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Frontal plane pelvic motion during gait captures hip osteoarthritis related disability

Stijn A.A.N. Bolink[1], Luke R. Brunton[2], Simon van Laarhoven[1], Matthijs Lipperts[1], Ide C. Heyligers[1], Ashley W. Blom[2], Bernd Grimm[1]

[1]AHORSE Foundation, Dept Orthopaedics, Atrium Medical Center Heerlen, the Netherlands
[2]Avon Orthopaedic Centre, Southmead Hospital Bristol, United Kingdom

Original Research

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Corresponding author:
Stijn A.A.N. Bolink, M.D.
Orthopedic resident at the Atrium Medical Center, Heerlen, The Netherlands
E-mail: stijn.bolink@mail.com
Tel: +31655341492
Address: Henri Dunantstraat 5, 6419 PC, Heerlen, The Netherlands

Abstract

Gait analysis has widely been accepted as an objective measure of function and clinical outcome. Ambulatory accelerometer-based gait analysis has emerged as a clinically more feasible alternative to optical motion capture systems but does not provide kinematic characterization to identify disease dependent mechanisms causing walking disability. This study investigated the potential of a single inertial sensor to derive frontal plane motion of the pelvis (i.e. pelvic obliquity) and help identify hip osteoarthritis (OA) related gait alterations. Patients with advanced unilateral hip OA (n=20) were compared to patients with advanced unilateral knee OA (n=20) and to a healthy control group (n=20). Kinematic characterization of frontal plane pelvic motion during gait demonstrated decreased range of motion and increased asymmetry for hip OA patients specifically.

Keywords: ambulatory gait analysis, inertial sensor, osteoarthritis, outcome assessment, frontal plane pelvic motion, pelvic obliquity, Trendelenburg, performance-based test.

Introduction

Gait analysis has widely been accepted as an objective measure of function, allowing researchers and clinicians to better understand biomechanical alterations in the presence of hip osteoarthritis (OA) and to quantitatively evaluate the functional success of total hip arthroplasty (THA) and rehabilitation strategies [1-3]. Besides pain relief, functional improvement following surgery has become more important for the new generation of younger and generally more active hip OA patients. Therefore, it has been advocated to supplement longitudinal follow-up studies with objective assessment of function like gait analysis [2, 4]. In clinical gait analysis, a skin marker based optical motion capture (MOCAP) system provides a non-invasive approach and is regarded as the gold standard. Unfortunately, a MOCAP system is not feasible for routine use because it is time consuming, expensive, artificial and limited to a single gait cycle. Advances in miniaturization and cost of ambulatory motion sensors have emerged accelerometer-based gait analysis as a potential ambulatory alternative to MOCAP systems [5]. In previous studies, a single accelerometer positioned at the dorsal side of the pelvis has been advocated for optimal clinical feasibility to derive spatiotemporal gait parameters (e.g. cadence, step length) based on heel strike (HS) events in the antero-posterior acceleration signal [6, 7]. These spatiotemporal gait parameters can discriminate gait between healthy subjects and OA patients [2-4, 8] and have demonstrated responsiveness to changes postoperatively [2, 3]. However, spatiotemporal gait parameters lack kinematic characterization to identify the mechanisms causing typical gait disturbances in hip OA patients such as Trendelenburg's gait. To supplement ambulatory spatiotemporal gait analysis with kinematic characterization outside the MOCAP laboratory, the use of a gyroscope in conjunction with an accelerometer (i.e. inertial sensor) has been advocated [9]. With an inertial sensor, spatiotemporal gait parameters and dynamic orientation angles of underlying body segments can be determined.

