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Exploring pelvis and thigh movement and coordination patterns during walking in patients after total hip arthroplasty

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ABSTRACT

Background: Patients after total hip arthroplasty (THA) have altered hip kinematics compared to healthy controls, specifically hip extension and range of motion are lower. Exploring pelvis-thigh coordination patterns and coordination variability may help to elucidate why differences in hip kinematics are evident in patients following THA.
Research Question: Do sagittal plane hip, pelvis and thigh kinematics, and pelvis-thigh movement coordination and coordination variability differ between patients following THA and healthy controls during walking?
Methods: Sagittal plane hip, pelvis and thigh kinematics were collected using a three-dimensional motion capture system while 10 patients who had undergone THA and 10 controls walked at a self-selected pace. A modified vector coding technique was used to quantify pelvis-thigh coordination and coordination variability patterns. Peak hip, pelvis and thigh kinematics and ranges of motion, and movement coordination and coordination variability patterns were quantified and compared between groups.
Results: Patients after THA have significantly ($p \leq .036$; $g \geq 0.995$) smaller peak hip extension and range of motion, and peak thigh anterior tilt and range of motion compared to controls. Additionally, patients following THA have significantly ($p \leq .037$; $g \geq 0.646$) more in-phase distally and less anti-phase distally dominated pelvis-thigh movement coordination patterns compared to controls.
Significance: The smaller peak hip extension and range of motion displayed by patients following THA is due to smaller peak anterior tilt of the thigh, which in turn limits thigh range of motion. The lower sagittal plane thigh, and in turn hip, motion used by patients after THA may be due to increases in the in-phase coordination of pelvis-thigh motion patterns, which cause the pelvis and thigh to work as a singular functional unit.

1. Introduction

Total hip arthroplasty (THA) is a common surgical technique, with 435,533 primary operations performed within England and Wales alone between 2017 and 2021 [1] Osteoarthritis is the primary reason for THA in 90 % of cases [1]. THA is considered a very successful operation from a clinical perspective [2]. However, a considerable number of patients (8.1 %) are dissatisfied post-operatively, in part due to limited functional recovery [3].

Studies [4–9] have revealed that while lower limb kinematics improve following THA, patients do not achieve normative movement patterns. Specifically, patients following THA have significantly smaller sagittal and frontal plane range of motion (RoM) at the hip, primarily due to lower peak extension and adduction [4–9]. The significant smaller peak hip extension is likely a contributing factor to the decreased stride lengths and walking velocities used by patients following THA [4,9].

While the influence of THA upon hip joint kinematics during walking has been widely researched, walking requires the coordination of various segmental movements [10]. Dynamical systems techniques, such as modified vector coding, provide a means of quantifying movement coordination patterns and variability, by exploring the relative

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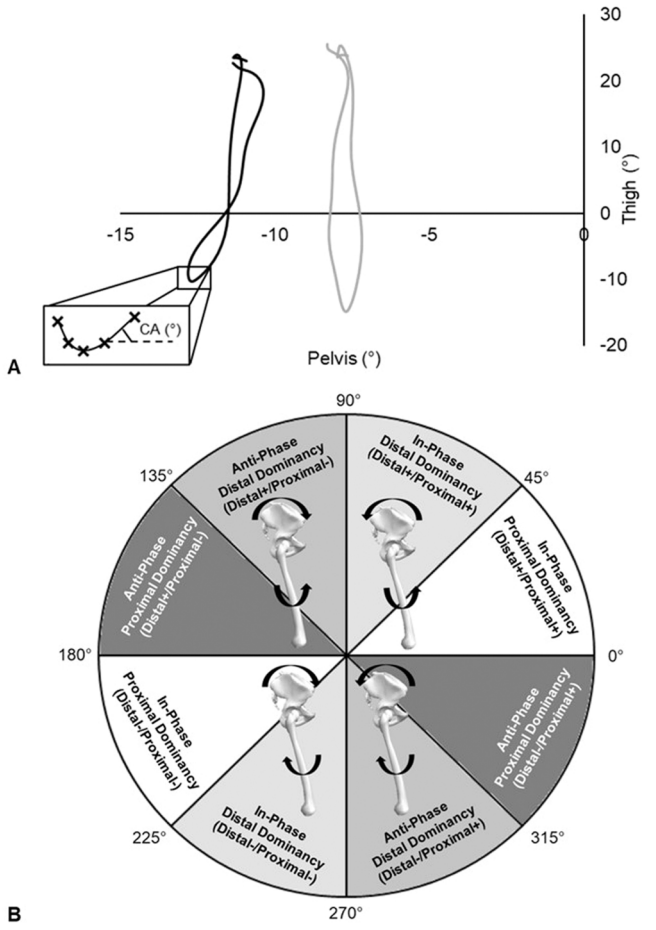

