# Inter-limb differences in total hip arthroplasty patients four to five years after surgery: a cross-sectional study

**Stefanie John** ( Stefanie.John@ovgu.de )
Otto von Guericke Universitat Magdeburg Fakultat fur Humanwissenschaften https://orcid.org/0000-0001-6722-7195
**David Weizel**
Otto von Guericke Universitat Magdeburg Fakultat fur Humanwissenschaften
**Anna Sophie Heumann**
Otto von Guericke Universitat Magdeburg Fakultat fur Humanwissenschaften
**Anja Fischer**
Otto von Guericke Universitat Magdeburg Fakultat fur Humanwissenschaften
**Katja Orlowski**
Technische Hochschule Brandenburg
**Kai-Uwe Mrkor**
Technische Hochschule Brandenburg
**Jürgen Edelmann-Nusser**
Otto von Guericke Universitat Magdeburg Fakultat fur Humanwissenschaften
**Kerstin Witte**
Otto von Guericke Universitat Magdeburg Fakultat fur Humanwissenschaften

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# Abstract

Background

Total hip arthroplasty (THA) is a successful method to reduce pain in end-stage hip osteoarthritis (OA) patients. If the pre-operatively existing deficits in the affected limb are persisting years after THA has not been thoroughly researched. Therefore, the aim of the study was to investigate potential side-to-side differences in long-time THA patients.

Methods

Sixteen patients (age: 65.20 ± 5.32 years), who had undergone unilateral THA four to five years ago and ten, healthy, age-matched controls (age = 60.85 ± 7.57 years) were examined for maximum isometric hip muscle strength, range of motion (ROM) of the hip joint, balance and gait on both limbs. Paired t-testes were used to assess the inter-limb differences in THA patients and controls and unpaired t-tests were applied to investigate differences between the two groups.

Results

In THA patients, significant deficits on the operated side were found for the center of pressure (COP) length, hip abduction torque and ROM of hip extension with small to medium effects. Compared to the controls, THA patients demonstrated highly significantly reduced hip strength in flexion, extension, abduction and adduction as well as limited ROM in hip flexion and abduction.

Conclusions

A few side-to-side difference were present in THA patients four to five years after the surgery, although the general hip muscle weakness and restricted hip ROM compared to the controls was more severe. Postoperative training focusing on strengthening hip muscles should be continued months and years after the surgery in order to compensate persisting deficits.



Trial registration

DRKS, DRKS00016945. Registered 12 March 2019 – Retrospectively registered, http://www.drks.de/DRKS00016945


# Background

Hip osteoarthritis (OA) is one of the most frequent joint diseases, which develops in approximately one in four people over their lifetime [1]. Patients with hip OA suffer from pain, reduced muscle strength and function, balance as well as limited range of motion (ROM) in the affected hip joint [2, 3]. First-line treatment of these impairments consists of conservative therapy. However, if conservative options are ineffective and fail to provide improvements, total hip arthroplasty (THA) is required. Following THA, most of the patients seemed to be satisfied with the operation result, reporting improvements for pain and function [4, 5]. Nevertheless, some studies have shown that pre-operative existing deficits persist up to two years after THA affecting functional performance when compared to healthy controls [6–8].

In order to assess the surgical outcome of the THA, several studies have concentrated on the performance differences concerning strength, balance, hip ROM and gait characteristics between the operated and the non-operated side. Winther et al. demonstrated reduced lower limb-strength in the operated leg performing leg press and abduction strength test three months after total hip replacement [9]. Even two years after THA, side-to-side strength differences were detected for hip extension, hip flexion and hip abduction [10]. According to Horstmann et al., lower limb strength is also important for improving gait function after THA, as hip extensor and hip flexor muscle strength and endurance were shown to be relevant for reducing post-operative limping [11]. OA patients develop characteristic gait patterns, such as lateral trunk shift towards the affected hip in order to compensate the pain and dysfunction of the affected hip joint [12]. The modifications in spatio-temporal parameters include slower walking speed, shorter step length and shorter stance duration on the OA affected side compared to the contralateral one [13]. After surgery, the gait of THA patients is known to improve but certain kinetic and kinematic gait abnormalities remain [14, 15]. Concerning the spatiotemporal parameters after THA, no consistent results were found in studies comparing the operated with the non-operated side [16].

