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Change in functional biomechanics following a targeted exercise intervention in patients with acetabular retroversion and femoroacetabular impingement syndrome

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ABSTRACT

Background: Acetabular retroversion is a form of hip dysplasia that may cause femoroacetabular impingement syndrome (FAIS), leading to pain and restricted hip range of motion. An exercise intervention aiming at altering pelvis tilt and related functional biomechanics may be a useful first-line intervention for patients who are not eligible for surgical repositioning.
Research question: Does squat and gait biomechanics change following an 8-week targeted exercise program in individuals with symptomatic acetabular retroversion and FAIS?
Methods: This prospective intervention study used participants as their own controls. Examinations were conducted at three time-points: T1 baseline; T2 following an 8-week control period; T3 after 8 weeks' intervention. At each time-point, three-dimensional motion analysis of a deep squat and level gait was performed, and pain intensity was recorded using a numerical rating scale (NRS 0–10). The intervention consisted of a home-exercise program to improve core stability and pelvic movement. Differences in waveforms between time-points across pelvis and lower-limb biomechanics were evaluated using statistical parametric mapping. Delta (Δ, differences between T1-T2 and T2-T3) was used to evaluate changes in spatiotemporal gait parameters and pain.
Results: Nineteen patients (18 females), mean age 22.6 (SD 4.5) years, BMI (kg/m2) 23.0 (SD 4.1), were included. Changes (Δ T1-T2 vs. Δ T2-T3) in squat biomechanics were observed as: (i) decreased anterior pelvic tilt, (ii) deeper vertical pelvis position, and (iii) increased knee flexion angle. Contrary, no significant changes in gait biomechanics, Δ walking speed, Δ step length, or NRS for pain were found.
Significance: Following a targeted exercise intervention, participants were able to squat deeper, potentially allowing better hip function. The deepened squat position was accompanied by increased knee flexion and reduced anterior pelvic tilt. Gait biomechanics and patient-reported pain remained unchanged post-intervention.

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These findings are important for future design of exercise interventions targeting pelvic tilt in symptomatic individuals.

1. Introduction

Acetabular retroversion is a form of hip dysplasia where the cranial opening of the acetabulum faces backward rather than forward in the sagittal plane [1,2]. The prevalence of acetabular retroversion is 4–7 % in individuals with pelvises exhibiting normal anterior pelvic tilt [3,4], and is most commonly seen in young females [5]. The condition is genuine [6], associated with increased antero-superior coverage of the femoral head [2], and it commonly co-exists with excessive anterior pelvic tilt [6] and/or femoroacetabular impingement syndrome (FAIS) [7].

For individuals with acetabular retroversion and severe symptoms and pain, surgical reorientation of the acetabulum can be performed through a periacetabular osteotomy (PAO) [8]. This surgery reduces pain [8], and has demonstrated good long-term outcomes [9,10]. However, the PAO is a complex and technically demanding procedure, associated with risk of complications (i.e., injury to vessels or nerves, thrombosis, penetrating the joint cavity, and delayed union of bone) [11,12]. Therefore, non-surgical treatment (i.e. targeted exercise), currently the first-line intervention, is recommended for the heterogeneous group of young to middle aged patients with hip pain who are not eligible for PAO [13]. Despite being the recommended treatment in clinical practice, there is a lack of evidence of the impact of non-surgical treatment on symptom relief and changes in functional biomechanics in patients with acetabular retroversion and FAIS [14].

For individuals with symptomatic acetabular retroversion and/or individuals with FAIS, movements that require a large range of motion (ROM) at the hip joint, particularly flexion, may provoke and aggravate symptoms [6,15,16]. These symptoms may be further exacerbated by anterior pelvic tilt due to excessive coverage of the femoral head and neck during this posture [17]. Therefore, this study aimed to evaluate change in squat and gait biomechanics before and after an 8-week home-based exercise program, targeted to improve core stability and pelvic movement, in individuals with acetabular retroversion and FAIS. It was hypothesized that improved pelvic mobility would lead to improved ability to perform a deep squat and display reduced anterior pelvic tilt during gait following the intervention.

