.81) and increased trunk ipsilateral lean ($p = 0.03$; effect size = 0.60). Therefore, hip resurfacing patients have some degree of asymmetry in long term, which may be related to hip weakness and decreased range of motion, to foot misalignments and to strategies implemented to reduce loading on the operated hip. Interventions such as muscle strengthening and stretching, insoles and gait feedback training may help improving symmetry following hip resurfacing.

1. Introduction

Total hip arthroplasty (THA) is a treatment option for end-stage hip failure, with a cost of $38,295 in the United States (International Federation of Health Plans, 2013). Because of the low durability and longevity of the prosthesis (Sharkey et al., 2006), THA is not promising for more active patients (Crowninshield et al., 2006). In fact, more candidates for THA have become physically active (Crowninshield et al., 2006). Metal-on-metal hip resurfacing arthroplasty (hereafter referred to as hip resurfacing) is an alternative to THA for active patients (Hing et al., 2007), since it is bone-conservative, has shorter recovery time and reduces the implant dislocation risk (Mehra et al., 2015; Pollard, 2006). Longitudinal studies have demonstrated favorable results for hip resurfacing in comparison to THA regarding aseptic loosening, stability, toxicity of wear and implant survivorship (Azam et al., 2016; Australian Orthopedic Association, 2015). In addition, hip resurfacing allows patients to return unrestrictedly to their activities within a year of the procedure (Pollard, 2006), which has driven younger patients to request hip resurfacing as an alternative to THA (Pollard, 2006). In Canada, between 2009 and 2014, there was an increase of 11.8% in the number of hip resurfacing (Canadian Joint Replacement Registry, 2015).

It is speculated that, in comparison to THA, hip resurfacing contributes to greater weight bearing on the operated side during activities such as walking (Aqil et al., 2013), which may be

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explained by the larger femoral head sizes used with the technique. Increased body weight bearing may help to explain the hip extension range of motion and abduction moments closer to normal as demonstrated after hip resurfacing in comparison to THA (Mont et al., 2007). However, it is not clear if the biomechanics of the lower limb with hip resurfacing are similar to the biomechanics of the contralateral lower limb. It is possible that individuals with unilateral hip resurfacing still have asymmetric gait patterns after surgery (Mellon et al., 2014), which may overload the contralateral side. For example, after THA, 79% of the patients developed osteoarthritis in the contralateral hip and 54% had undergone another arthroplasty (Ritter et al., 1996). In addition, asymmetric mechanics in other joints might be expected. For example, it is possible that hip resurfacing individuals increase trunk ipsilateral lean during gait to laterally shift the body center of mass and consequently minimize the hip abduction moment on the operated side. Although this strategy may reduce the load on the operated hip, it may overload the spine joints, such as the intervertebral and facet joints (Popovich et al., 2013).

This study compared the biomechanics of the operated side of individuals with unilateral hip resurfacing with the biomechanics of the contralateral side during gait. It was hypothesized decreased hip abduction and extension moments along with decreased hip extension angle and increased ipsilateral trunk lean during the stance phase in the operated side.

2. Material and methods

2.1. Participants

Sample size was determined using the software G∗Power (Faul et al., 2007) with the following input data: two-tailed dependent *t*-test, statistical power of 80%, significance level of 0.05, and the mean effect size of the differences in hip flexion-extension angle ($d = 0.65$), adduction-abduction moment ($d = 0.79$) and internal-external rotation moment ($d = 1.31$) found in a pilot study with 5 subjects ($d = 0.92$). This resulted in an estimated sample size of 12 participants. Twenty-three potential participants were invited to participate in the study, but 11 did not want to take part in the study or did not meet the inclusion criteria. Therefore, ten males and two females with unilateral metal-on-metal hip resurfacing participated in the study. The senior author was responsible for the hip resurfacing surgery in all participants using a direct lateral approach to the hip joint, with the specific inclusion and exclusion criteria for the surgery described in a previous study (Bow et al., 2012). All implants were the Depuy Orthopaedic ASR (Warsaw, Ind). The surgical technique has been previously described in detail (Bow et al., 2012; Kunz et al., 2010). Patients were allowed to fully weight bear soon after surgery. Mobilization with physiotherapy began within 24 h of surgery and continued until the patient was discharged, usually within 2–3 days of surgery. A non-supervised home exercise program was provided to the patients on discharge to continue to improve their strength and range of motion about the hip joint.

