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# Lower limb biomechanics during gait do not return to normal following total hip arthroplasty

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ABSTRACT

Although total hip arthroplasty (THA) is known to be a successful surgical procedure to alleviate hip pain and to improve health-related quality of life, these outcome measures in THA patients do not reach those of the general population. As a result, several investigators have assessed THA patients' gait mechanics, but most of them have ignored adjacent joints, as well as the effect that THA may have on the non-operated limb. The purpose of this investigation was to determine the effect of THA on the pelvis, hip, knee and ankle joint kinematics, as well as the hip, knee and ankle kinetics of both the operated and non-operated limbs during walking. These data were recorded for 20 patients having undergone unilateral THA and 20 healthy, matched control participants. Results revealed that the gait mechanics of THA patients did not return to normal 10.6 months, on average (±2.6 mo), following surgery. THA patients walked with lower operated-hip abduction moments, sagittal-plane range of motion, as well as lower generated and absorbed power, that may be consequential to pain-avoidance strategies adopted pre-operatively or to apprehensions associated with their new prosthesis. They also displayed various kinematic adaptations at the ankle joint of the operated limb and at the non-operated hip joint that may be leaving them at risk of developing other joint diseases. Further investigation is needed to confirm the reasons why THA patients' gait mechanics do not return to normal following surgery to develop better surgical techniques and/or rehabilitation programs.



## 1. Introduction

Total hip arthroplasty (THA) is known to be a successful joint replacement procedure given that most patients experience significant pain alleviation, as well as an improvement in their health-related quality of life [1,2]. The literature reveals, however, that despite these post-operative improvements, the level of pain and the quality of life of these patients undergoing THA do not reach those of the general population [1–3]. In addition, more than 25% of these individuals are not able to return to sports, in which they participated pre-surgery, due to the joint arthroplasty [4]. And a return to recreational activities is a valued expectation among this population [5] that has a positive impact on their quality of life post-surgery [6].

These discrepancies in pain and quality of life between THA patients and the general population may stem from a weakness of the hip musculature, especially of the hip abductors and extensors, that may increase their risk of injury and jeopardise the longevity of the implant due to higher interfacial stresses [7]. In fact, several researchers have hypothesised that such muscle weakness is responsible for gait adaptations that have been found to be present following THA [8–10]. In comparison with healthy individuals, THA patients generally exhibit lower hip adduction and extension angles, and thus generate lower hip abduction and extension moments of force during level walking [8,10–13]. Although many researchers have performed gait analyses on THA patients post-operatively, most studies have ignored adjacent joints that are essential parts of the kinetic chain without performing a complete biomechanical analysis and without evaluating the effect of THA on the non-operated limb [8,10,14]. By completing such a thorough analysis, we might gain a better understanding of the source(s) of these patients' deficiencies, which could be subsequently targeted during rehabilitation and result in improved patient function and greater patient satisfaction during daily and athletic activities. Such an analysis may also elucidate potential debilitative effects of THA on adjacent joints of the operated limb and/or joints of the non-operated limb. Consequently, the purpose of this study was to determine the effect of THA on mobility by comparing hip, knee

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and ankle joint angles, moments and powers of both the operated and non-operated limbs, as well as pelvic angles, during level walking of THA patients with those of healthy, matched control participants.