2. Methods

2.1. Study design

The STROBE guidelines were followed in the development and reporting of this study [18]. The study reports ancillary data from a single-center, prospective intervention study using participants as their own controls [19]. Following baseline examinations (time-point 1; T1), an 8-week control period (time-point 2; T2) was followed by an 8-week home-based exercise period (time-point 3; T3) (Fig. 1). The control period enables controlling for inter-session variation (T1 vs. T2), and change related to the intervention (T2 vs. T3). This study is compliant with the Helsinki Declaration and was approved by the Regional Ethics Committee (ID: S-20160072) and registered with ClinicalTrials.gov (NCT03578562). A priori sample size estimation was made for a different aim on self-perceived level of hip-related pain, and resulted in 36 participants for the primary analysis [19]. Out of these, 20 participants were randomly extracted for the present elaborated sub-study on joint biomechanics.

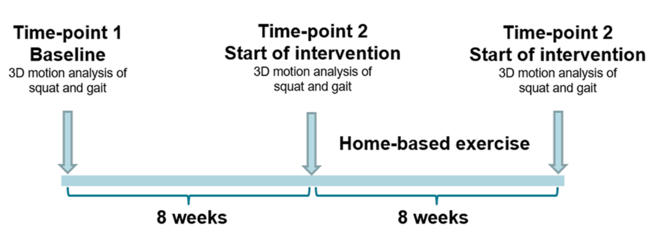

Fig. 1. Timeline of included study participants and study design.

2.2. Participants

Participants were recruited at Odense University Hospital, Denmark, from November 2018 to December 2019. Inclusion criteria were 18–40 years of age; acetabular retroversion verified from a frontal pelvic radiograph in a standard standing position by the cross-over sign (COS) and the posterior wall sign (PWS) [2]; and symptoms not severe enough for PAO. Exclusion criteria were pelvic-tilt-ratio greater than 0.5 (from a frontal pelvic radiograph in standard standing position), indicating posterior pelvic tilt [20]; radiographic signs of hip osteoarthritis (<2 mm joint space) [21]; previous lumbar, pelvic, or hip-related surgery; conditions not allowing exercise therapy; a body mass index (BMI) above 35; or not understanding spoken and/or written Danish. All included participants gave written informed consent prior to testing.

2.3. Intervention

The intervention consisted of patient education of the hip condition, activity modification, stretching exercises for posterior pelvic tilt mobility, strengthening muscles for posterior pelvic tilt, improving core stability, and pelvic movement control. The home-based exercise program was inspired by the Warwick consensus statement on FAIS [7], previous exercise studies regarding various types of FAIS [22–25], and functional anatomy [26], and took around 30–45 min to complete. Participants were instructed to complete the program three times per week, with an optional extra exercise session, allowing for one rest day between sessions. Every second week the progression, including intensity, number of repetitions and/or level of difficulty of the exercises, increased. Individualization of the exercise program was permitted (i.e., doing fewer repetitions or omitting an exercise that caused pain) and encouraged to be noted in the training diary. For further details, the reader is referred to Brekke et al. [19].

2.4. Patient characteristics

At baseline, the following characteristics were evaluated: gender (% female), age (years), height (cm), body weight (kg), BMI (kg/m^2), and sagittal pelvic tilt by a standing weight-bearing EOS (low-radiation X-ray) scanning (EOS Imaging, Paris, France) [27] as the angle between a line connecting the upper border of the symphysis with the sacral promontory and a horizontal line [28].

2.5. Patient-reported outcomes

At each test session, study participants were asked to rate their perceived pain using a verbal numerical rating scale (NRS) ranging from 0 (no pain) to 10 (worst imaginable pain) [29]. Participants kept a training diary throughout the study to document number of exercise sessions and potential serious exercise-related adverse events.

2.6. Three-dimensional (3D) motion analysis

3D motion analyses were conducted at Odense University Hospital, Odense, Denmark. Kinematic data were recorded at 100 Hz using an eight-camera system (Vicon Motion Systems Ltd, Oxford, UK), and a conventional biomechanical model, the Plug-In-Gait model [30]. A single assessor placed the markers at each time-point. Reliability studies of kinematic data indicate moderate to good reliability for sagittal and coronal plane variables, with the exception of pelvic tilt and knee varus/valgus in some reports [31]. Most studies reported estimates of error (standard deviation or standard error) of less than 5 degrees for all gait variables, excluding hip and knee rotation [31].