Besides determining hip muscle strength and gait parameters, it is also important to examine balance performance and hip ROM for assessing the functional status for THA patients, since muscular weakness may have an effect on the ability of maintaining balance [17]. According to Pop et al., deficits in static balance were revealed in comparison to a healthy control group two to three years after THA [18]. Regarding the hip ROM, Davis et al. found these motion parameters to be relevant indicators for the evaluation of the hip function after surgery [19]. Preoperatively, significant differences in hip flexion, extension, adduction and abduction as well as for internal and external rotation were evident in patients with hip OA compared to healthy controls [20]. Six months after hip resurfacing, dela Rosa et al. could show that their patients significantly improved hip ROM compared to preoperative values [21]. No study comparing the side-to-side differences in hip ROM or comparing the absolute ROM values to a control group was found.

Interlimb-differences between the operated and the non-operated hip in strength, gait performance und postural control have been shown to exist two to three years post-THA. However, no study has examined if these deficits persist beyond this time and how these lateral differences could be interpreted in comparison to a healthy, age-matched control group.

The purpose of this study was to quantify the potential side-to-side differences in hip muscle strength, spatio-temporal gait parameters, postural stability and hip ROM in patients who had undergone THA four to five years ago and to compare the differences in relative and absolute terms to age-matched controls. We hypothesized that patients four to five years after THA will show between-limb asymmetry in hip strength, hip ROM, balance and gait parameters. Secondly, we hypothesized that the THA patients will demonstrate lower absolute hip strength and hip ROM values when compared with healthy, age-matched peers.

## Methods

# Participants

Sixteen patients with unilateral hip replacement (10 females, 6 males) voluntarily participated in this study. Further subject characteristics are presented in Table 1. Post-operation time amounted to 4.7 ± 0.7 years and the operation side was seven times the right and nine times the left hip. Besides a post-operation time between four and five years, further inclusion criteria included no neurological and cardiovascular diseases or acute injuries of the musculoskeletal system as well as being physically active at least two times a week. Ten healthy age-matched subjects served as controls (6 females, 4 males). The control subjects were also excluded in case of neurological or cardiovascular diseases, acute injuries of the lower-limb extremities or end-stage arthritis in hip or knee joints. Controls and THA patients were similar in sex distribution, height, weight and age as shown in Table 1. All participants gave written consents to participate in this study after being informed about the procedure, its purpose and possible risks linked to the participation. The study was approved by the local ethics committee of the Otto-von-Guericke-University Magdeburg presided by Dr. med. Norbert Beck and carried out in line with the Declaration of Helsinki (no. of vote: 155/18 on December 3, 2018). It was retrospectively registered in the German Registry of Clinical Trials under the ID: DRKS00016945.

**Table 1**: Demographic characteristics of THA patients and control group

| | THA group (n=16) | Control group (n=10) | p-value |
|---|---|---|---|
| Age [years] | 65.20±*5.32* | 60.85±*7.57* | 0.10 |
| Female [%] | 62.50 | 60.0 | 0.90# |
| Height [cm] | 166.69±*10.40* | 171.75±*12.73* | 0.28 |
| Weight [kg] | 72.28±*17.41* | 71.10±*20.45* | 0.52U |
| Post-Op time [years] | 4.66±*0.72* | - | - |

# Chi-squared test

U Mann-Whitney-U-Test

# Measurement protocol

For the cross-sectional study, the participants were asked to attend one testing, in which all measurements were conducted. First, a gait analysis was performed followed by examinations of balance, hip ROM and isometric strength of the hip muscles. Data was collected on both legs. For the THA patients, the legs were differentiated in the operated and the non-operated side whereas for the control group, the legs were differentiated in a dominant and a non-dominant one. According to van

Melick et al. the leg dominance was determined by asking the participants with which leg they would prefer kicking a ball [22].

# Gait analysis

The gait analysis was performed with InvestiGAIT, an inertial sensor-based system consisting of four Shimmer3 sensors (Shimmer, Realtime Technologies Ltd, Dublin, Ireland) and an in-house Matlab program for recording and analyzing gait data. The basics of this sensor-based system, the calculation of the gait parameters and the measurement methods are detailed in Orlowski and Loose [23] and Orlowski et al. [24].

For the gait analysis, two of the inertial sensors were laterally placed above each ankle. In order to quantify the movement of the hip and the upper body, the third and the fourth Shimmer sensors were centered at the height of the posterior superior iliac spine and at the thoracic vertebra II. The subjects were asked to walk a predefined distance (approx. 12.5 m) marked by two pylons at their self-selected, comfortable walking speed. For each participant, twelve gait sequences were recorded. Outcome spatio-temporal gait parameters involved step length, stance and swing duration as well as one-leg-stance as a percentage of the gait cycle. The gait parameters were determined for both legs, differentiated in the operated and the non-operated side in the THA patients and in the dominant and non-dominant side in the control group.