Fig. 1. (A) Angle-angle diagram of group mean pelvis-thigh coordination over the walking GC for healthy controls (grey line) and patients after THA (black line), with a visual representation of the coupling angle (CA) depicted. (B) Coordination pattern classification, using the terminology of Needham et al., [22], based upon coupling angle values, with visual representations of the respective segmental motions superimposed over relevant quadrants of the polar plot.

Table 1
Descriptive characteristics and spatiotemporal parameters (mean (SD)) for the health control and THA groups, respectively.

	Healthy	THA	*p*	Hedge's *g*
Age (years)	65 (6)	70 (6)	.112	-0.717
Height (m)	1.68 (0.09)	1.65 (0.13)	.644	0.201
Mass (kg)	80 (14)	79 (21)	.892	0.059
Body Mass Index (kg/m^2)	28.3 (3.7)	28.6 (5.2)	.903	-0.053
Sex (M:F)	6:4	7:3	-	-
Walking Velocity (m/s)	1.43 (0.15)	1.25 (0.31)	.118	0.716
Stride Length (m)	1.38 (0.14)	1.22 (0.24)	.077	0.805
Stride Frequency (stride/s)	1.04 (0.08)	1.02 (0.11)	.709	0.163

motion of adjoining segments [11]. Specifically, modified vector coding enables movement patterns to be classified as in- or anti-phase, which refers to the proximal and distal segments moving in the same or opposing directions respectively, and whether the movement is proximally or distally dominated [11]. Furthermore, dynamical systems theory suggests that variability within a movement coordination pattern is important to facilitate successful task completion [12]. Theoretically, both excessive and limited movement coordination variability, which are linked to poorly controlled or overly stable movement patterns, respectively, have been suggested to negatively influence injury risk and/or performance outcomes [13].

Within a clinical setting the assessment of movement coordination patterns and variability would help to elucidate differences in neuromuscular control strategies, and the stability of these, between healthy and patient populations, aiding clinical decision making and (p)rehabilitation programme design [10,11]. Application of the modified vector coding technique to explore the coordination of pelvis and thigh motion may offer valuable insights into whether alterations in movement control may help to explain the smaller sagittal plane hip kinematics displayed by patients following THA. Previous work [14] has demonstrated that patients with hip osteoarthritis use more in-phase and less distal-phase movement coordination patterns when exploring the pelvis-thigh couple in the sagittal plane, compared to healthy controls. Additionally, the variability in the coordination of the pelvis-thigh movement coupling was greater for patients with hip osteoarthritis compared to controls. Greater reliance on in-phase movement coordination has been linked to more rigid movement patterns, which may be due to mechanical restriction or pain avoidance to reduce the loading upon tissues around the joint [13,15,16]. While the increased movement coordination variability maybe the result of joint instability or pain avoidance [16]. Understanding whether these alterations in pelvis-thigh movement coordination patterns and variability are still evident in patients following THA would help further our understanding of the mechanisms responsible for the abnormal hip kinematics displayed by this group. While previous studies [10,17] have demonstrated altered inter-joint (hip-knee and knee-ankle) coordination patterns in patients following THA when compared to healthy controls, no work to our knowledge has explored pelvis-thigh coordination in this population. As such the aim of this pilot study was to compare sagittal plane hip, pelvis and thigh kinematics, and pelvis-thigh movement coordination and coordination variability between patients after THA and healthy controls during walking. The hypotheses associated with the study were that patients after THA would display reduced (1) hip, (2) pelvis and (3) thigh movement, increased in-phase distally dominant pelvis-thigh coordination (4) and increased coordination variability relative to the healthy control group.