## 2. Materials and methods

### 2.1. Participants

Twenty THA patients (10 women, 10 men; age: 66.2 ± 6.7 yr; BMI: 27.2 ± 5 kg/m$^2$) and 20 healthy control participants (10 women, 10 men; age: 63.5 ± 4.4 yr; BMI: 24.9 ± 3.5 kg/m$^2$), matched for gender, age ($p = 0.142$) and BMI ($p = 0.092$) were recruited on a voluntary basis. THA patients were excluded from the study if they had undergone hip replacement surgery for the contralateral hip joint, hip replacement due to an infection, a fracture or a failure of a previous prosthesis or hip replacement during which a concomitant surgical procedure was performed. Potential participants were also excluded if they suffered from any former or current condition that could alter their gait (e.g., stroke) or serious lower limb injury or disease (with the exception of the hip implant for the experimental group). All of the THA patients were operated by one of three surgeons who all used a lateral approach, splitting the anterior third and posterior two-thirds of the abductors which were repaired. All patients received a cementless press fit implant (Stryker, Allendale, NJ; or Wright Medical Technologies, Memphis, TN) and followed the same post-operative rehabilitation programs involving core and lower extremity strengthening. They were subsequently tested between 6 and 15 months post-operatively. Informed written consent, approved by the institutions' research ethics boards, was obtained from each participant prior to their involvement in the study.

### 2.2. Instrumentation

A nine-camera digital optical motion capture system (Vicon MX, Oxford, UK) was used to capture, at 200 Hz, 45 spherical retro-reflective markers placed on various landmarks of the participants, according to a modified Plug-in Gait (PiG) marker set (Vicon, Oxford, UK) [15], as they executed the various walking trials. Furthermore, a force platform (AMTI, Model ORC-6-2000, Watertown, MA, USA) was used to record, at 1000 Hz, ground reaction forces during the stance phase of the gait cycle. This force-measuring device was embedded in the floor to create a level walking surface.

### 2.3. Protocol

After the participants changed into a tight-fitting pair of shorts and short-sleeve shirt, retro-reflective markers were affixed to the participants and several anthropometric measurements were obtained. Subsequently, a static trial was recorded, during which the participants stood in a neutral position, with their feet shoulder-width apart, toes pointing anteriorly and hip and knee joints in full extension (but not hyper-extended). This static trial was used to determine neutral pelvis, hip, knee and ankle angles.

To be able to record the participants' natural gait, the participants performed several practice walking trials, for which they were instructed to walk across a walkway at a natural, self-selected speed and refrain from looking down in order to avoid targeting of the force platform. Each participant performed six successful walking trials with their own flat shoes (no heel), three trials with their left foot and three with their right foot landing on the force platform. Walking trials during which the participant altered his/her gait to make contact with the force platform were discarded.

### 2.4. Data processing and analysis

Kinematic and kinetic data of each participant were analysed for six gait cycles. The beginning of the gait cycle was defined by the event of foot strike (FS) on the force platform. The end of the cycle was defined by the following strike of the same foot with the ground.

The raw three-dimensional (3D) marker trajectories were filtered using a Woltring filter (predicted mean square error value of 15 mm$^2$) [16], whereas a low pass Butterworth filter (cut-off frequency of 6 Hz) was applied to the ground reaction forces. From the filtered 3D marker trajectories, a kinematic model consisting of the pelvis, thigh, shank and foot segments was previously described [17]. Modifications to the conventional PiG model included the addition of markers on the medial femoral epicondyles and the medial malleoli to define the knee and ankle joint centres, respectively. These joint centres were defined as the mid-point between the medial and lateral markers at each joint. Rotations of the pelvis segment were calculated relative to the global coordinate system. The rotations at the hip, knee and ankle joints were expressed as the orientation of the proximal segment in relation to the distal segment and were defined by means of the Euler angle convention. All joint angles were expressed relative to each participant's neutral standing position. Hip, knee and ankle moments and powers were calculated by means of a conventional inverse dynamics analysis [18].

The peak and range of the joint angles during the gait cycle were extracted as variables of interest in the sagittal, frontal and transverse planes for the pelvis segment and the hip joint and in the sagittal plane for the knee and ankle joints. In addition, peak joint kinetics during the stance phase of the cycle were extracted in all three planes for the hip joint and in the sagittal plane for the knee and ankle joints. The variables acquired from the three trials during which the operated limb of the THA patients (THA-O) landed on the force platform were averaged and compared to the average of the variables extracted from the six trials (three left limb; three right limb) performed by the control group. The variables acquired from the three trials performed with the non-operated limb of the THA patients (THA-NO) were also compared to those of the control participants. Furthermore, several spatio-temporal parameters were extracted and compared between groups: cadence, stride length and walking speed.