# Balance assessment

Static balance was assessed in the bipedal and single-leg stance using a force plate (PLUX-Wireless Biosignals S.A, Lisbon, Portugal). For the bipedal stance, subjects were asked to take off shoes and stand with both legs, hip width apart, on the force plate with the arms hanging down at the sides. Two trials with a duration of thirty seconds were recorded. For the single-leg stance, the participants were instructed to position one leg in the center of the force plate, slightly lifting off the other foot and fixating the wall in front of them. Before collecting data, the participants were asked to practice this posture. Two trials on each leg, starting with the operated side (THA group) or the non-dominant side (control group) and then alternating, were captured with a duration of ten seconds. The acquisition time in the single-leg stance was limited to ten seconds as most subjects were not able to hold the position for much longer. Balance data was sampled at 250 Hz and further processed using Matlab (Version 2018b, The Math-Works Inc., Natick, MA). The dataset was filtered applying a 4th order Butterworth low-pass filter with a 10 Hz cut-off frequency. The length of the center of pressure (COP) during unilateral stance was computed as well as its standard deviations (SD) in antero-posterior (AP) and in medio-lateral (ML) directions. The best trials of each leg were chosen for further analyses.

# Hip ROM analysis

The examination of the active hip ROM was performed in a self-developed diagnostic machine. Subjects were fixated into the diagnostic machine right above the pelvis in order to avoid compensational movements with the upper body but still providing free movement of the hip joint. Isolated ROM of the hip was measured in flexion, extension and abduction each in standing position, first on the operated (THA group)/ non-dominant (control group) leg and then on the non-operated/dominant one. Adduction was excluded due to potential risk of luxation of the prosthesis. The angles of the three movement directions were quantified with an acceleration sensor (PLUX-Wireless Biosignals S.A, Lisbon, Portugal) placed distally on the lateral side of the thigh. After initializing the sensor in the neutral zero position, participants were instructed to slowly perform three maximal hip flexion movements followed by three maximal extension and abduction movements. Data from the motion analysis was acquired at 1000 Hz and filtered in Matlab with a 4th order Butterworth low-pass filter (5 Hz). Out of the three trials, the maximum hip angles in flexion, extension and adduction on each side were extracted for further analyses.

# Isometric strength analysis

Maximum isometric strength of the hip muscles was also measured in the diagnostic machine in which subjects remained fixated in the upright position. A neoprene brace was placed distally at the thigh as an attachment possibility for the hauling rope (Fig. 1). An integrated force transducer (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) measured the isometric strength in the respective pulling directions flexion, extension, abduction and adduction in the neutral hip position, starting with the operated/non-dominant leg. For each motion direction, one pretest and two main tests were performed. Subjects were instructed to build up strength and contract maximally without an abrupt push. A resting period of one minute between each trial was maintained. Force data from the strength analysis was acquired at 1000 Hz and filtered in Matlab with a 4th order Butterworth low-pass filter (5 Hz). Out of the two main trials, the trial with the highest torque was normalized to the body mass of the participants and used for further analyses. The distance between the greater trochanter and the point of applied force (the middle of the neoprene brace) served as the lever arm.

# Statistical Analyses

All analyses were performed using SPSS 25 (SPSS Inc., Chicago, IL) with a significance level set to $p < 0.05$. All variables were verified for normal distribution applying the Shapiro-Wilk test. In order to investigate potential differences between the operated and non-operated side of the THA patients and the dominant and non-dominant side of the control group, a paired t-test was applied for each parameter. In case of violation of normal distribution, the Wilcoxon test was used instead. For the comparison of the parameters between the THA patients and the control group, the unpaired t-test was calculated. In order to compare each leg of the two groups, the operated side of the THA patients was compared to the non-dominant side of the control group and the non-operated side was compared to the dominant one. In case of violation of normal distribution, the Mann-Whitney-U-test was applied instead. The effect sizes were determined by the calculation of Cohen’s d and only displayed if the result was significant. Values for $d = 0.2$ represent a small effect, $d = 0.5$ a medium effect and $d = 0.8$ a large effect.

## Results

# THA group: operated vs. non-operated side

Comparing the parameters of the operated hip with the non-operated side, a few significant differences were detected (Table 2). The COP length of the single-leg stance was significantly longer on the operated side than on the non-operated one, although with a small effect size (p = 0.04, d = 0.29). Concerning the motion analysis, a significant deficit on the operated side was evident in the hip flexion with 89.13° compared to 100.19° on the non-operated (p = 0.001). A medium effect size (d = 0.74) was seen for this difference.