2. Methods

2.1. Participants

A priori sample size calculations undertaken within G*Power [18] using hip extension and sagittal plane RoM data from Varin et al. [5] and Beaulieau et al., [7] revealed that 8 – 9 participants per group were required to achieve 80 % statistical power, with an alpha level of 0.05. As such 10 patients following THA and 10 healthy controls were recruited for this study. Patients had undergone a unilateral THA due to osteoarthritis, performed using a posterior surgical approach, at least 1 year prior to recruitment (mean ± standard deviation time post-operative; 21 ± 16 months [minimum; 12 months, maximum; 62 months]), and were required to have a body mass index < 40 kg/m^2, no other known pathologies, arthroplasty or neurological conditions which may influence gait, and the ability to walk 10 m unaided to meet the inclusion criteria for the study. On average, patients following THA reported excellent Oxford Hip Scores (mean ± standard deviation; 46 ± 3). Inclusion criteria for the control group were that the participants had no known musculoskeletal or neurological conditions which may influence gait. Ethical approval for the study was granted by the National Health Research Authority (17/LO/1584) and all participants provided written informed consent prior to testing.

2.2. Procedures

Participants attended a single testing session, in which they were asked to walk along a 7 m walkway at a self-selected velocity until five valid trials were recorded, in line with previous work exploring movement coordination and coordination variability [11]. Valid trials were