The inclusion criteria were a minimum of 12 months of follow-up after the surgery, no history of falls and no other surgeries or injury to either lower limbs in the past twelve months, no history of stroke or any other form of arthritis, neuromuscular or cardiovascular disorders, being able to walk without assistive device and a city block, and to climb stairs in a reciprocal fashion. The exclusion criterion was the report of pain or walking unsteadily during data collection. Each participant signed a consent form approved by the university's Ethical Research Committee.

2.2. Procedures

The participants answered the Western Ontario and MacMaster Universities Osteoarthritis Index (WOMAC) and the Lower Extremity Activity Scale (LEAS). The WOMAC is validated for evaluating outcome after THA (Bellamy et al., 1988), with scores varying from 0 to 100 and higher scores indicating better condition in the pain, stiffness and function dimensions. The LEAS is validated for the assessment of patients' actual activity levels (Saleh et al., 2005), with scores varying from 1 to 18 and higher scores indicating higher activity level. Then, the heights and masses of the participants were measured. Subsequently, gait data were recorded at 200 Hz using a 12-camera motion capture system (Oqus 4, Qualisys, Gothenburg, Sweden) synchronized with six force platforms (Custom BP model, AMTI, Massachusetts, USA). The force platforms registered ground reaction force data at a frequency of 1000 Hz, which was subsequently downsampled at 200 Hz.

Anatomical and clusters of tracking markers were used to determine the coordinates of the trunk, pelvis, thigh, shank and feet (Cappozzo et al., 1995) using data obtained with the participant in a relaxed standing position (static trials). Participants then walked at their self-selected speed wearing their own shoes for five trials along a 15-m distance (Fig. 1).

2.3. Data reduction

Gait data were processed using the Visual3D (C-motion, Inc., Rockville, USA). Raw kinematic and force data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency set at 6 Hz and 18 Hz, respectively. Heel contact and toe-off were determined automatically in Visual3D using the vertical ground reaction force at threshold of 20 N. The following joint kinematics were calculated: (1) ankle dorsiflexion-plantar flexion (medio-lateral axis), inversion-eversion (antero-posterior axis) and adduction-abduction (longitudinal axis) with respect to the shank; (2) knee flexion-extension, adduction-abduction and internal-external rotation, represented by the motion of the shank relative to the thigh; (3) hip flexion-extension, adduction-abduction and internal-external rotation, represented by the motion of the thigh relative to the pelvis; (4) pelvic anteversion-retroversion (medio-lateral axis), ipsilateral-contralateral drop (antero-posterior axis) and external-internal rotation (longitudinal axis) with respect to the lab; (5) trunk flexion-extension (medio-lateral axis), ipsilateral-contralateral lean (antero-posterior axis) and external-internal rotation (longitudinal axis) with respect to the lab. Kinetic data included ankle, knee and hip internal moments in the sagittal, frontal and transverse planes. Both kinematic and kinetic data were computed in the joint coordinate system (Grood and Suntay, 1983). Joint moments were calculated using the inverse dynamic approach, normalized to body mass (kg), and reported in Nm/kg. Internal joint moments were reported throughout the text. Kinematics and kinetics data were normalized to 101 data points, one for each percentage of the gait cycle.

2.4. Data analysis

2.4.1. Principal component analysis (PCA)

Extracting discrete variables from temporal series has at least four limitations: (i) severe data reduction, (ii) loss of temporal information, (iii) difficulty to define the parameter to extract and (iv) high correlation between the extracted discrete variables (i.e. redundancy). Therefore, we chose PCA since it is the recommended choice as a first step for gait waveform data reduction (Chau, 2001), without loss of temporal information, which generates independent principal components and scores (Deluzio et al., 2014) that were used for the hypothesis tests of this study. The procedure resembles those previously described for analysis of gait-derived waveforms (Brandon et al., 2013; Deluzio and Astephen, 2007; Kirkwood et al., 2011). PCA was performed on 24 gait variables arranged in 24 separate 24×101 data matrices (12 subjects $\times$ 2 sides $\times$ 101 time points per gait cycle). Data related to each measure m were organized in an $n \times p$ matrix X_m. Each row in the matrix X_m represented a temporal series m for each side of each participant. Each column represented the time samples of measure m at one particular instant for each side of all participants.