The primary aim of the study was to investigate the potential of a single inertial sensor positioned at the dorsal side of the pelvis to derive clinically relevant frontal plane gait kinematics in patients with hip OA, supplementary to spatiotemporal gait parameters. We hypothesized that motion of the pelvis in the frontal plane (i.e. pelvic obliquity) could accurately be characterized from a single inertial sensor positioned at the dorsal side of the pelvis [10], and

that it would be decreased in patients with hip OA [11]. A second aim was to investigate whether gait kinematics of pelvic obliquity are influenced by a main effect of osteoarthritis on gait or related to hip OA specifically. Therefore, hip OA patients were compared to knee OA patients and it was hypothesized that pelvic obliquity would be decreased in hip OA patients only, as a result of compensating for abductor muscle weakness and pain of the affected hip joint during the single limb supportive gait phase [1, 12]. A third aim was to investigate gait kinematics of pelvic obliquity in a healthy cohort to provide reference data and to investigate the influence of demographic variability.

Materials and Methods

Gait was studied in 20 patients with unilateral end stage hip OA and 20 patients with unilateral end stage knee OA (table 1). These patients were randomly recruited from the outpatient clinic if they were listed for a total joint replacement by an orthopaedic surgeon. All patients reported activity limitation because of OA and scored 3 or 4 on the Kellgren-Lawrence radiographic osteoarthritis index [13]. Patients with polyarthritis or any other condition affecting gait, except single joint osteoarthritis, were excluded from this study. Furthermore, gait was studied in 80 healthy participants (age range 19-77yrs; mean 40.0yrs ±16.0; m/f=39/41) who had no joint pain and no medical history of lower extremity joint surgery. A control group of 20 healthy subjects was selected from this healthy cohort by age and gender for comparison with the osteoarthritis patient groups. However, a significantly higher body mass index (BMI) for knee OA patients was found compared to this control group (table 1).

Data acquisition

The study methods were in accordance with a previously published study [4]. Briefly, all participants were invited to walk 20 meters along a straight flat corridor at their own preferred speed. A 3D inertial sensor (41x63x24mm; 39g; Microstrain Inertia Link) was used. The sensor was positioned at the dorsal side of the pelvis, centrally between both posterior superior iliac spines. At this position, a single inertial sensor allows heel strike detection from the antero-posterior acceleration signal [6, 7] and kinematic characterization of pelvic motion [10]. Using automated algorithms in Matlab, spatiotemporal gait parameters were derived: 1) speed (m/s); 2) cadence (steps/min); 3) step time (s); 4) step length (m); 5) step time irregularity (coefficient of

variance: 100% * SD/mean) and 6) step time asymmetry (100% * abs(left-right))/((left+right)/2)) [2, 4, 14]. Dynamic orientation angles of the pelvis were obtained through the inertial sensor's inbuilt fusion algorithms of acceleration, angular rate and magnetic field vector measurements and compared to gold standard MOCAP system measures. The waveform of pelvic obliquity during gait was further characterized to allow assessment of asymmetry. Kinematic gait parameters of pelvic obliquity included: a) range of motion (ROM, °); b) asymmetry (100% * abs(left-right)/mean) and c) pelvic obliquity at heel strike (POHS; 100% * (δ / ROM)) in which δ represents the ROM of pelvic obliquity between consecutive heel strikes (figure 1). The pelvic obliquity at heel strike indicates the orientation of the pelvis in frontal plane for which a value of 50% represents a horizontal pelvic position. Capturing asymmetry of pelvic obliquity and the pelvic obliquity at heel strike from a single inertial sensor is a novel approach with no previous results reported in literature.

Statistical analysis

Data were analyzed using SPSS version 17.0. To compare mean values of gait parameters between patients with hip OA, patients with knee OA and the matched control group, a one-way ANOVA test was used. The interactions between gait parameters and the demographic covariates gender, age, height, weight and BMI in these three groups were calculated with MANCOVA which provides the level of statistical significance for the interaction (p-value) and the proportion of variance accounted for by the interaction (partial Eta^2). Because previous studies have found that variance of walking speed can significantly influence kinematic gait parameters, especially in patients with osteoarthritis [15, 16], we performed analysis of covariance to compare speed-adjusted mean values of the range of motion of pelvic obliquity. In our cohort of 80 healthy participants, the association between the demographic variables gender, age, height, weight and BMI with individual gait parameters were measured using multiple linear regression analysis which provides the level of statistical significance (p-value) and the strength of the association (beta standardized coefficient).