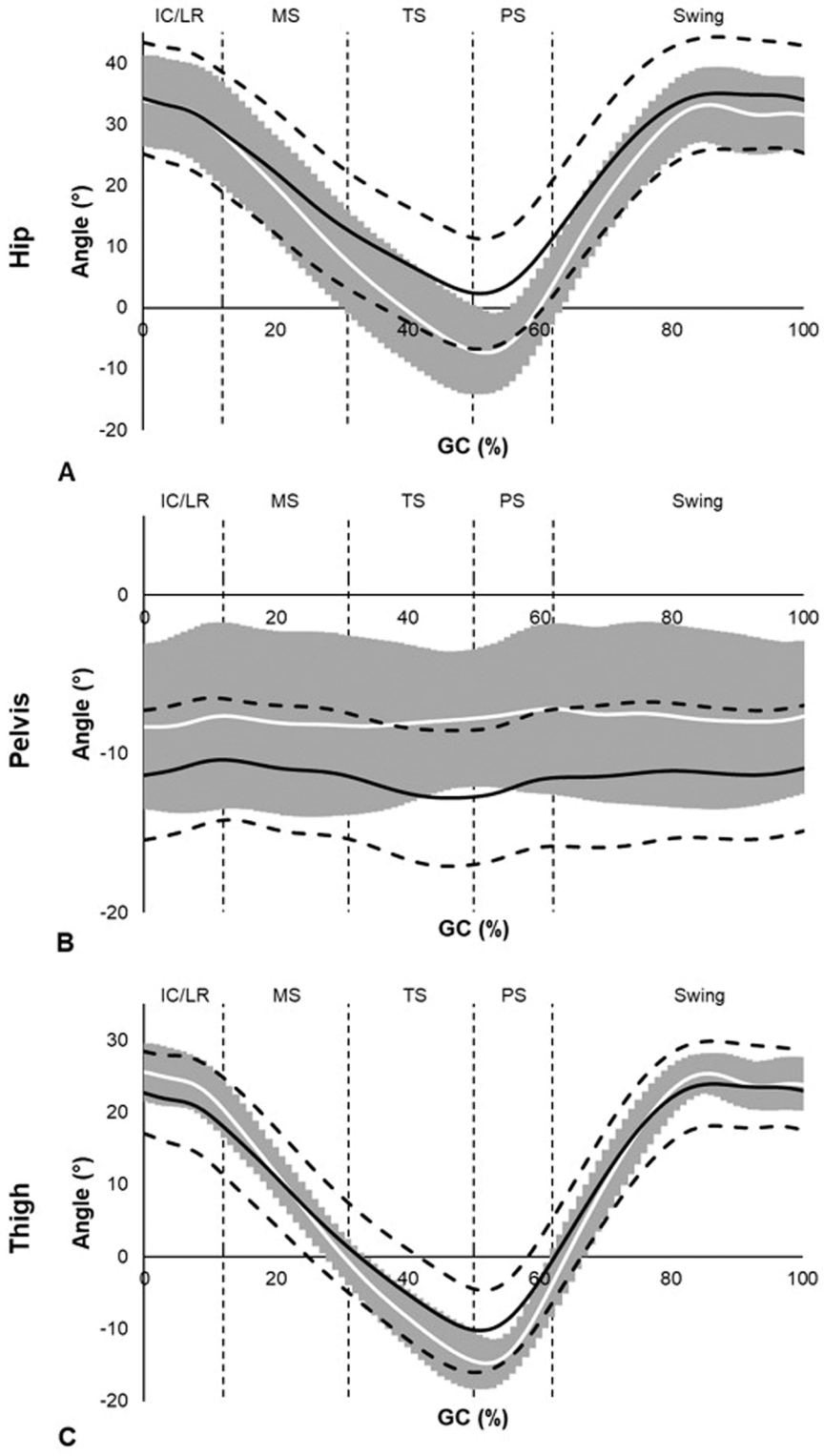

Fig. 2. Sagittal plane (A) hip, (B) pelvis and (C) thigh motion over the walking GC for healthy controls (mean = solid white line; SD = shaded grey region) and patients after THA (mean = solid black line; SD = dashed black lines), with subphases of the walking gait cycle identified by dashed vertical lines. IC/LR = Initial Contact & Loading Response; MS = Midstance; TS = Terminal Stance; PS = Pre-Swing.

defined as a trial in which participants made contact with one or both of the force plates with the relevant foot, defined as the operated limb for patients following THA or an arbitrarily selected limb for controls, without noticeable deviations in their movement pattern. Prior to the experimental trials participants completed five familiarisation trials to become accustomed to walking within the laboratory environment. Walking velocity was monitored during both familiarisation and experimental trials using timing gates (SmartSpeed, Fusion Sport, Brisbane, Australia), and only trials that were within 5 % of the participants mean walking velocity from the familiarisation trials were accepted during data processing. A 10-camera motion capture system (Oqus 3 +, Qualisys, Gothenburg, Sweden) and two synchronised force plates

Table 2
Discrete parameters (mean (SD)) associated with hip, pelvis and thigh kinematics over the walking gait cycle for healthy control and THA patients. Significant differences are identified in bold font.

		Healthy	THA	*p*	Hedge's *g*
Hip	Peak Flexion (°)	35.3 (6.7)	35.7 (9.2)	.893	-0.580
	Peak Extension (°)	**-7.8 (6.2)**	**1.9 (8.8)**	**.011**	**-1.268**
	Range of Motion (°)	**43.0 (4.7)**	**33.9 (5.3)**	**< .001**	**1.753**
Pelvis	Peak Posterior Tilt (°)	-6.4 (4.8)	-9.9 (3.8)	.087	0.776
	Peak Anterior Tilt (°)	-9.3 (5.4)	-13.1 (4.2)	.097	0.750
	Range of Motion (°)	3.0 (0.8)	3.2 (1.4)	.656	-0.194
Thigh	Peak Posterior Tilt (°)	26.8 (3.0)	24.5 (6.0)	.304	0.453
	Peak Anterior Tilt (°)	**-15.3 (2.9)**	**-10.7 (5.6)**	**.036**[†]	**-0.995**
	Range of Motion (°)	**42.1 (4.4)**	**35.2 (4.9)**	**.004**	**1.425**

[†]denotes p value from Mann-Whitney U test; positive values denote a flexed position at the hip and posteriorly tilted positions at the pelvis and thigh, with negative values denoting hip extension and anterior tilt of the pelvis and thigh

(Kistler, Winterthur, Switzerland), sampling at 200 Hz and 2000 Hz respectively, recorded kinematic and kinetic data. Prior to the walking trials a short static trial was recorded where participants stood in a relaxed position to enable the relevant segmental co-ordinate systems to be calculated.