Each data matrix was mean centered, and the associated covariance matrix was subsequently calculated. The next step in computation involved the eigenvalue decomposition of the covariance matrix; this was achieved according to the principal component model $Z = [U^t X]$, where U is the transformation matrix that rotates the original data observations into a new coordinate system. The columns of U are the eigenvectors of the covariance matrix of the original data set, and are termed principal component (PC) loading vectors (Deluzio and Astephen, 2007). The PCs were extracted in a hierarchical fashion based on the amount of variation they explained; this was calculated by dividing the specific eigenvalue for each corresponding PC by the trace of the covariance matrix (Resende et al., 2016). A criterion of 90% of variance explained was used to determine the number of PCs to retain for data analysis (Resende et al., 2015).

2.4.2. Statistical analysis and interpretation of the PC-scores

The scores of the PCs retained for analysis were tested for normal distribution using Kolmogorov–Smirnov and Shapiro–Wilk tests, and then compared between sides using dependent *t*-tests (for normally distributed scores) and Wilcoxon signed-rank test (for non-normally distributed scores). The significance was set at $\alpha = 0.05$. The effect sizes (e.g. *r-value*) of the comparisons with statistically significant differences were also calculated as follows: if *t*-test was used, $r = \sqrt{\frac{t^2}{t^2 - d_f}}$ where t is the *t*-value and d_f is the degree of freedom; if Wilcoxon signed-rank test was used, $r = \frac{z}{\sqrt{24}}$ where z is the z-score (Field, 2006).

The method of single component reconstruction was used to interpret the differences between sides in PC-scores (Brandon et al., 2013). This method isolates the pattern of variance captured by the specific PC where the sides differed, and had three steps. First, the waveforms representing the operated side and the contralateral side (hereafter referred to as healthy side) pattern of variance on the specific PC were plotted in the same graph (Figs. 2 and 3). The waveforms representing the operated and the healthy sides correspond to a high or low value of the PC-score, depending on which side had higher or lower scores on that specific PC. These waveforms were calculated by first multiplying one standard deviation of the corresponding PC-scores by the PC loading vector and then adding (high) or subtracting (low) the resulting product to the sample mean waveform (Brandon et al.,

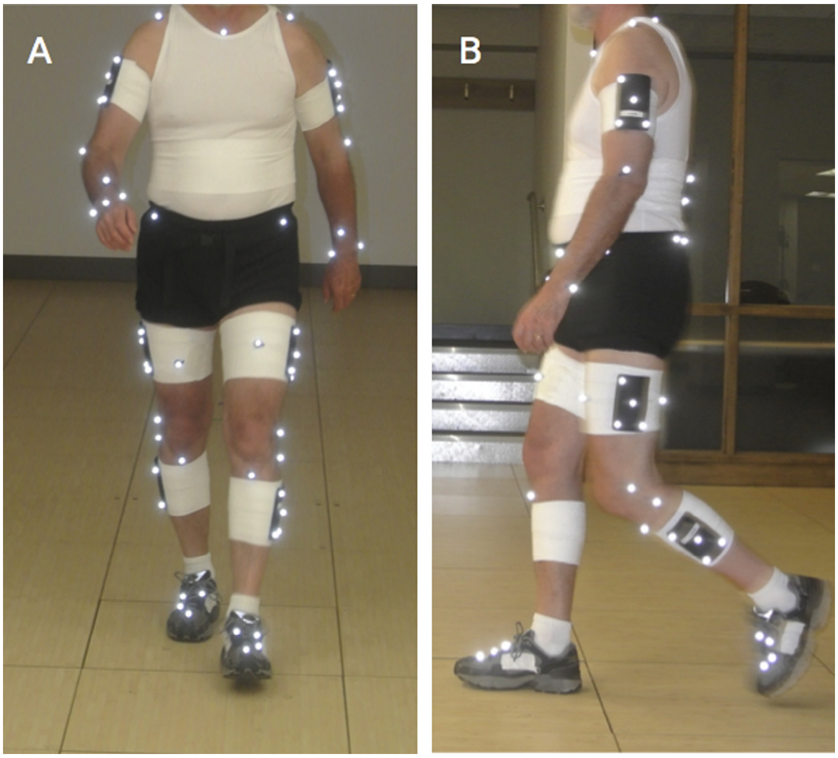

Fig. 1. Marker placement, anterior (A) and lateral (B) view.