2.6.1. Deep squat

Participants were standing with their feet on separate ethylene-vinyl acetate (EVA)-foam wedges (22 degrees) (L: 24 cm, W: 15 cm, H: 9 cm), to prevent short calf muscles from hampering hip and knee joint movement. The toes had contact with the floor with the rest of the foot supported by the wedge, and feet were kept parallel at shoulder width. For the analysis of the deep squat, participants were instructed to squat as deep as possible with the arms stretched forward and bringing the buttocks as close to the heels as possible, allowing for flexion of the lumbar spine. Outcome measures derived from the squat included pelvis and hip kinematic waveforms in all three planes, the deepest vertical position of the pelvis, and knee and ankle kinematics in the sagittal plane. The sign conventions used in the present study adopt anterior pelvis tilt, hip flexion, knee flexion, and ankle dorsiflexion as positive motions. Participants performed two practice trials to familiarize themselves with the movement and to allow for a squat as deep as possible. The third repetition was recorded and used in the analysis.

2.6.2. Gait analysis

At all time-points, participants were instructed to walk barefoot at a self-selected speed. The outcome measures derived from the gait analyses included waveforms of the pelvis and hip kinematics in all three planes, knee and ankle kinematics in the sagittal plane. The sign conventions used in the present study adopt anterior pelvis tilt, hip flexion, knee flexion, and ankle dorsiflexion as positive motions. Spatiotemporal gait parameters were collected simultaneously. All gait data were calculated based on three gait cycles per participant and averaged to obtain mean values for each test session.

2.7. Data processing

3D motion analysis data were processed using Vicon Nexus software (2.1), and raw motion capture data was filtered using a Woltring filter. For the gait analysis, the gait cycle was time normalized to 100% from heel strike until the next heel strike. A custom-made script in MATLAB (MATLAB and Statistical Toolbox Release R2020b, The MathWorks, Inc., Natick, Massachusetts, US) was used to extract the following time events during the squat movement: (I) start of squat: time-point where the average (left and right side) sagittal hip angle was larger than 2% of the average sagittal hip angle during standing; (II) deepest squat position: the largest displacement of the average (left and right side) hip position (Femur proximal markers (RFEP and LFEP)) compared to the start of squat position; and (III) end of squat: time-point where the average (left and right side) sagittal hip angle was smaller than 2% of the average hip angle during standing. The squat was subsequently time normalized to 100% between the starting and endpoint.

2.8. Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics version 26 (Chicago, IL, USA). Normality of data was assessed using Shapiro-Wilks test and Q-Q plots. Delta (Δ), defined as the difference between time-points (T1-T2 and T2-T3), was calculated and used to evaluate Δ walking speed (m/s) and Δ step length (m) using paired sample t-tests. Differences in NRS for pain between time-points were evaluated using Friedman's test. Differences across kinematic waveforms (100% of squat and gait cycle, respectively) between time-points were evaluated using the statistical parametric mapping (SPM) version of repeated-measures one-way-ANOVA [32]. In case of a significant difference, post hoc analyses were performed using paired t-tests with Bonferroni corrections. SPM analyses were performed in MATLAB.

3. Results

Out of the 20 included participants, kinematic data was available for 19 (18 females). One participant was excluded from the analysis on the basis of occluded markers during the deep squat trials. The included participants (with complete data-sets ($n = 19$)) had a mean age of 22.6 (SD 4.5) years, BMI (kg/m^2) of 23.0 (SD 4.1), and a sagittal pelvic tilt of 74° (SD 8) (Table 1). Acceptable adherence (≥75% of sessions) to exercise was demonstrated by (18/19) 95% of the participants. In accordance with an intention to treat, all 19 participants were included in the kinematic analysis.