A 6-degrees of freedom model, described in detail in Langley et al., [19], was used to define the pelvis, thighs, shanks and feet. The pelvis was defined and tracked by nine-millimetre diameter retro-reflective markers attached to the anterior and posterior iliac spines. The thigh was defined by the hip joint centre proximally, which was calculated using regression equations developed by Bell et al. [20], and the medial and lateral femoral epicondyles distally. The thigh was tracked during dynamic trials using 4 non-colinear markers attached to a rigid plastic shell and secured to the posterior-lateral aspect of the segment using elasticated wrapping. Segmental coordinate systems were oriented as follows; x = medial-lateral, y = anterior-posterior and z = vertical.

2.3. Data processing

Marker trajectories were reconstructed, labelled and gaps of up to 10 frames were filled using a polynomial fill within Qualisys Track Manager (Version 2.18.1, Qualisys, Gothenburg, Sweden). Processed trials were exported to Visual 3D (v2021.09.1, C-Motion, Germantown, MD, USA). Hip joint angles and the orientation of the pelvis and thigh segments relative to the global coordinate system were calculated using an XYZ cardan sequence of rotations. Kinematic data were filtered using a 6 Hz Butterworth low pass filter and time normalised to 100 % gait cycle (GC) duration. GC events were calculated using the automatic gait events option within Visual 3D, with the first initial contact and toe off identified using a 10 N threshold applied to the vertical ground reaction force data, and the subsequent initial contact identified based upon the trajectory of the relevant foot segment [21]. Additionally, the GC was divided in to subphases in accordance with Needham et al., [11]; initial contact and loading response (0 – 12 % GC), midstance (13–31 % GC), terminal stance (32 – 50 % GC), pre-swing (51 – 62 % GC) and swing (63 – 100 % GC).

The modified vector coding technique described by Needham et al., [11] was used to calculate the coupling angle and coupling angle variability, based upon the motion of the pelvis and thigh segments in the sagittal plane. Briefly, for each participant coupling angles were calculated at each instance (i) of the normalised gait cycle using Eq. 1, for each trial.

$$Coupling \quad angle = \tan^{-1}\left(\frac{\theta_{thigh(i+1)} - \theta_{thigh(i)}}{\theta_{pelvis(i+1)} - \theta_{pelvis(i)}}\right) \tag{1}$$

Coupling angles were corrected to range from 0° to 360° [11]. The mean coupling angle and coupling angle variability for each participant were calculated using circular statistics [11]. Group mean coupling angles were calculated using circular statistics, and group mean coupling angle variability calculated using a linear mean. Coupling angles were categorised into one of eight categories based upon whether the motion of the pelvis and thigh were in- or anti-phase, proximally (pelvis) or distally (thigh) dominated and the direction of the respective rotations (Fig. 1) [22]. Example data displaying hip, pelvis, thigh, pelvis-thigh angle-angle diagrams, coupling angles and coupling angle variability are presented in Supplementary Figs 1−3 for one healthy control and one patient following THA.

for one healthy control and one patient following total hip arthroplasty are provided in Supplementary Figs 1−3.

2.4. Data analysis

All statistical analysis was undertaken within SPSS (Version 28.0.1.0, IBM, Armonk, NY, USA). The dependent variables within the study were; peak hip, pelvis and thigh angles over the walking gait cycle and RoM; the percentage of time spent in each coordination category over the walking GC; the percentage of time spent within the dominant coordination categories within each subphase of the walking GC; and the average coordination variability during each subphase of the walking GC. Initially the distribution of the data was explored using Shapiro-Wilk tests. Where data met parametric assumptions independent samples t-tests were used to explore for differences between groups, with Mann-Whitney U tests used where data violated parametric assumptions. Additionally, Hedge's g, corrected for a small sample size, was calculated as an estimate of effect size and interpreted as follows; small $< .5$, medium $\geq .5$ and $< .8$, large $\geq .8$ [23]. The alpha level for the study was set at $p < .05$.