2013). Second, the portions of the gait cycle that contributed most to the biomechanical feature captured by the specific PC, and consequently to the differences between sides, were defined based on the portions of the gait cycle that had greater PC loading vector magnitude (defined by vertical dashed lines and shaded areas in Figs. 2 and 3) (Brandon et al., 2013), since these coefficients were linearly combined to the original waveforms time samples to calculate the PC-scores. More specifically, portions of the gait cycle with loading vector magnitude equal or greater than half of the maximum loading vector for that specific PC were shaded. Third, the differences between the waveforms representing the healthy and the operated sides on the shaded areas in the graphs were analyzed in order to interpret the meaning of the differences between sides in the PC-scores.

3. Results

3.1. Characterization of the participants and gait temporal-spatial measures

Eight participants had surgery on the dominant lower limb. The participants' characteristics and the gait temporal-spatial measures are presented in Table 1. The WOMAC score of 87 indicates that the participants had low hip pain and stiffness intensity and better physical function. The score 14 in the LEAS means: *"I am up and about at my will in my house and outside. I also work participate in relaxed physical activity such as jogging, dancing, cycling and swimming 2–3 times per week"*.

3.2. Gait angular displacement and moments of force

The comparisons of the PC scores between operated and healthy sides demonstrated that 9 PCs had PC-scores different between sides, and these results are described in Table 2. The loading vectors of these PCs and the waveforms representing the pattern of variance of the operated and healthy sides, either high (+ 1SD) or low (− 1SD) PC-scores, depending on the operated and healthy sides' mean score, are represented in Figs. 2 and 3. In summary, the operated side had prolonged ankle eversion angle during late stance, decreased knee abduction moment during stance, decreased hip abduction moment and range of motion in the sagittal plane, increased hip range of motion in the transverse plane, decreased hip internal rotation moment in the transition from loading response to midstance and increased trunk ipsilateral lean.

4. Discussion

This study investigated the differences between the biomechanics of the operated and healthy sides of unilateral hip resurfacing subjects during gait. At the hip, the operated side had decreased range of motion in the sagittal plane, shorter and decreased range of abduction moment during stance, increased range of motion in the transverse plane and decreased internal rotation moment during the loading response phase. These asymmetries might be associated to impairments in the operated side, such as hip extensor and abductor muscles weakness (Barker et al., 2013) and decreased hip range of motion in the sagittal plane (dela Rosa et al., 2007). In addition, the increased trunk ipsilateral lean may be a strategy implemented to reduce demand on the operated side, which may overload the lower back joints and may have also contributed to the increased loading at the knee on the healthy side. These results may help to guide the rehabilitation following hip resurfacing, since most of these asymmetries might be reduced by specific rehabilitation interventions, such as muscle strengthening in specific positions, stretching, use of insoles and gait feedback training.

Gluteus maximus is responsible for hip extension during early stance of gait. Therefore, weakness of this muscle may compromise hip extension during stance (Arnold et al., 2005). In addition, it has been demonstrated that two years after surgery, hip resurfacing patients had less than 10° of hip passive extension (Penny et al., 2013), which may also help to explain the decreased hip range of motion of the operated side, finding that is similar to the results of studies investigating THA patients (Beaulieu et al., 2010; Miki et al., 2004; Queen et al., 2014). Decreased hip range of motion