Results

Characterization of pelvic obliquity during gait by a single inertial sensor attached at the dorsal

side of the pelvis provided waveforms that were qualitatively and quantitatively comparable to MOCAP measures (figure 2).

In patients with hip OA and knee OA, the accelerometer based spatiotemporal gait parameters demonstrated significant differences compared to the control group (table 2). Patients with hip OA demonstrated significantly decreased step length and walking speed compared to the control group. Step time irregularity and step time asymmetry were not significantly different between patients with hip OA and the control group. Patients with knee OA demonstrated significantly decreased walking speed, decreased cadence, increased step time irregularity and increased step time asymmetry. Comparing spatiotemporal gait parameters between patients with hip and knee OA demonstrated only a significantly higher step time asymmetry for knee OA patients.

Kinematic gait parameters of pelvic obliquity demonstrated lower range of motion (ROM) of pelvic obliquity in both hip OA and knee OA patients compared to the control group (table 2). After statistical correction for the variance of walking speed between groups, the range of motion of pelvic obliquity at a walking speed of 1.13m/s demonstrated significantly lower outcomes for hip OA patients compared to controls (ROM pelvic obliquity: 5.6° ±2.1 vs. 8.0° ±2.4; $p<0.01$; respectively) and compared to knee OA patients (ROM pelvic obliquity: 5.6° ±2.1 vs. 7.3° ±2.3; $p<0.01$; respectively) whereas no significant difference was observed between knee OA patients and controls anymore. Furthermore, significantly higher asymmetry of pelvic obliquity was found for hip OA patients compared to controls and compared to knee OA patients (32.2% ±25.6 vs. 15.9% ±13.1 and vs. 16.1% ±12.4; $p<0.05$ respectively). Knee OA patients demonstrated significantly higher pelvic obliquity at heel strike (POHS) compared to controls (73.6% ±22.4 vs. 50.2% ±15.4 respectively) however no significant difference was observed compared to hip OA patients. Analysis of demographic variability (MANCOVA) in the groups of hip OA patients, knee OA patients and healthy controls demonstrated only a significant interaction between BMI and POHS ($Eta^2 = 0.08$; $p<0.05$).

Results of gait parameters in all healthy subjects and results of multiple linear regression analysis between gait parameters and demographic variables are shown in table 3. Multiple analysis of covariance for the demographic variables age, gender, height, weight, BMI with gait parameters demonstrated a significant negative effect of age on the range of motion of pelvic obliquity (beta standardized coefficient= -0.33).

Discussion

This study investigated the potential of a single inertial sensor positioned at the dorsal side of the pelvis to characterize frontal plane pelvic motion (i.e. pelvic obliquity) during gait, supplementary to spatiotemporal gait parameters, and describes its clinical relevance for patients with hip OA. First, measures of pelvic obliquity assessed with an inertial sensor were compared to a MOCAP system. In a previous study [17], assessment of pelvic kinematics during gait by a MOCAP system with reflective markers attached onto a rigid plate at the dorsal side of the pelvis demonstrated good accuracy compared to single markers placed over the anterior and posterior superior iliac spines (ASIS and PSIS). A more recent study by Borhani et al. [18] demonstrated that reflective markers on a rigid plate provide more accurate results with less skin artefacts, especially in overweight and obese patients. In this study, a single inertial sensor was placed at the dorsal side of the pelvis and qualitatively and quantitatively comparable waveforms for pelvic obliquity during gait were found between inertial sensor based measures and MOCAP system based measures with reflective markers placed over the anterior and posterior superior iliac spines. These findings are in accordance to results of previous validation studies demonstrating good accuracy and reliability for the assessment of trunk motion measured by inertial sensors and MOCAP systems [9, 10, 19-21].