3. Results

3.1. Group descriptive characteristics and spatiotemporal parameters

No significant ($p > .05$) differences were reported for descriptive characteristics or spatiotemporal parameters between groups (Table 1). However, moderate to large effect sizes (Hedge's $g \geq 0.716$) were reported for age, walking velocity and stride length, with patients after THA being older, walking slower with smaller stride lengths on average.

3.2. Sagittal plane hip, pelvis and thigh kinematics

Hip, pelvis and thigh motion in the sagittal plane during the walking GC for each group is displayed in Fig. 2. Patients following THA have significantly ($p \leq .036$) lower peak hip extension and RoM, and peak thigh anterior tilt and RoM compared to controls, with large effect sizes (Hedge's $g \geq 0.995$) reported for all differences (Table 2). While no other significant ($p > .05$) differences were identified, medium effect sizes (Hedge's $g \geq 0.580$) were reported for the higher peak hip flexion and anterior pelvic tilt, and lower posterior pelvic tilt displayed by patients following THA.

3.3. Coordination patterns and variability

Pelvis and thigh coordination patterns and variability for patients after THA and healthy controls are displayed in Fig. 3. Patients following THA have significantly ($p \leq .037$) more in-phase distally dominated and less anti-phase distally dominated coordination patterns compared to healthy controls (Fig. 3B), with moderate effect sizes (Hedge's $g \geq$