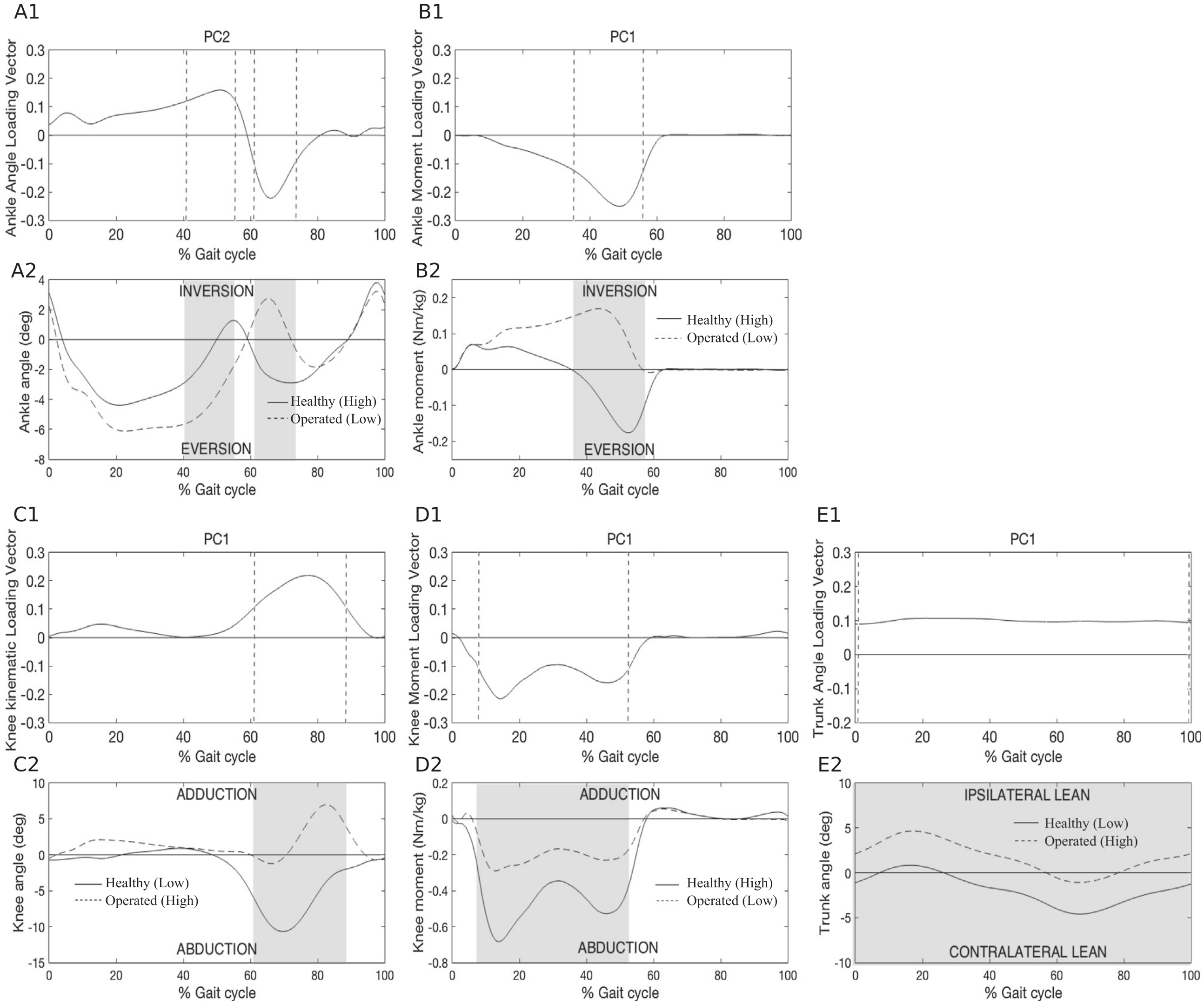

Fig. 2. Healthy versus operated sides differences in the ankle, knee and trunk demonstrated by the statistical comparisons. Shown in the figures are the waveforms that represent high and low PC scores for the indicated measure. In all cases, the waveform that represents the PC score (i.e. high or low PC score) that characterizes the operated sided is shown as a dashed line; the waveform that represents the PC score that characterizes the healthy side is shown as a solid line. The shaded areas demonstrate the portions of the gait cycle that most significantly contributed to the PC score and, thereby, to the differences observed between sides. The shaded areas were defined based on the magnitudes of the PC loading vector. The ankle inversion angle PC2 (A1 and A2); ankle inversion moment PC1 (B1 and B2); knee adduction angle PC1 (C1 and C2); knee adduction moment PC1 (D1 and D2); and the trunk ipsilateral lean angle PC1 (E1 and E2).