In patients with unilateral end stage hip OA, measures of pelvic obliquity during gait demonstrated less ROM and higher asymmetry compared to healthy controls. To investigate whether these gait alterations are due to a main effect of osteoarthritis on gait, or related to hip OA specifically, gait was also compared to patients with unilateral end stage knee OA. In order to allow a meaningful comparison of gait parameters between hip OA patients, knee OA patients and healthy controls, standardization of walking speed was aimed for as a significant influence of walking speed on kinematic gait parameters has been reported in literature [1, 15]. To avoid artificial measures of gait with a treadmill, we instructed subjects to walk freely at preferred speed in a hospital's corridor and a statistical correction for the variation of walking speed between groups was applied with ANCOVA [16]. After this statistical correction, hip OA patients demonstrated even lower ROM of pelvic obliquity and twice the amount of pelvic obliquity asymmetry compared to healthy controls and to patients with knee OA. These findings could suggest that alterations in pelvic obliquity during gait are not due to a main effect of

osteoarthritis on gait, but related to hip OA specifically. Moreover, knee OA patients demonstrated no significant difference for ROM of pelvic obliquity compared to healthy controls after correcting for the differences in walking speed. However, significantly higher pelvic obliquity at heel strike (POHS) was found for knee OA patients compared to healthy controls whereas no significant difference was observed for POHS between knee OA and hip OA patients. Interpretation of these findings are made with caution as they can be confounded by the significantly higher BMI in knee OA patients compared to healthy controls and BMI demonstrating a significant interaction with POHS.

Alterations of frontal plane pelvic motion during gait have been related to hip OA causing pain, limited range of motion of the hip joint and decreased muscle strength of the hip abductor muscles [22, 23], often resulting in a limp or gait asymmetry by compensatory mechanisms of the trunk [24]. During single-limb support in the stance phase of gait, pelvic equilibrium in the frontal plane is ensured by the hip abductor muscles which help maintaining balance of the trunk [25]. In patients with hip OA, weakness of the hip abductor muscles can result in two distinct walking patterns. In "Trendelenburg gait" [26], a pelvic drop on the non-supportive swing limb with increased hip adduction on the stance limb is found (i.e. Trendelenburg's sign) [12, 27], moving the compressive force laterally tot the acetabulum [28]. This pelvic drop is frequently compensated by increased lateral trunk lean, shifting the body's center of mass towards the stance limb and shortening the moment arm of the hip abductor muscles, resulting in a typical "Duchenne gait" [29] or "abductor lurch" [28] with the pelvis level or elevated on the non-supportive swing limb. When pain arises in the hip joint during walking, there is also compensatory trunk lean towards the supporting side with significant hip joint load reduction achieved by a combined sideways shift of the pelvis [30]. These patterns of hip unloading mechanisms have also been observed in other hip conditions such as Legg Calvé Perthes Disease (LCPD) [31], congenital hip dislocation [32], and the relationship between severity of hip abductor muscle weakness and the amount of pelvic drop and compensatory lateral trunk lean has been demonstrated in patients with cerebral palsy (CP) [33]. A limitation of this study is that we only measured frontal plane angles at the level of the pelvis and did not obtain the contribution of compensatory lateral trunk lean from the upper trunk. The aim of the study was to obtain frontal plane gait kinematics from a single inertial sensor to supplement spatiotemporal gait parameters derived at the dorsal side of the pelvis for optimal clinical feasibility and

reliability. Measuring lateral trunk lean would necessitate the use of a second sensor and may be less feasible for routine clinical gait analysis.