3.1. Squat biomechanics

The SPM ANOVA revealed changes in the waveforms of squat biomechanics between the three time-points for deepest vertical pelvis position, pelvic tilt (anterior/posterior in the sagittal plane), and knee flexion angle (Fig. 2). Patients were able to squat deeper, characterized by an increased depth of the vertical pelvis position (distance from the floor to the deepest vertical pelvis position measured in mm) after the exercise intervention (Table 2). SPM post hoc analysis confirmed a significant difference between T1-T3 and T2-T3. The deepest vertical pelvis position was increased by 61 mm and 57 mm at T3 vs. T1 (between 39 % and 52 % of the squat cycle, $p < 0.001$) and T3 vs. T2 (between 44 % and 52 % of the squat cycle, $p = 0.012$), respectively. The anterior pelvic tilt was significantly reduced to − 1° (SD 9) at T3 compared to 5° (SD 10°) at T1 (between 46 % and 52 % of the squat cycle, $p = 0.022$) and 4° (SD 9°) (between 47 % and 52 % of the squat cycle, $p = 0.027$) at T2 (Table 2). Finally, knee flexion was increased with 10° at T3 compared to both T1 (between 42 % and 48 % of the squat cycle, $p = 0.025$) and T2 (between 45 % and 51 % of the squat cycle, $p = 0.029$), respectively (Fig. 2). Peak ROM values are presented in Table 2. No statistical differences were observed between T1 and T2 (control period) for any squat kinematics. No statistical differences were found in hip and ankle kinematics between T2 and T3 (Appendix).

3.2. Gait biomechanics

The SPM ANOVA revealed no changes in gait biomechanics between the three time-points for pelvis and hip kinematics in all three planes, nor in knee or ankle kinematics in the sagittal plane (Appendix). The average pelvic tilt in the frontal plane did not change significantly between time-points (mean (SD) T1: 13° [2]; T2 14° [6]; T3 14° [6]). Furthermore, no significant differences were found in Δ walking speed or Δ step length between time-points T1 and T2 (control period) or T2 and T3 (exercise period) (Table 3).

Table 1
Baseline characteristics of included patients with acetabular retroversion and femoroacetabular impingement syndrome (FAIS).

	Acetabular retroversion and FAIS group n = 19
Female, n (%)	18 [95]
	Mean (Standard Deviation)
Age, years	22.5 (4.2)
Height (cm)	171 (8)
Bodyweight (kg)	67.9 (11.4)
Body Mass Index (m^2/kg)	23.0 (4.1)
Sagittal pelvic tilt (°)*	74 (8)

* Normal sagittal pelvic tilt is 60–65° and equal across the sexes with the pelvis positioned in neutral tilt [22].