affects step length, and in fact, hip resurfacing patients present shorter stride length, in comparison with healthy controls, even 9 months after surgery (Benedetti et al., 2012). It is possible that strengthening the hip extensor muscles and increasing the flexibility of the hip flexors, by stretching (Watt et al., 2011) and strengthening them in the lengthened position (Aquino et al., 2010), may contribute to reduce these asymmetric patterns and consequently contribute to increase stride length. However, this needs further investigation.

The shorter and decreased range of hip abduction moment and decreased knee abduction moment during stance on the operated side are probably related to the increased trunk ipsilateral lean (Hunt et al., 2008). Increased trunk ipsilateral lean is a strategy frequently implemented by patients following THA (Vogt et al., 2003) to reduce the mechanical demand on the weaker hip abductors muscles (Barker et al., 2013; Neptune and McGowan, 2016), which may also be the case for hip resurfacing patients. This strategy may overload the lower back joints (Popovich et al., 2013). Degenerative diseases at the lumbar spine and hip frequently coexist, and although there are no hip resurfacing data, for THA patients, the occurrence of lumbar spine disorder reduces the functional level and the quality of life of these patients up to 60 months after surgery (Ellenrieder et al., 2015). In addition, the increased trunk contralateral lean on the healthy side may have contributed to the increased knee abduction moment of the healthy side, which is similar to studies investigating THA patients (Shakoor et al., 2003; Foucher and Wimmer, 2012). This finding may help to explain why asymmetric hip pain have worse pain and structure outcomes in the knee contralateral to the more affected hip (Joseph et al., 2016). Although the participants of this study were provided with a home exercise program to improve hip strength and mobility, it is not clear that they recovered appropriate hip strength and mobility. Future studies should investigate if strengthening of the hip extensors and abductors muscles and the increase of the hip passive extension will reduce the asymmetries demonstrated by this study.

The increased range of motion in the transverse plane of the operated hip may be related to the deficit in the hip external