The maximum isometric strength analysis revealed a significant deficit in abduction on the operated hip (p = 0.02), although with a rather small effect size (d = 0.38). No significant differences were found in the spatio-temporal gait parameters.

**Table 2**: Balance, motion, strength and gait parameters of the operated and non-operated side in THA patients

| | Operated side | Non-operated side | p-value | Cohen's d |
|---|---|---|---|---|
| Balance | | | | |
| COP length [mm] | *783.1±309.65* | 696.8±*293.33* | 0.04* | 0.29 |
| SD in AP [mm] | *9.23±4.17* | 9.42±*5.30* | 0.96 | - |
| SD in ML [mm] | *10.01±5.17* | 7.87±*2.74* | 0.09 | - |
| Motion | | | | |
| Flexion [°] | *89.13±17.27* | 100.19±*12.24* | 0.001* | 0.74 |
| Extension [°] | 33.92±*7.22* | 33.04±*8.79* | 0.44$^{w}$ | - |
| Abduction [°] | 36.74±*8.58* | 37.65.9±*10.45* | 0.79 | - |
| Strength | | | | |
| Flexion [Nm/kg] | *1.43±0.35* | 1.46±*0.30* | 0.67 | - |
| Extension [Nm/kg] | 0.83±*0.17* | 0.86±*0.20* | 0.51 | - |
| Abduction [Nm/kg] | 0.96±*0.23* | 1.06±*0.28* | 0.02* | 0.38 |
| Adduction [Nm/kg] | 1.05±*0.29* | 1.06±*0.29* | 0.86 | - |
| Gait | | | | |
| Step length [m] | *0.74±0.09* | *0.73±0.09* | 0.87 | - |
| Stance duration [s] | 0.58±*0.08* | 0.58±*0.08* | 0.94 | - |
| Swing duration [s] | 0.47±*0.04* | 0.47±*0.03* | 0.98 | - |
| One leg stance [%] | 44.90±*2.57* | 44.94±*3.34* | 0.96 | - |

$^{w}$ Wilcoxon-test

* Differences statistically significant

# Control group: dominant vs. non-dominant side

Comparing the parameters of the dominant and the non-dominant side of the control group, two significant differences were found (Table 3). The motion analysis showed a significant reduced extension angle of 38.31° on the non-dominant side compared to 41.40° on the dominant one, although with a small effect size (p = 0.008, d = 0.35). Concerning the strength analysis, a significant deficit was observed for the non-dominant side in hip adduction with 1.24 N m/kg compared to 1.34 N m/kg on the dominant side with a small effect size (p = 0.04, d = 0.40). No significant side-to-side differences were detected in the balance parameters or in the gait parameters.

**Table 3**: Balance, motion, strength, and gait parameters of the non-dominant and dominant side in the control group

| | Non-dominant side | Dominant side | p-value | Cohen's d |
|---|---|---|---|---|
| Balance | | | | |
| COP length [mm] | 660.51±170.66 | 692.76±244.66 | 0.41 | - |
| SD in AP [mm] | 7.25±1.79 | 7.57±1.83 | 0.63 | - |
| SD in ML [mm] | 7.80±1.62 | 7.86±2.22 | 0.95 | - |
| Motion | | | | |
| Flexion [°] | 108.12±8.79 | 106.01±6.79 | 0.42 | - |
| Extension [°] | 38.31±8.65 | 41.40±9.08 | 0.008* | 0.35 |
| Abduction [°] | 51.73±6.05 | 52.64±6.88 | 0.72 | - |
| Strength | | | | |
| Flexion [Nm/kg] | 1.82±0.35 | 1.97±0.48 | 0.13 | - |
| Extension [Nm/kg] | 1.14±0.29 | 1.23±0.33 | 0.14 | - |
| Abduction [Nm/kg] | 1.37±0.26 | 1.45±0.26 | 0.18 | - |
| Adduction [Nm/kg] | 1.24±0.23 | 1.34±0.25 | 0.04* | 0.40 |
| Gait | | | | |
| Step length [m] | 0.80±0.09 | 0.80±0.08 | 0.83 | - |
| Stance duration [s] | 0.56±0.07 | 0.56±0.06 | 0.94 | - |
| Swing duration [s] | 0.47±0.03 | 0.47±0.03 | 0.79 | - |
| One leg stance [%] | 45.47±2.65 | 45.31±2.62 | 0.70 | - |

* Differences statistically significant

# THA group vs. Control group

For absolute comparison of the parameters of both legs in both groups, the operated side was compared to the non-dominant side and the non-operated side to the dominant side (Table 4). Concerning the motion analysis, significant differences between THA patients and the controls were revealed for both sides in hip abduction with a large effect. THA patients showed significant lower abduction angles on the operated (p < 0.001, d = 2.05) and non-operated side (p = 0.001, d = 1.65) than the control group on the non-dominant and dominant side. A further significant difference with a large effect was seen in hip flexion with 89.13° on the operated side compared to 108.12° on the non-dominant side (p = 0.004, d = 1.29).