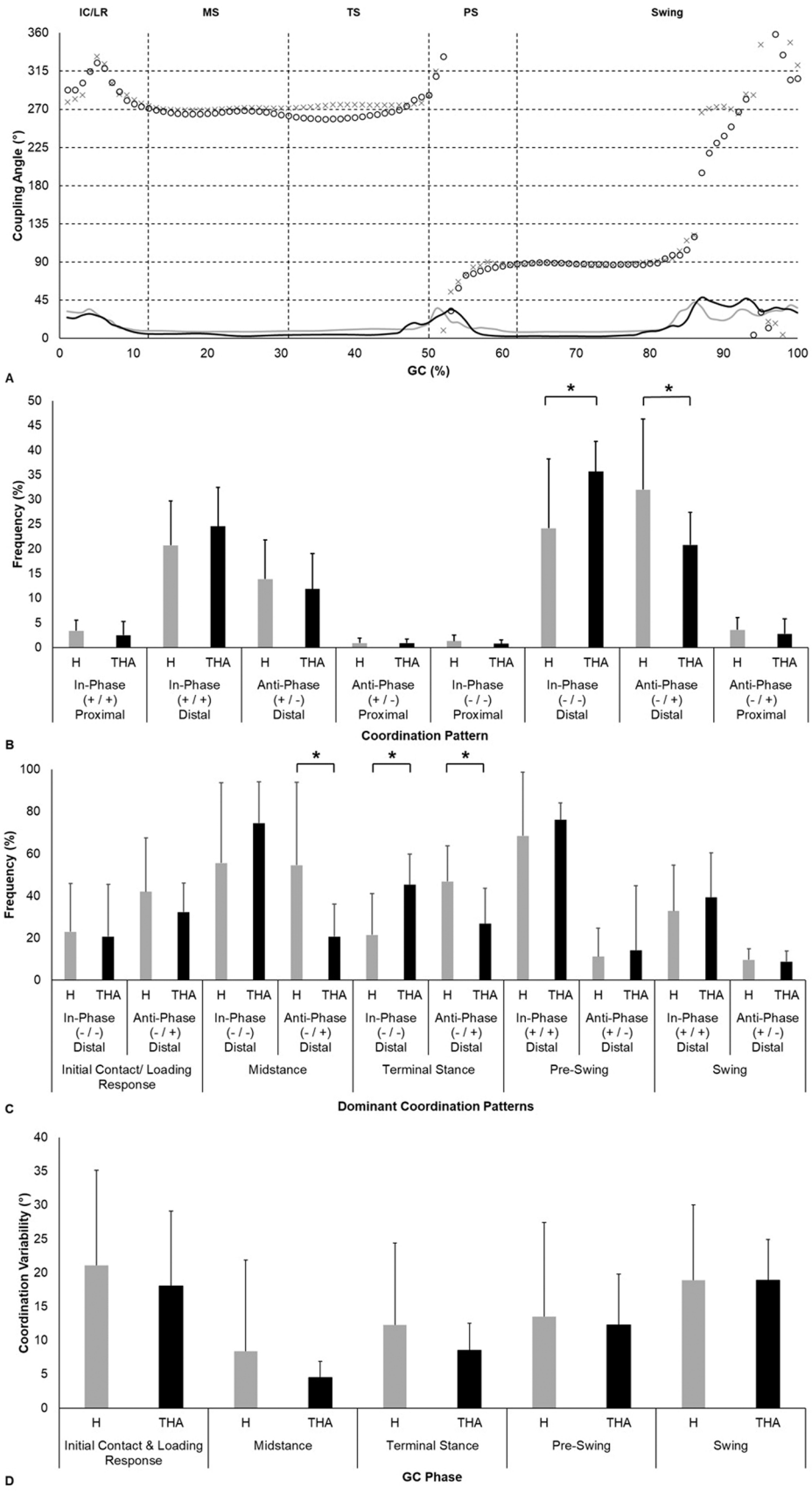

Fig. 3. (A) Coupling angles and coordination variability over the walking GC for healthy controls (grey crosses and solid grey line) and patients following THA (black circles and solid black line). Dashed vertical lines denote the relevant subphases of the walking GC and dashed horizontal lines the boundaries for each coordination pattern classification. (B) Frequency of the walking GC spent in each coordination pattern classification group, (C) frequency of the dominant coordination patterns within each subphase of the walking GC and (D) mean coordination variability within each subphase of the walking GC for healthy controls (grey bars) and patients following THA (black bars). * denotes < 0.05.

0.646) reported for these differences. When comparing the dominant movement coordination patterns during each subphase of the walking GC, THA patients have significantly ($p \leq .043$) lower amounts of anti-phase distally dominated coordination during midstance and terminal stance compared to controls (Fig. 3C). In contrast, patients following THA have significantly ($p = .006$) higher in-phase distally dominated pelvis-thigh coordination during midstance (Fig. 3C). Large effect sizes (Hedge's $g \geq 0.730$) were reported for these significant changes in movement coordination patterns. No significant ($p \geq .123$) differences in coordination variability were reported (Fig. 3D).

4. Discussion

The aim of this pilot study was to compare sagittal plane hip, pelvis and thigh kinematics, and pelvis-thigh movement coordination and coordination variability between patients after THA and healthy controls during walking. The findings of the work support hypotheses 1, 3 and 4 with patients following THA having significantly smaller hip and thigh kinematics and higher in-phase distally dominant pelvis-thigh movement coordination patterns. In contrast, hypotheses 2 and 5 were rejected, with no significant differences in pelvic kinematics or pelvis-thigh coordination variability reported between groups. These findings suggest that the altered hip kinematics displayed by patients following THA are primarily due to reductions in the motion of the thigh segment, which in turn is likely, at least in part, to be the result of increased in-phase movement coordination between the pelvis and thigh.

The significantly lower peak hip extension and sagittal plane RoM used by patients after THA are comparable with previous studies [4–9], both in terms of the direction and the magnitude of change. These findings demonstrate that participants within this study are representative of those used previously within the literature [4–9]. The significantly lower peak hip extension likely explains the smaller stride length used by patients after THA, which in turn would explain the lower walking velocity. However, it should be noted that the lower stride length and walking velocity used by patients following THA within this work were not statistically significant, but the relatively large magnitudes of change and moderate to large effect sizes suggest these are likely meaningful differences between groups. Again, the differences in walking velocity and stride length are consistent with previous studies [4,9].