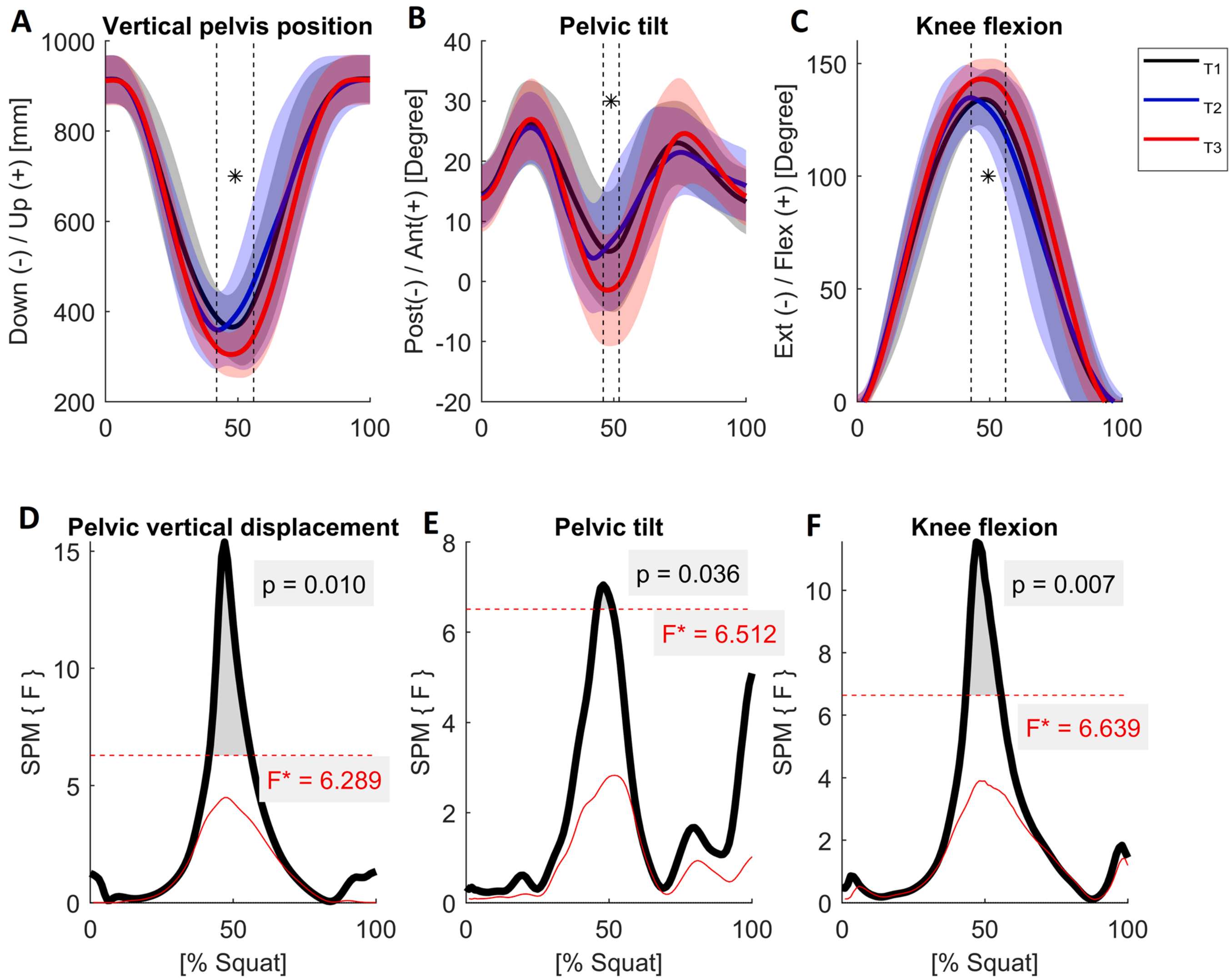

Fig. 2. The three upper figures (A, B, C) show the mean ± SD for vertical position of the pelvis, sagittal pelvic tilt angle, and knee flexion angle during a squat-cycle. The three lower figures (D, E, F) display the SPM-ANOVA plot for each of the above corresponding squat-cycles. The black line indicates the within-subject model; the thin red line indicates the critical threshold (F*). If the black or thin red line crosses the critical threshold limit, it is indicative of a statistical difference in the period in which the critical threshold is exceeded.

Table 2
Squat biomechanics before and after an 8-week exercise intervention in patients with acetabular retroversion and femoroacetabular impingement syndrome.

	Time-point 1 (T1)	Time-point 2 (T2)	Time-point 3 (T3)	T2 vs T3 SPM analysis
Squat biomechanics (n = 18)	Mean (Standard Deviation)			p-value
Deepest vertical position of the pelvis (mm)*	366 [72]	361 [89]	304 [49]	**0.010**
Peak pelvic tilt angle (°) (+anterior -posterior)	5 (10)	4 (9)	-1 (9)	**0.036**
Peak knee flexion angle (°)	133 (12)	133 (15)	143 (10)	**0.007**

* The distance from the floor to the position of the pelvis. Peak values corresponding to Fig. 2.

Table 3
Spatiotemporal gait parameters before and after an 8-week exercise intervention in patients with acetabular retroversion and femoroacetabular impingement syndrome.

Spatiotemporal gait parameters (n = 19)	Time-point 1 (T1)	Time-point 2 (T2)	Time-point 3 (T3)	Δ T1-T2 vs. Δ T2-T3
	Mean (Standard Deviation)			p-value
Walking speed (m/s)	1.04 (0.04)	1.03 (0.04)	1.04 (0.04)	0.179
Step length (m)	0.61 (0.06)	0.63 (0.02)	0.63 (0.02)	0.193

3.3. Patient-reported pain

Group median (range) NRS pain across time-points was T1: 2 (0–8), T2: 3 (0–8), and T3: 1 (0–7) and demonstrated no statistically significant difference between time-points (p = 0.06). Individual NRS pain scores are presented as a slope graph in Fig. 3.