Spatiotemporal gait parameters demonstrated significant differences for hip OA and knee OA patients compared to healthy controls. These findings are in accordance to previous studies comparing gait between healthy subjects and hip OA or knee OA patients prior to arthroplasty [2, 3, 8]. In patients with unilateral hip OA, step length and walking speed were significantly decreased compared to healthy controls. Patients with hip OA tend to walk with smaller steps, and because the step frequency (i.e. cadence) was not significantly different, it results in decreased walking speed. The disability to walk with larger steps may demonstrate a general effect of osteoarthritis on gait, as step length and walking speed are also reduced in knee OA patients, and these spatiotemporal gait parameters do not identify underlying mechanism related to hip OA specifically. Kinematic gait parameters on the other hand demonstrated significant lower ROM of pelvic obliquity and almost twice the amount of pelvic obliquity asymmetry compared to healthy controls after correcting for variance in walking speed, whereas knee OA patients demonstrated no significant difference for ROM of pelvic obliquity or pelvic obliquity asymmetry compared to healthy controls. These findings could suggest that alterations in pelvic obliquity during gait are not due to a main effect of osteoarthritis on gait, but related to hip OA specifically. Hence, additional assessment of pelvic obliquity during gait could be a clinically relevant measure of functional outcome following THA. For instance, the abductor-sparing anterior approach for THA has demonstrated a closer-to-normal ROM of pelvic obliquity during gait with significantly reduced pelvic obliquity (2°) at ipsilateral foot-off compared to patients with a lateral approach [34]. Furthermore, restoring offset during THA to match that of the normal contralateral side has been shown to improve abductor strength and to reduce the incidence of Trendelenburg's gait [35].

A third aim was to investigate gait kinematics of pelvic obliquity in a healthy cohort, to provide reference data and to investigate the influence of demographic variability. Spatiotemporal gait parameters of eighty healthy participants demonstrated similar results compared to previous reports [6, 14, 36]. The asymmetry of pelvic obliquity during gait and the pelvic obliquity measured at heel strike have not been reported previously in literature. According to our results, asymmetry in pelvic obliquity up to 15% can be regarded as normal and healthy participants

demonstrated a perfect horizontal orientation of the pelvis in the frontal plane at heel strike (POHS = 50.6%). In our healthy cohort, the range of motion of pelvic obliquity was significantly decreased by ageing, however the effect size was rather small (beta standardized coefficient -0.33). Still, these findings could hypothetically suggest that measurements of pelvic obliquity during gait capture decreased physiological functions caused by ageing such as muscle atrophy resulting in hip abductor weakness. In contrast to previous reports [36, 37], we did not find a significant correlation between walking speed and range of motion of pelvic obliquity in healthy subjects. Gard et al. [36] compared the range of motion of pelvic obliquity during gait, measured by a MOCAP system, in three healthy subjects (age 22-29) walking at eight different walking speeds between 1.0-2.4m/s at increments of 0.2m/s. Over the range of walking speeds, the range of motion of pelvic obliquity ranged from 5-20° with a linear increase with the walking speed for each individual. Furthermore, a study by Michaud et al. [37] investigated the range of motion of pelvic obliquity during gait in nine persons with transtibial or transfemoral amputation, and compared their results with results from the study cohort of Gard et al. A linear relationship was found for range of motion of pelvic obliquity with speed, demonstrating correlation coefficients all exceeding 0.70. We measured range of motion of pelvic obliquity in eighty healthy subjects while they walked at preferred speed only. We found inter-subject variability in the range of motion of pelvic obliquity during gait within a limited range of walking speeds. Because we did not measure different walking speeds, we cannot truly compare our results with the previous findings from Gard et al. and Michaud et al. Individual differences in the range of motion of pelvic obliquity may be multifactorial, but may change with a similar magnitude between subjects by increasing walking speed.

Conclusion

This study demonstrates that ambulatory gait analysis with a single inertial sensor positioned at the dorsal side of the pelvis allows both spatiotemporal and kinematic characterization of gait. Focusing on pelvic motion in the frontal plane (i.e. pelvic obliquity), patients with hip OA demonstrated significantly less range of motion and higher asymmetry compared to healthy controls and compared to patients with knee OA. Therefore, kinematic characterization of pelvic obliquity during gait seems to capture hip OA related disability. Pelvic obliquity seems a valuable biomechanical measure of gait that is independent of time, and could be used to

objectively assess functional disability in patients with hip OA and to monitor functional improvement after total hip arthroplasty.