### 2.5. Statistical analysis

A series of one-way ANOVAs were executed to determine the presence of significant differences between the THA-O and control groups, as well as between the THA-NO and control groups, with regard to the 3D pelvis kinematic variables, the 3D hip, knee and ankle kinematic and kinetic variables and the spatio-temporal parameters. Given that multiple comparisons were made between the groups of interest, the alpha values used to determine statistical significance were adjusted accordingly, by means of a Bonferroni correction. For the kinematic variables, the alpha value was adjusted to 0.0167 ($p < 0.05/3$) because three comparisons were made in each plane (minimum value, maximum value, range of motion). For the kinetic variables, the alpha value was adjusted to 0.025 ($p < 0.05/2$) because two comparisons were made in each plane (minimum value, maximum value).

With regard to the spatio-temporal parameters, it was found that the THA patients walked significantly slower (THA: 1.1 ± 0.2 m/s; Controls: 1.3 ± 0.2 m/s; $p = 0.016$) due to a shorter stride length (THA: 1.3 ± 0.2 m; Controls: 1.5 ± 0.1 m; $p = 0.005$). Consequently, a series of one-way ANCOVAs, with walking speed and stride length as covariates, were performed to eliminate any effect these spatio-temporal variables may have had on the kinematic and kinetic dependant variables. Only the results of the ANCOVAs are presented below.

## 3. Results

Results from the one-way ANCOVAs revealed no significant differences between the THA patients (i.e., THA-O and THA-NO) and the control participants in the kinematics of the pelvis and the knee joint ($p > 0.0167$) and in the kinetics of the knee joint ($p > 0.025$) during level walking.

With regard to the operated hip of the THA patients, the THA group displayed a significantly lower peak flexion angle, peak extension angle, total sagittal-plane range of motion (ROM), peak adduction angle and peak external rotation angle, in comparison with the control group. The THA group also produced lower peak operated-hip abduction and external rotation moments. Peak power generated and absorbed was also found to be smaller at the operated hip of the THA patients in comparison with the control participants. The sagittal-plane hip angles for the operated limb and the non-operated limb of the THA patients, as well as those of the average of both limbs of the control participants, are depicted in Fig. 1; whereas the frontal-plane hip angles and moments for the same populations are depicted in Fig. 2. With regard to the non-operated hip of the THA patients, the THA group executed the level walking trials with a smaller peak adduction angle than the control group (Fig. 2). At the ankle joint of the operated lower limb, the THA group walked on the level surface with a smaller peak dorsiflexion angle in comparison to the control group. None of the other hip and ankle joint kinematic and kinetic variables were found to differ between the groups.

The means and standard deviations of the variables found to be statistically significant between both the operated and non-operated lower limbs of the THA patients and the control participants are presented in Table 1.

## 4. Discussion

The present investigation examined the effect of unilateral total hip arthroplasty on the mechanics of both the operated and non-operated lower limb joints during level walking at a natural, self-selected speed. It was found that the THA patients' gait mechanics