The comparison of the hip strength between the THA patients and the control group revealed significant strength deficits on the part of the THA patients in flexion, extension, abduction and adduction in both legs. Large effect sizes (d > 0.8) were observed for all significant results.

No significant absolute differences were detected in the balance parameters or in the gait parameters. However, trends were seen for increased standard deviations for the THA patients in the ML direction of the bipedal stance and for the AP direction on the operated leg in the single-leg stance.

**Table 4**: Comparison of balance, motion, strength, and gait parameters between THA patients and control group

| | THA patients | Control group | p-value | Cohen's d |
|---|---|---|---|---|
| Balance bipedal stance [mm] | | | | |
| COP length | *417.06±156.78* | 382.81±*121.39* | 0.68$^{U}$ | - |
| SD in AP | *3.18±1.00* | *2.84±0.94* | 0.41 | - |
| SD in ML | *5.31±1.55* | 4.19±*1.09* | 0.06 | - |
| Balance single-leg stance [mm] | | | | |
| COP length op/nd | *783.10±309.65* | 660.51±*170.66* | 0.27 | - |
| COP length nop/d | 696.8±*293.33* | 692.76±*244.66* | 0.97 | - |
| SD in AP op/nd | *9.23±4.17* | *7.25±1.79* | 0.08$^{U}$ | - |
| SD in AP nop/d | 9.42±*5.30* | *7.57±1.83* | 0.26$^{U}$ | - |
| SD in ML op/nd | *10.01±5.17* | *7.80±1.62* | 0.46$^{U}$ | - |
| SD in ML nop/d | 7.87±*2.74* | 7.86±*2.22* | 0.68$^{U}$ | - |
| Motion [°] | | | | |
| Flexion op/nd | *89.13±17.27* | *108.12±8.79* | 0.004* | 1.29 |
| Flexion nop/d | 100.19±*12.24* | 106.01±*6.79* | 0.18 | - |
| Extension op/nd | 33.92±*7.22* | 38.31±*8.65* | 0.18$^{U}$ | - |
| Extension nop/d | 33.04±*8.79* | 41.40±*9.08* | 0.03* | 0.61 |
| Abduction op/nd | 36.74±*8.58* | 51.73±*6.05* | 0.000* | 2.05 |
| Abduction nop/d | 37.65±*10.45* | 52.64±*6.88* | 0.001* | 1.65 |
| Strength [Nm/kg] | | | | |
| Flexion op/nd | *1.43±0.35* | *1.82±0.35* | 0.01* | 1.13 |
| Flexion nop/d | 1.46±*0.30* | 1.97±*0.48* | 0.002* | 1.29 |
| Extension op/nd | 0.83±*0.17* | 1.14±*0.29* | 0.002* | 1.31 |
| Extension nop/d | 0.86±*0.20* | 1.23±*0.33* | 0.001* | 1.37 |
| Abduction op/nd | 0.96±*0.23* | 1.37±*0.26* | 0.000* | 1.65 |
| Abduction nop/d | 1.06±*0.28* | 1.45±*0.26* | 0.001* | 1.48 |
| Adduction op/nd | 1.05±*0.29* | 1.24±*0.23* | 0.08 | - |
| Adduction nop/d | 1.06±*0.29* | 1.34±*0.25* | 0.01* | 1.09 |
| Gait | | | | |
| Velocity [km/h] | *4.65±0.88* | 5.16±*0.62* | 0.13 | - |
| Step length op/nd [m] | *0.74±0.09* | *0.80±0.09* | 0.10 | - |
| Step length nop/d [m] | *0.73±0.09* | *0.80±0.08* | 0.07 | - |
| Stance duration op/nd [s] | 0.58±*0.08* | 0.56±*0.07* | 0.55 | - |
| Stance duration nop/d [s] | 0.58±*0.08* | 0.56±*0.06* | 0.57 | - |
| Swing duration op/nd [s] | 0.47±*0.04* | 0.47±*0.03* | 0.77 | - |
| Swing duration nop/d [s] | 0.47±*0.03* | 0.47±*0.03* | 0.79 | - |
| One leg stance op/nd [%] | 44.90±*2.57* | 45.47±*2.65* | 0.59 | - |
| One leg stance op/nd [%] | 44.94±*3.34* | 45.31±*2.62* | 0.77 | - |