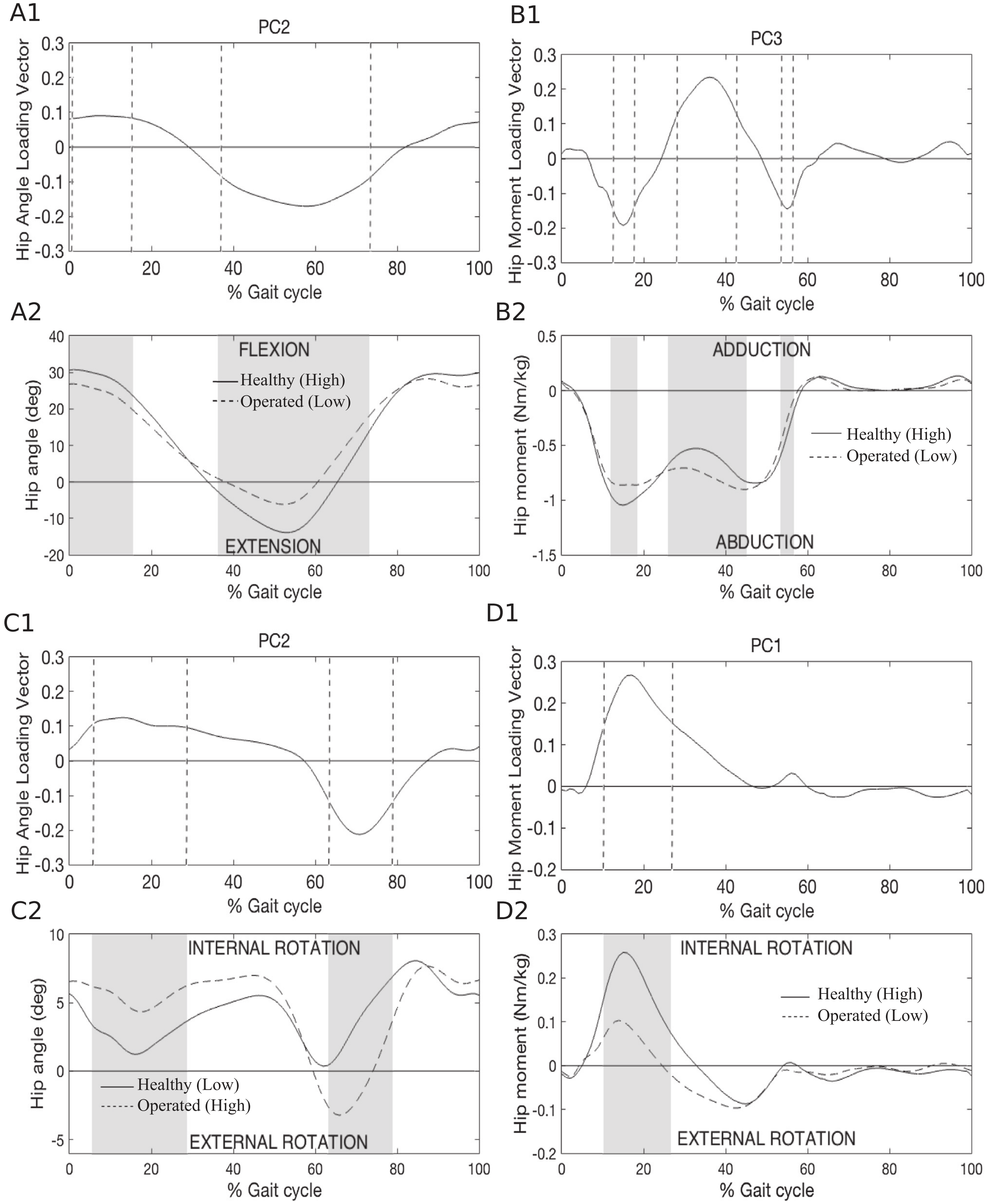

Fig. 3. Healthy versus operated sides differences in the hip demonstrated by statistical comparisons. Shown in the figures are the waveforms that represent high and low PC scores for the indicated measure. In all cases, the waveform that represents the PC score (i.e. high or low PC score) that characterizes the operated sided is shown as a dashed line; the waveform that represents the PC score that characterizes the healthy side is shown as a solid line. The shaded areas demonstrate the portions of the gait cycle that most significantly contributed to the PC score and, thereby, to the differences observed between sides. The shaded areas were defined based on the magnitudes of the PC loading vector. The hip flexion angle PC2 (A1 and A2); hip adduction moment PC3 (B1 and B2); hip internal rotation angle PC2 (C1 and C2); and the hip internal rotation moment PC1 (D1 and D2).

Table 1
Mean (standard deviation) and coefficient of variation of the participants' characteristics and gait temporal-spatial variables.

Measures	Mean and standard deviation	Coefficient of variation
Age (years)	60 (5.2)	0.09
Height (cm)	178 (7.73)	0.04
Mass (kg)	88.3 (15)	0.17
Follow up time (months)	45 (24)	0.53
WOMAC score	87.4 (16.8)	0.19
LEAS score	14.2 (2.8)	0.20
Gait speed (m/s)	1.39 (0.24)	0.17
Stride length (m)	1.47 (0.17)	0.12
Operated side		
Step length (m)	0.735 (0.081)	0.11
Stance time (s)	0.668 (0.058)	0.09
Swing time (s)	0.404 (0.029)	0.07
Healthy side		
Step length (m)	0.729 (0.086)	0.12
Stance time (s)	0.669 (0.061)	0.09
Swing time (s)	0.399 (0.032)	0.08

cm: centimeters; kg: kilograms; m: meters; s: seconds.