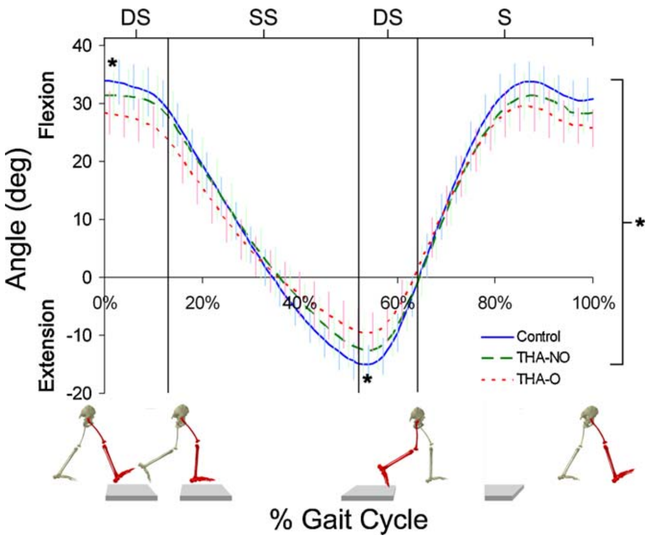


**Fig. 1.** Average (and standard deviation represented by vertical lines) hip angles in the sagittal plane during level walking, time-normalised to the gait cycle. The asterisks (*) represent statistically significant differences between the THA-O and control groups. DS = double-limb stance; SS = single-limb stance; S = swing phase.

did not return to normal following surgery, even after taking into account the slower speed at which the THA patients executed the walking trials.

Our study confirmed the findings of several published investigations [8,10,19] that, following surgery, THA patients produce a smaller operated-hip abduction moment while this hip is in a less adducted position, in comparison with healthy individuals, as most of the body weight shifts on the operated hip (Fig. 2). By placing their hip in this less adducted position, THA patients required a smaller hip abduction moment to counteract an opposing moment produced by their centre of mass, and to thus stabilise their pelvis in the frontal plane. It has been speculated that this altered gait pattern results from a weakness of the hip abductors [8,9]. Given that muscle strength at the hip was not measured in the present study, we cannot confirm this plausible speculation. We can provide further hypothetical explanation, however, for the measured frontal-plane deficiencies at the

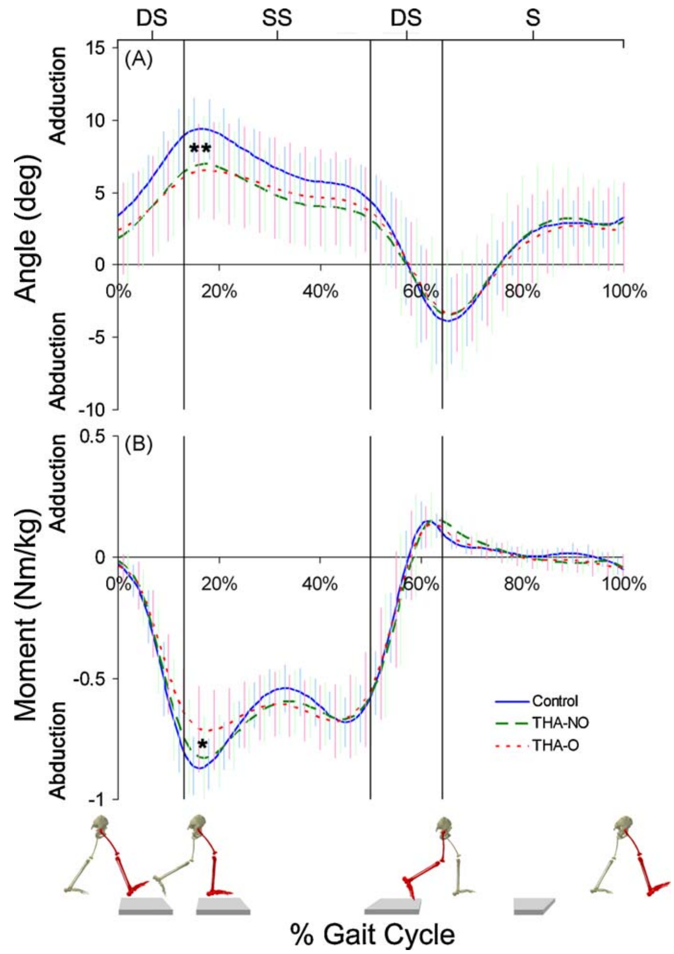


**Fig. 2.** Average (and standard deviation represented by vertical lines) (A) hip angles and (B) hip moments of force in the frontal plane during level walking, time-normalised to the gait cycle. The single asterisk (*) represents statistically significant differences between the THA-O and control groups; the double asterisks (**) represent statistically significant differences between the THA-O and control groups, as well as between the THA-NO and control groups. DS = double-limb stance; SS = single-limb stance; S = swing phase.