Fundamentally, changes in hip motion are the result of alterations in the relative orientation of the pelvis and thigh segments within the global coordinate system. As such, the significant smaller hip kinematics appear to be primarily due to significant alterations in the orientation of the thigh segment. Patients following THA have significantly smaller peak anterior tilt of the thigh, resulting in lower thigh RoM. It is evident within Fig. 2C that the orientation of the thigh deviates outside of the standard deviation for the control group throughout terminal stance and pre-swing, before returning to a more typical range throughout the swing phase. Interestingly, it is throughout midstance and terminal stance where the movement coordination patterns of the pelvis and the thigh differ between the patients following THA and healthy controls (Fig. 3A & C). As such it may be that the altered movement coordination pattern used by patients after THA explains the abnormal hip and thigh motion during this phase of the walking GC.

Patients after THA have significantly more in-phase distally dominated movement coordination compared to the control group, who in turn have greater amounts of anti-phase distally dominant movement (Fig. 3). The in-phase coordination pattern used by the patients following THA demonstrates that the pelvis and thigh are moving in the same direction and as such are working as a singular functional unit. More in-phase coordination of the pelvis and thigh has been reported previously in patients with hip osteoarthritis [14] and as such this may be the result of persistent pre-operative gait alterations, which were developed to reduce pain or hip joint loading. It is unlikely that the persistent alterations in pelvis-thigh movement coordination are due to pain, with all patients following THA within this study reporting no pain usually and being able to walk without pain for 30 min or more on the Oxford Hip Score. Speculatively, reduced available range of motion, potentially due to hip flexor muscle contractures, or altered neuromuscular control strategies developed preoperatively may explain the increased in-phase pelvis-thigh coordination used by patients following THA. While the increased in-phase pelvis-thigh coordination may in turn explain the lower hip extension used by the patients following THA. However, further work is required to confirm the validity of the suggested mechanisms potentially underlying persistent alterations in walking gait displayed by patients following THA.

Functionally, it has been suggested that greater in-phase pelvis-thigh movement coordination highlights individuals relying more on anterior pelvic tilt to achieve larger stride lengths [14]. A greater reliance on more anterior pelvic tilt to enhance stride length may in turn explain why the patients following THA have greater, but not significantly so, anterior pelvic tilt throughout the walking gait cycle (Fig. 2B). Speculatively, exercise interventions or gait retraining which look to enhance patients following THA's ability to produce anti-phase movement of the pelvis and thigh may be beneficial in helping achieve more normal hip kinematics, in turn increasing stride lengths and walking velocity. Restoration of more normal hip kinematics and likely associated improvements in walking velocity would increase hip joint loading [24], potentially reducing the risk of implant failure [25]. Alternatively, if hip flexor contractures are the cause of the greater in-phase pelvis-thigh coordination patterns further surgical intervention may be required to increase the available RoM at the hip.

The findings of this study need to be interpreted in light of its limitations. Firstly, the sample size maybe a potential limitation of the study. The study was designed to have sufficient statistical power to identify changes in sagittal plane hip kinematics and as such may have been underpowered to detect changes in pelvic kinematics or coordination variability. Furthermore, a greater number of trials may be required to achieve more reliable estimates of coordination variability. Recent work [26], published after data collected was completed, highlights that between six and ten trials are required to achieve stable coordination variability values. Future work should therefore utilise a greater number of gait trials to further explore the influence of THA upon movement variability. Additionally, while all patients following THA were at least 12 months post-surgery, the exact time frame was variable (21 ± 16 months [minimum; 12 months, maximum; 62 months]). However, further analysis revealed no relationships between time post-surgery and sagittal plane hip, pelvis and thigh kinematics, and pelvis-thigh movement coordination and coordination variability.

5. Conclusion

Patients after THA have significant alterations in hip and thigh kinematics, and pelvis-thigh movement coordination compared to healthy controls. Specifically, patients following THA have significantly lower peak hip extension and RoM, which is the result of significantly less anterior tilt of the thigh, which limits thigh RoM. Furthermore, patients after THA use significantly more in-phase pelvis-thigh coordination patterns during midstance and terminal stance of the walking GC compared to controls. Higher in-phase pelvis-thigh coordination suggests that the pelvis and thigh are working as a single functional unit, which may in explain the reduced hip extension reported by patients following THA.

Declaration of Competing Interest

The authors report no conflict of interests related to this study.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.05.023.

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