rotation strength demonstrated by hip resurfacing patients (Borg et al., 2009). In addition, it is possible that asymmetric foot alignment also plays a role (Snyder et al., 2009). During the stance phase, hip internal rotation is partially controlled by hip external rotator muscles (Snyder et al., 2009). Therefore, hip external rotators weakness may have contributed to the increased range of motion in the transverse plane. In addition, hip internal rotation is coupled with ankle eversion (Souza et al., 2010), which is influenced by the forefoot alignment (Monaghan et al., 2013). Therefore, it is possible that the hip resurfacing patients had increased forefoot varus alignment on the operated side, which may also explain the prolonged ankle eversion angle demonstrated by this side (Monaghan et al., 2013). Although this hypothesis is speculative, it is in accordance with a previous study demonstrating the association between forefoot varus and the need of THA (Gross et al., 2007). Increased hip range of motion in the transverse plane might be deleterious, since it may contribute to a multidirectional motion pattern of the femur head (Bennett et al., 2008) and consequently to increased wear of the implants (Mellon et al., 2014). In activities such as single-leg squat, hip external rotators strengthening associated with neuromuscular reeducation consisting of mirror and verbal feedback on proper mechanics resulted in decreased hip internal rotation after six weeks of training (Willy and Davis, 2011). Therefore, hip resurfacing patients may also benefit from this training, which is not frequently included in the rehabilitation programs for these patients (Cheatham et al., 2016).

The participants' variance in follow-up time was high, which may be a limitation of this study. However, all of the participants had a minimum of 12 months of follow-up, time after which they do not present any significant changes in strength (Jensen et al., 2011), functional level and gait pattern (Benedetti et al., 2012). Moreover, the participants had small variances in the WOMAC and LEAS scores and in the gait temporal-spatial variables, showing that the high variance in the follow-up time did not result in high variance in the symptoms, physical function, functional level and gait pattern of the sample. Finally, although the occurrence of asymmetry in able-bodied subjects during gait is still controversial (Sadeghi et al., 2000; Sadeghi, 2003; Seeley et al., 2008; Cabral et al., 2016), part of the findings of this study might be due to asymmetries the participants had before developing hip conditions. Nonetheless, most of our findings had large effect sizes and most of our findings are in agreement with studies investigating THA patients.

5. Conclusions

Individuals following hip resurfacing have differences in the kinematics and moments in the three planes of motion of the hip and in the frontal plane of the ankle, knee and trunk. Therefore, some degree of asymmetry is long-term persistent in hip resurfacing individuals. Some of these findings, such as the increased ipsilateral trunk lean on the operated side, the increased hip and knee abduction moments and the increased hip sagittal plane range of motion on the healthy side, suggest that these individuals adopt strategies on the proximal segments and on the healthy side to reduce loading at the operated hip, which may however overload the trunk and healthy side joints. In addition, the hip increased transverse plane range of motion may contribute to the implants wearing. Therefore, these individuals may benefit from specific interventions, such as strengthening of the hip extensors, external rotators and abductors muscles and stretching and strengthening in the lengthened position of the hip flexors. Finally, these individuals may benefit from non-local interventions, such as gait feedback training and use of insoles, which is however speculative at this point.

Conflict of interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Table 2
Principal components (PCs) that demonstrated differences between operated and healthy sides. Percentage of variance explained and a description of the differences in scores between sides in each PC are also provided.

Measure	PC	Variance explained (%)	*p-value*	Effect size	Results description based on the pattern of the operated side
Ankle inversion-eversion angle	2	14.3	0.008	0.70	Prolonged ankle eversion angle during late stance and delayed and increased ankle inversion angle during early swing
Ankle inversion-eversion moment[a]	1	78.5	0.001	0.78	Increased ankle inversion moment during late stance
Knee adduction-abduction angle	1	75.4	0.044	0.57	Increased knee adduction angle during initial and mid swing
Knee adduction-abduction moment[a]	1	75.4	0.05	0.40	Decreased knee abduction moment during most of the stance phase
Hip flexion-extension angle	2	24.0	0.046	0.56	Decreased hip range of motion in the sagittal plane during stance
Hip adduction-abduction moment	3	15.8	0.02	0.63	Decreased range of hip abduction moment during stance and shorter hip abduction moment during late stance
Hip internal-external rotation angle	2	14.7	0.02	0.62	Increased hip range of motion in the transverse plane during the gait cycle
Hip internal-external rotation moment	1	48.2	0.001	0.81	Decreased hip internal rotation moment during the transition from loading response to the midstance phases
Trunk ipsilateral-contralateral lean	1	67.3	0.03	0.60	Increased trunk ipsilateral lean throughout the gait cycle

[a] Wilcoxon signed-rank test.

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