**Table 1**
Means (standard deviations) of the pelvis, hip, knee and ankle kinematic and kinetic variables found to be statistically significant between the THA patients and the control participants. The time (as a percentage of the gait cycle) at which each variable occurred can also be found in the following table.

| Joint | Variable | Group | | Timing† (% of gait cycle) | ANCOVA *p*-value |
|---|---|---|---|---|---|
| | | THA | Control | | |
| THA-O vs. Control | | | | | |
| Angle (°) | | | | | |
| Hip | Peak flexion | 28.4 (3.7) | 33.9 (4.1) | 0% | 0.002 |
| Hip | Peak extension | −10.1 (3.4) | −15.1 (3.4) | 54% | 0.001 |
| Hip | Flexion/Extension ROM | 40.7 (5.2) | 51.0 (3.7) | N/A | 0.000 |
| Hip | Peak adduction | 7.6 (2.5) | 9.8 (2.2) | 17% | 0.007 |
| Hip | Peak external rotation | 0.6 (3.6) | −3.5 (3.4) | 64% | 0.004 |
| Ankle | Peak dorsiflexion | 14.1 (3.1) | 10.3 (2.8) | 48% | 0.005 |
| Moment of force (Nm/kg) | | | | | |
| Hip | Peak abduction | −0.76 (0.15) | −0.90 (0.11) | 17% | 0.025 |
| Hip | Peak external rotation | −0.12 (0.06) | −0.16 (0.04) | 46% | 0.020 |
| Power (W/kg) | | | | | |
| Hip | Peak generation | 1.17 (0.41) | 1.57 (0.34) | 59% | 0.000 |
| Hip | Peak absorption | −0.44 (0.22) | −0.62 (0.19) | 44% | 0.006 |
| THA-NO vs. Control | | | | | |
| Angle (°) | | | | | |
| Hip | Peak adduction | 7.4 (3.1) | 9.8 (2.2) | 17% | 0.005 |

ROM: Range of motion; THA-O: operated limb of the THA patients; THA-NO: non-operated limb of the THA patients.
† Represents an approximate value given that the peak values did not necessarily occur at the same instant in time for all participants.

operated hip joint. These may be a result of disuse atrophy of the hip abductors developed pre-operatively as a result of adopted gait patterns that limited their contraction in order to reduce hip loading, and thus reduce pain. In fact, researchers have found lower hip abductor strength in patients pre-operatively, in comparison with control participants [20], although this strength measurement may be questionable given that most THA candidates experience hip pain [21], which may limit their ability to maximally contract their hip abductors. Conversely, Foucher et al. [8] found that post-surgery hip abduction moments were not correlated with pre-surgery moments in THA patients performing the task of walking. Hence, pre-surgery muscle atrophy cannot be entirely responsible for the lower hip abduction moments measured post-surgery in THA patients. Instead, deficiencies in hip abduction may be an effect of surgery seeing that the lateral surgical approach to THA involves the detachment (and repair) of the anterior third of the gluteus medius. Yet, hip abductor deficiencies during level walking were found to be present in a group of THA patients even though the majority of these patients had surgery by means of the posterior approach–an approach that leaves the hip abductors intact [8]. It seems, therefore, that these muscular deficiencies cannot be due entirely to the surgical procedure. We therefore suggest, that the deficiency observed in hip abduction mechanics of the THA patients may be a result of both these occurrences. Consequently, further investigation is needed to confirm the cause of the deviations in hip adduction motion and hip abduction moments from those of the control group. If indeed these are due to weakness of the musculature surrounding the operated hip joint, it should be addressed pre- and post-operatively, as such a weakness may reduce the protection of the surface on which the implant is affixed, especially during activities that are more demanding than level walking, and thus may be detrimental to implant fixation and longevity.