4. Discussion

This study evaluated change in functional biomechanics following an 8-week targeted exercise intervention among participants with acetabular retroversion and FAIS, not eligible for PAO. To this end, pelvis and lower limb kinematics were analyzed during a deep squat and level gait,

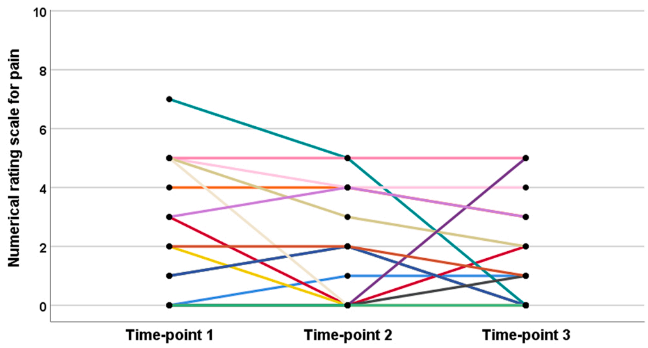

Fig. 3. Slope graph of numerical rating scale for pain (0 =no pain at all, 10 =worst imaginable pain) for each individual study participant (different lines) at each time-point; Time-point 1 baseline; Time-point 2 start of the intervention (following a control period of 8 weeks); and Time-point 3 after 8 weeks' intervention.

following a control period and an intervention period. Analyses of the entire movement cycle revealed that patients were able to squat deeper, characterized by an increased depth of the vertical pelvis position (distance from the floor to the deepest vertical pelvis position T1:366 mm (SD 72), T2: 361 mm (SD 89), T3: 304 mm (SD 49)) after the exercise intervention. The increased squat depth was accompanied by increased knee flexion and reduced anterior pelvic tilt. More specifically, the anterior pelvic tilt during the deep squat following the intervention was significantly reduced to − 1° (SD 9) at T3 compared to 5° at T1, and 4° at T2. This change is close to previously reported measures of error of 4–5° [31]. It should be noted though, that the deep squat position post-intervention did not result in increased patient-reported pain. Thus, despite that no minimal clinical important change for pelvic tilt is known, the observed reduction in anterior pelvic tilt could potentially reduce symptoms associated with FAIS due to less excessive coverage of the femoral head and neck during this posture [6]. Moreover, to determine whether the observed reduction in anterior pelvic tilt is clinically relevant, a different study design is needed.

Gait biomechanics, spatiotemporal gait parameters, and patient-reported pain remained unchanged after 8 weeks' intervention. The unchanged gait pattern could indicate that the improved ROM in posterior pelvic tilt following the intervention does not influence the pelvis and lower limb kinematics during gait, possibly due to lesser ROM requirements during gait as compared to a deep squat or other movements requiring end-rang hip flexion (i.e. lunges).

To the best of our knowledge, no previous literature has examined the impact of an exercise intervention on squat and gait biomechanics among individuals with radiographically verified acetabular retroversion. However, both squat and gait biomechanics have been evaluated in individuals with FAIS and compared to healthy controls [33–36]. While level walking does not require a large ROM in the hip joint, significantly lower peak hip abduction, as well as attenuated pelvic frontal ROM has been observed in individuals with FAIS compared to healthy controls [35]. Previous literature, concerning somewhat similar pathology, report less ROM in the sagittal plane during gait [37], and reduced hip external rotation moments during gait pre-operatively in individuals with FAIS compared to controls [34]. Moreover, alterations in hip biomechanics during both gait and squat, as compared to controls, were observed before and six months postoperatively in patients treated with arthroscopic hip surgery for FAIS [34]. In accordance with findings of the present study, Lamontagne et al. compared squat biomechanics in individuals with FAIS and healthy controls and reported decreased pelvic tilt in the sagittal plane (FAIS:14.7° vs. controls: 24.2°) and limited squat depth (FAIS:41.5% of leg length vs. controls: 32.3% of leg length) [36]. The authors conclude that restricted sagittal pelvic ROM may contribute to the reduced squat depth [36].