op=operated, nop=non-operated, d=dominant, nd=nondominant

$^{U}$ Mann-Whitney-U-test

* Differences statistically significant

# Discussion

Following THA, most patients seem to be pleased about the clinical and functional outcome concerning pain, mobility, muscle strength and quality of life [25]. Nevertheless, some studies have found persisting deficits in strength, postural control and gait parameters up to two to three years after surgery. The goal of this study was to investigate and evaluate potential between-limb differences in THA patients beyond three years of surgery by comparing the side-to-side differences as well as the absolute values to a healthy, age-matched control group.

In order to examine the side-to-side differences in balance, we assessed the COP length and the standard deviation of the COP displacement in the AP and ML direction in the single-leg stance. We observed a significantly increased COP length on the operated side in the THA patients, although with a small effect size. In previous studies, the increased COP variables were interpreted as a decreased performance of the postural system [26, 27] indicating less postural stability on the operated side than on the non-operated one. Trudelle-Jackson et al. reported significant lower measures of postural stability on the side of the operated hip one year after THA [28]. Concerning the control group, no significant side-to-side differences between the dominant and non-dominant leg were observed. This is in line with the literature as studies with healthy subjects showed that lower-limb dominance does not influence the balance performance [29, 30]. In absolute terms, the controls demonstrated shorter COP lengths and lower oscillations in the bipedal and single-leg stance but this did not reach statistical significance.

Restoring hip ROM is another important goal for THA as articular deformation in OA joints was shown to induce lower ROMs [31] and to be associated with high levels of disability [32]. Our side-to-side active motion analysis of the hip joint in flexion, extension and abduction revealed a significant reduced hip flexion on the operated side with an average deficit of 11° flexion angle. Similar results were obtained in the study of Häkkinen et al. One year after hip resurfacing the patients showed a 6° lower flexion angle on the operated hip compared to the non-operated one [33]. As the THA patients are obliged not to flex the hip joint over 90° up to 12 weeks post-surgery, this prohibition might still be present in the mind and the motion might not be involved in everyday life beyond the 12 weeks. This may explain the difference seen in the flexion angle. The motion analysis of the control group revealed a significant reduced hip extension angle on the non-dominant side with a mean deficit of 2°. Macedo et al. also investigated differences in ROM between the dominant and non-dominant side in healthy subjects. They observed several statistically significant differences between the limbs including the active hip ROM. As their maximum mean differences for all ROMs measured amounted to 7.5°, they concluded that although significant results were present, these differences may not be clinically relevant [34]. Based on the small effect size seen in hip extension in our control group, we can also assume that this deficit on the non-dominant side is not clinically meaningful. However, the 11° deficit in hip flexion on the operated side in our THA patients seems to be more relevant. When comparing the absolute values between the THA patients and the controls the deficit of the hip flexion in THA patients became more evident. We observed a significant difference of 19° between the operated leg and the non-dominant one. Significant absolute differences between THA patients and controls were also seen in the ROM of hip abduction. Abduction angles on the operated and the non-operated leg were reduced by 15° when compared to the non-dominant and dominant leg of the control group. These absolute differences may indicate a persisting deficit in hip ROM in THA patients four to five years after surgery. As severely reduced hip ROM is associated with functional performances, it cannot be ruled out that THA patients may also demonstrate limitations in this field.

The gait of THA patients has been extensively examined. Most studies show an improvement after the surgery, but the gait is not considered to reach the level of the healthy control subjects [16]. Our side-to-side analysis of spatio-temporal gait parameters indicated a symmetry of the operated and non-operated leg after THA, which is mostly in accordance with previous studies. Kiss et al. demonstrated that the pre-operatively existing significant different step lengths between the affected limb and the non-affected one recovered after twelve months post-THA [35]. Also, Rasch et al. could not find any persisting difference in the percentage of single support between the operated limb and the non-operated six months and two years after THA [10]. Only our findings in stance duration seem to contradict the study of Talis et al. and Bhargava et al. [36, 37]. They reported significant reduced stance time on the operated leg implying possible compensatory load shifting to the non-operated leg, which may still result from the years of restrictive posture and limited mobility before the surgery. The side-to-side analysis in our control group also did not show any significant differences in spatio-temporal gait parameters between the dominant and the non-dominant leg. Comparing the absolute values between the THA patients and the controls, no significant deficits on side of the THA patients were found. Four to five years after surgery, our THA patients presented symmetry concerning the spatio-temporal gait parameters between the operated and the non-operated leg and showed comparable values to the healthy control group.