Interestingly, most statistically significant differences found between the THA and control groups with regard to the sagittal-plane kinematic and kinetic variables of interest occurred simultaneously during the gait cycle. These group differences were found to occur in proximity to the transition from single- to double-limb stance (i.e., near foot strike of the contralateral limb). In agreement with the literature [10,22], the THA patients walked with a smaller hip ROM of the operated limb regardless of their reduced stride length and walking speed, in comparison with the control participants (Fig. 1). At this same point in time, this group also displayed a greater peak ankle dorsiflexion angle, which has been suggested to act as a shock absorbing motion to reduce the loading response during walking [19]. Hence, the THA group may have been displaying persisting pain-avoidance strategies adopted pre-operatively, especially at the operated hip joint. To avoid hip pain pre-surgery, they may have reduced contraction of muscles spanning the hip joint. Such a strategy can cause muscle tightness (e.g., hip flexors contracture) [23] and/or muscle weakness from disuse muscle atrophy. Consequently, the sagittal-plane deviations from normal measured in the THA patients of the present study may be attributed to persisting muscle contractures and/or muscle weakness. On the other hand, they may have adopted this strategy post-operatively due to apprehensions associated with their new prosthesis. As a result of these mechanical impairments at the operated hip joint in the sagittal plane, as well as those in the frontal plane, lower peak resultant powers generated and absorbed were found in the THA group than the control group.

Furthermore, gait adaptations to THA were also found at the non-operated hip. As with the operated hip, the THA patients transitioned from single- to double-limb support with a less adducted hip, in comparison with healthy individuals (Fig. 2). These deviations from normal gait mechanics may lead to other joint disorders requiring arthroplasty [24]. Consequently, if indeed these modified gait mechanics adopted by THA patients lead to other joint disorders, it is imperative that the cause of these gait adaptations are further investigated and thus addressed in terms of better surgical techniques and/or rehabilitation programs.

It should be noted that the interpretation of our results is limited by the fact that pre-operative fitness, strength and gait mechanics data were not collected. Despite our ability to match our groups for age, gender and BMI, they may not have been matched in terms of the above-mentioned variables pre-surgery. If such differences were indeed present pre-surgery, differences in post-operative gait mechanics may be attributed to these [25] as oppose to the surgical procedure itself. Consequently, a pre-operative assessment, including gait analysis, may have revealed the origin of some of the gait adaptations found to be present in the THA group. Furthermore, a comparison of the presented data with those from THA patients for which an anterior approach to surgery was used would potentially elucidate the origin of the hip abductor weakness exhibited by the THA patients. This is being currently addressed in an ongoing study that is focusing on the role of different surgical approaches. Another limitation of our study was the large post-surgery time interval during which the THA patients were assessed (6–15 months post-surgery). This large interval may have added variability to this experimental group's data, thus masking group differences that would have been present otherwise.

## 5. Conclusion

Consequently, the results of the present study revealed that the gait mechanics of patients walking on a level surface did not return to normal following total hip arthroplasty, notably at the operated hip joint. These deviations from the control group may be consequential to pain-avoidance strategies adopted pre-operatively or to apprehensions associated with their new prosthesis. Moreover, gait kinematics at the ankle joint of the operated limb, as well as those of the non-operated hip joint, were also affected. Further investigation is needed to confirm the reasons why THA patients' gait mechanics do not return to normal following surgery, especially if patients want to return to activities that are more demanding than level walking. By elucidating these causes, better surgical techniques and/or rehabilitation programs may be developed to address them, and thus improve post-operative patient function.

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## Conflict of interest statement

The authors have no conflicts of interest to disclose.

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