In the present study, exercise as a first-line of treatment for individuals with symptomatic acetabular retroversion yielded a significantly deeper squat depth after the intervention period. This may be transferred into improved execution of activities of daily living (i.e., tying shoelaces, picking up objects from the floor), and other leisure activities requiring end-range hip flexion. No changes were observed in gait biomechanics, indicating that the adaptations to the exercise program were only observed during the deep squat which, contrary to level gait, is a movement requiring a large degree of hip flexion and/or pelvic tilt. Patient-reported pain was variable (Fig. 3), and no significant change in group median NRS for pain was found. It is possible that the present study was underpowered to yield a significant decrease in patient-reported pain. Nevertheless, in this group of patients, the increased squat depth following the intervention period, without a concomitant *increase* in pain, should be viewed as a positive outcome. The effect of surgical treatment on physical impairments in individuals with symptomatic FAI has been evaluated in a systematic review [16]. Results of the review were inconsistent, although in line with some of the current findings, suggesting that squatting depth improves following surgical intervention [16]. Another type of non-surgical intervention is progressive resistance training that focuses on improving maximal muscle strength, in contrast to the current multi-purpose intervention focusing on posterior pelvic movement control and core stability. However, the effect of progressive resistance training as a non-surgical treatment in patients with hip dysplasia remains to be elucidated and is currently under investigation [38].

As for limitations, the included group of participants consisted of 18 women and one man. Therefore, results may not be generalizable to males. Secondly, the present study reports secondary data from a prospective intervention study with a different aim. Hence, there was no a priori sample size estimation performed for the research question addressed in the current study. In individuals with pelvises exhibiting normal anterior pelvic tilt the prevalence of acetabular retroversion is 4–7% [3,4]. However, in individuals with symptomatic acetabular retroversion anterior pelvic tilt is increased in comparison to the general population [6]. The group mean sagittal pelvic tilt was 74° (SD 8), which is higher than the normal pelvic tilt of 60°– 65° [39]. In the general population, radiographic sign of acetabular retroversion is highly prevalent (COS≈50%) [35], and even higher when individuals with excessive anterior pelvic tilt are not excluded (COS+PWS=24%) [8]. However, large variability in dynamic pelvic tilt was observed during gait among the included participants, indicating a heterogeneous group. With a larger study sample, it is possible that stratifying participants based on the degree of pelvic tilt could have displayed a positive result for the sub-group of individuals yielding the highest deviations in pelvic tilt. Strengths of this study include a group of participants with radiographically verified acetabular retroversion. In other studies, evaluating hip pain in young adults, a case-mix of patients in terms of impingement type has been included [40,41]. Secondly, the present study included a control period which enabled controlling for inter-session variation (T1 vs. T2), and change related to the intervention (T2 vs. T3). The current study design used the participants as their own controls which offered a pragmatic method to evaluate the impact of the intervention. However, the exact cause-and-relationship cannot be drawn from the current study design. Finally, SPM was used to evaluate potential biomechanical changes of kinematic waveforms. Use of this method entailed avoiding the bias of selecting discrete metrics and associated multiplicity in statistical findings.

In a clinical perspective, findings of the present study suggest that the home-based exercise intervention was feasible in terms of adherence to exercise, and had a positive impact on squat biomechanics after 8 weeks. Future studies should evaluate if alternative interventions, such as progressive resistance training, supervised sessions, and interventions lasting for a longer duration of time (i.e. 3 months or longer) could reduce patient-reported pain and symptoms, and alter sagittal plane pelvis position during gait.

5. Conclusion

After the intervention period, participants were able to squat deeper. The deeper squat position was accompanied by increased knee flexion and reduced anterior pelvic tilt. Gait biomechanics, characterized by anterior pelvic tilt, spatiotemporal gait parameters, and patient-reported pain, remained unchanged. In perspective, the targeted exercise program may improve function in daily living activities requiring end range hip flexion in patients with acetabular retroversion not eligible for surgical treatment. These findings are important for future design of exercise interventions targeting pelvic tilt in symptomatic individuals.

CRediT authorship contribution statement

Josefine E Naili: Methodology, Formal analysis, Visualization, Writing – original draft. **Anders Falk Brekke:** Conceptualization, Funding acquisition, Investigation, Methodology, Formal analysis, Writing – original draft. **Morten Bilde Simonsen**: Software, Data curation, Visualization, Writing – review & editing. **Rogerio Pessoto Hirata:** Software, Data curation, Writing – review & editing. **Søren Overgaard**: Conceptualization, Supervision, Funding acquisition, Writing – review & editing. **Anders Holsgaard-Larsen:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Conflict of interest statement

The listed authors of this paper have no conflicts of interest to disclose for this manuscript.

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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.2022.11.017.

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