The analysis of hip strength is one of the most important components of the examination of the functional status after THA. In our isometric maximum strength analysis, a significant between-limb asymmetry was found for hip abduction in the THA patients. An average deficit of 0.1 N m/kg (9%) was seen for the operated side. Similar to our results, Rasch et al. showed a remaining significant deficit of 15% in the hip abductors two years after THA. The other pre-operatively existing significant asymmetries in hip extension, hip adduction and hip flexion in this study had recovered within two years [10]. In the study of Trudelle-Jackson et al., THA patients showed reduced strength values in hip flexion, hip extension and hip abduction one year post-surgery. None of these reached statistical significance, though [28]. In the control group, a significant side-to-side difference was found for the hip adduction with an average deficit of 0.1 N m/kg (8%) on the non-dominant side. Side-to-side strength imbalances of the lower extremities have been reported to not only exist for injured athletes but also in asymptomatic healthy individuals [38–40]. The side differences of strength might differ for each joint and functional task as well as might be influenced by age [39]. For the side-to-side comparisons, the THA group and control group both demonstrated strength differences around 9%. The small effect sizes for these differences may indicate that the deficits on the operated leg or the non-dominant leg may not be great enough to reach clinical relevance. Nevertheless, symmetric strength relations in the hip muscles should always be pursued in order to avoid the overloading of one side.

The comparison of absolute strength values of the THA patients to the controls revealed that the THA patients have significantly reduced strength in hip flexion, extension, abduction and adduction. The differences were not only significant between the operated and the non-dominant leg but also between the non-operated and the dominant one, which implies that the THA patients were generally weaker than the controls. Similar results were reported in the study of Bertocci et al., in which four to five months after THA, patients generated significantly less peak torque in hip extension, flexion and abduction than the healthy control group [8]. Our study showed that the weakness of hip muscles in THA patients is still persistent even four to five years after surgery. The strength deficits in the THA patients may be a consequence of the physical inactivity due to pain and restricted hip ROM before the surgery and due to habitualness after the surgery.

Some limitations have to be addressed in our study. First, no data on the operation method was collected. Different operation approaches may be associated with different muscle and tissue damages [41], which might have had an influence on the results of our isometric maximum strength analysis and should be considered in future studies. In addition, when measuring the balance abilities of THA patients and controls, we should have not only assessed static balance but also dynamic balance in order to evaluate functional performance.

Our hypothesis that long-time THA patients will demonstrate side-to-side asymmetry in the investigated parameters for gait, balance, hip strength and hip ROM was not supported, as most parameters between the operated and non-operated side did not show significant differences. Exceptions were significant deficits on the operated side for the parameters COP length, hip abduction torque and ROM of hip flexion. The second hypothesis, however, that THA patients would have lower hip strength and hip ROM values than the age-matched controls was confirmed.

# Conclusions

Four to five years after THA, patients demonstrated quite symmetric relations for balance and gait parameters as well as for hip ROM and hip strength between the operated and non-operated side with three exceptions. Significant deficits with small to medium effects were found in the COP length of the single-leg stance, hip abduction torque and ROM of hip flexion on the operated side. The control group showed side-to-side symmetry except for significantly reduced adduction torque and ROM of hip extension on the non-dominant side. Highly significant, however, were the comparison of the absolute hip ROM and hip strength values between the THA patients and the controls indicating a persisting muscle weakness and limited ROM on side of the THA patients even four to five years after THA. Our results imply that the lateral differences between the operated and the non-operated side in THA patients are not as severe as the general hip strength and ROM deficit compared to controls. Therefore, postoperative training should be continued for months to years after the surgery targeting all hip muscles and hip ROMs.

# Abbreviations

THA: Total hip arthroplasty, OA: Osteoarthritis, ROM: Range of motion, COP: Center of pressure, SD: Standard deviation, AP: Antero-posterior, ML: Medio-lateral

# Declarations

## Ethics approval and consent to participate

All participants were informed orally and in writing before giving their written informed consent to participate. All participants could withdraw from the study at any time without giving a reason. The study was approved by the local ethics committee of the Otto-von-Guericke-University Magdeburg presided by Dr. med. Norbert Beck (no. of vote: 155/18 on December 3, 2018) and carried out in line with the Declaration of Helsinki.

## Consent for publication

Not applicable.

## Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Competing interests

The authors declare that they have no competing interests.


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None of the authors received any funding for this study.


## Authors' contributions

The idea for this research was prompted by KW. SJ conceived of the study, performed the measurements, analyzed the data and drafted the manuscript. DW contributed to data analysis, helped conducting the measurements and revised the manuscript critically. AH and AF were involved in performing the measurements. KO and KM provided the software for data recording, contributed to data analysis and revised the manuscript. JEN and KW critically reviewed the manuscript. All authors read and approved the final version of the manuscript, and agree with the order of the presentation of the authors.


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# Figures

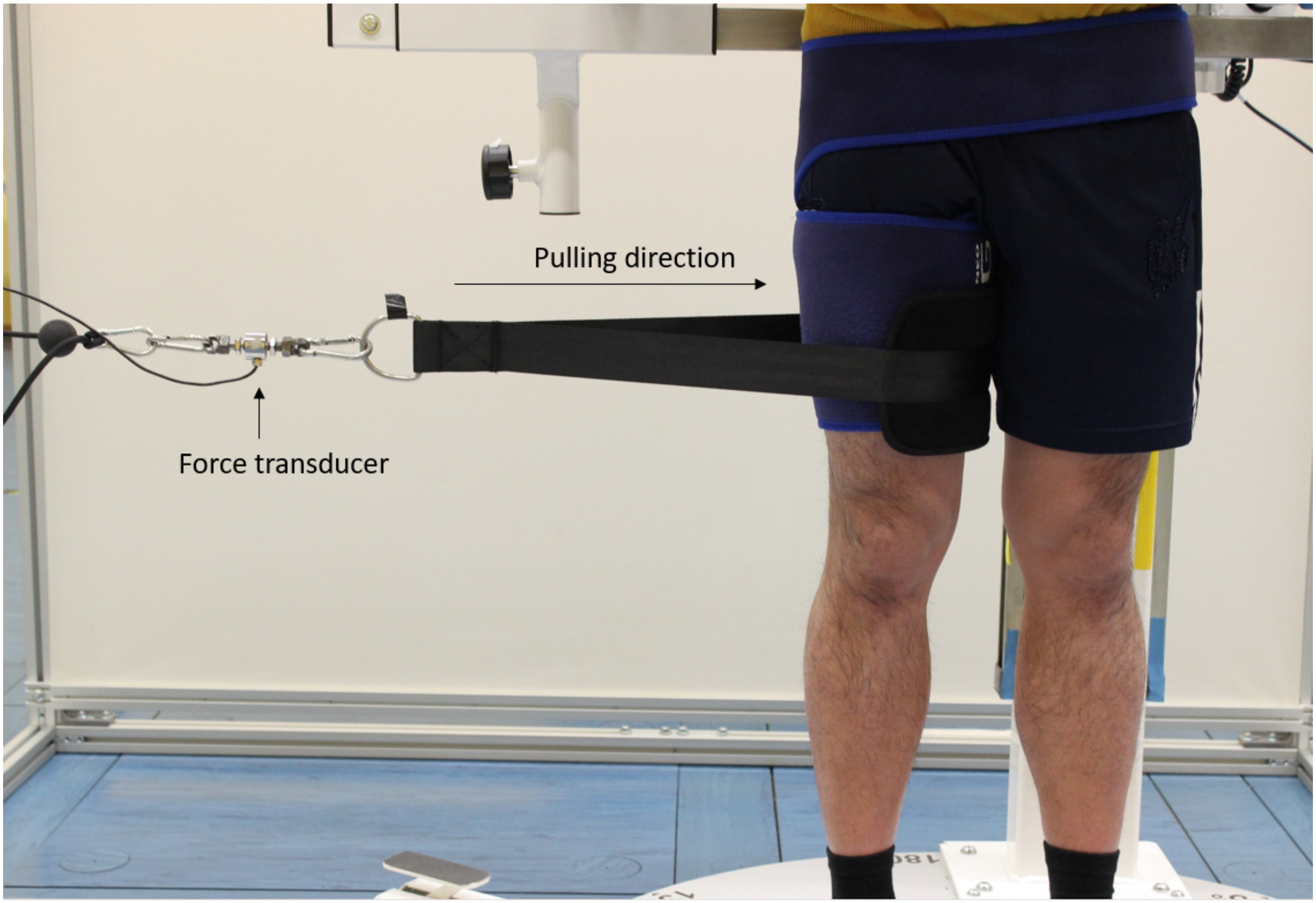


**Figure 1**

Set-up for measuring the maximum isometric strength in hip adduction