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Legends

Figure 1: Characterization of pelvic obliquity (PO) during gait demonstrating primary peaks, secondary components which occur at heel strike (HS), range of motion (ROM) and δ.

Figure 2: waveforms of pelvic obliquity during gait in a healthy subject. Left figure shows a MOCAP system based measurement of one gait cycle. Right figure shows an inertial sensor based measurement of one gait cycle.

Table I: Group demographics. *p<0.05 Knee OA vs. Control group.

Table II: Gait parameters of hip OA patients, knee OA patients and the control group. P-values correspond with level of significance compared to healthy controls.

Table III: Reference data for gait parameters in healthy subjects demonstrating mean values and standard deviations (SD), and beta standardized coefficients from multiple linear regression analysis between gait parameters and demographic variables. *p<0.05

Tables:

	Control group n=20 male:female = 9:11		**Hip OA n=20** male:female = 10:10		**Knee OA n=20** male:female = 9:11	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	61.0	6.1	63.4	8.5	65.4	9.3
Height (cm)	173	8.4	172	9.7	167	9.1
Weight (kg)	77.2	12.7	81.1	17.8	84.2	18.6
BMI	25.8	3.0	27.2	4.9	30.2*	7.3

Table I

	Control group n=20		**Hip OA n=20**			**Knee OA n=20**			**Hip OA vs Knee OA**
Gait parameters	Mean	SD	Mean	SD	p-value	Mean	SD	p-value	p-value
Speed	1.30	0.15	1.10	0.19	<0.01	0.98	0.19	<0.001	n.s.
Cadence	114.8	8.0	109.7	8.4	n.s.	105.9	11.3	<0.05	n.s.
Step time	0.53	0.04	0.55	0.04	n.s.	0.57	0.06	<0.05	n.s.

Step length	0.68	0.07	0.61	0.09	<0.01	0.55	0.07	<0.001	n.s.
Step time irregularity (%)	0.04	0.03	0.04	0.03	n.s.	0.06	0.03	<0.05	n.s.
Step time asymmetry (%)	2.50	1.84	2.31	1.61	n.s.	5.05	2.30	<0.001	<0.001
RoM pelvic obliquity (°)	8.6	2.8	5.5	1.7	<0.001	6.7	1.8	<0.05	<0.05
RoM pelvic obliquity (°) corrected for speed	8.0	2.4	5.6	2.1	<0.01	7.3	2.3	n.s.	<0.01
PO asymmetry (%)	15.9	13.1	32.2	25.6	<0.05	16.1	12.4	n.s.	<0.05
POHS (%)	50.2	15.4	66.4	24.9	n.s.	73.6	22.4	<0.01	n.s.

412 Table II

	Healthy subjects n=80		**Demographic variables**				
Gait parameters	Mean	SD	Age	Gender	Length	Weight	BMI
Speed (m/s)	1.29	0.15	0.09	0.28	-0.61	0.74	-0.78
Cadence (steps/min)	113.65	8.34	0.09	-0.03	-0.68	0.23	0.28
Step time (s)	0.53	0.04	-0.09	0.03	0.67	-0.22	0.30
Step length (m)	0.68	0.06	0.07	0.27	0.30	0.90	0.87
Step time irregularity (cv)	4.62	2.90	-0.05	-0.14	0.85	-1.49	1.28
Step time asymmetry (%)	3.13	2.32	0.04	-0.13	0.56	-0.68	0.43
RoM pelvic obliquity (°)	10.1	3.2	-0.33*	0.15	0.47	-0.62	0.50
PO asymmetry (%)	14.9	12.6	0.00	-0.22	0.08	0.02	-0.08
POHS (%)	50.6	14.8	-0.05	0.17	-0.34	0.00	0.25

413 Table III

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