Measuring gait kinematics in patients with severe hip osteoarthritis using wearable sensors

Petros Ismailidis, Corina Nüesch, Mara Kaufmann, Martin Clauss, Geert Pagenstert, Anke Eckardt, Thomas Ilchmann, Annegret Mündermann

PII: S0966-6362(20)30237-X

DOI: https://doi.org/10.1016/j.gaitpost.2020.07.004

Reference: GAIPOS 7612

To appear in: *Gait & Posture*

Received Date: 31 January 2020

Revised Date: 2 July 2020

Accepted Date: 4 July 2020

Please cite this article as: Ismailidis P, Nüesch C, Kaufmann M, Clauss M, Pagenstert G, Eckardt A, Ilchmann T, Mündermann A, Measuring gait kinematics in patients with severe hip osteoarthritis using wearable sensors, *Gait and amp; Posture* (2020), doi: https://doi.org/10.1016/j.gaitpost.2020.07.004

Original Research Article

Measuring gait kinematics in patients with severe hip osteoarthritis using wearable sensors

Petros Ismailidis[1,2,3], Corina Nüesch[1,2,3,4] Mara Kaufmann[1], Martin Clauss[1], Geert Pagenstert[2,5], Anke Eckardt[6], Thomas Ilchmann[6], Annegret Mündermann[1,2,3,4]
[1]Department of Orthopaedics and Traumatology, University Hospital Basel, Basel, Switzerland
[2]Department of Clinical Research, University of Basel, Basel, Switzerland
[3]Department of Biomedical Engineering, University of Basel, Basel, Switzerland
[4]Department of Spine Surgery, University Hospital Basel, Basel, Switzerland
[5]Clarahof Clinic of Orthopaedic Surgery, Clarahofweg 19a, 4058 Basel, Switzerland
[6] ENDO-Team, Hirslanden Klinik, Birshof, Reinacherstrasse 28, 4142 Münchenstein, Switzerland

July 2020

Submitted to: *Gait and Posture*

Manuscript # GAIPOS-D-20-00101

Address of correspondence: Dr. Petros Ismailidis; Department of Orthopaedics and Traumatology, University Hospital Basel, Spitalstrasse 21, 4031 Basel, Switzerland, Tel. +41 61 328 7133

Email petrosismailidis@gmail.com

Word count:

Highlights

- Hip osteoarthritis kinematics are measured with wearable sensors.
- Results for novel method agrees well with literature.
- RehaGait® use for hip osteoarthritis is feasible

Abstract

Background: The popularity of inertial sensors in gait analysis is steadily rising. To date, an application of a wearable inertial sensor system for assessing gait in hip osteoarthritis (OA) has not been reported.

Research question: Can the known kinematic differences between patients with hip OA and asymptomatic control subjects be measured using the inertial sensor system RehaGait®?

Methods: The patients group consisted of 22 patients with unilateral hip OA scheduled for total hip replacement. Forty-five age matched healthy control subjects served as control group. All subjects walked for a distance of 20 meters at their self-selected speed. Spatiotemporal parameters and sagittal kinematics at the hip, knee, and ankle including range of motion (ROM) were measured using the RehaGait® system.

Results: Patients with hip OA walked at a slower walking speed (-0.18m/s, P<0.001) and with shorter stride length (-0.16m, P<0.001), smaller hip ROM during stance (-11.6°, P<0.001) and swing (-11.3°, P<0.001) and smaller knee ROM during terminal stance and swing (-9.0° and -11.5°, P<0.001). Patients had a smaller hip ROM during stance and swing and smaller knee ROM during terminal stance and swing in the affected compared to the unaffected side (P<0.001).

Significance: The differences in spatiotemporal and kinematic gait parameters between patients with hip OA and age matched control subjects assessed using the inertial sensor system agree with those documented for camera-based systems. Hence, the RehaGait® system can measure gait kinematics characteristic for hip OA, and its use in daily clinical practice is feasible.

Key words: inertial sensors; hip osteoarthritis; gait analysis; wearable sensors; kinematics

1. Introduction

Hip osteoarthritis (OA) is a very common disease that will affect 25% of the population in the course of a lifetime [1]. Its prevalence is expected to increase over the next decades because of the aging population [2]. The potential of gait analysis in understanding the OA disease process and its treatment has long been recognized [3]. For instance, gait analysis can help understand the underlying gait adaptation processes, assist in designing

conservative and surgical management strategies as well as evaluate the treatment outcome. Various studies have reported spatiotemporal and kinematic changes in patients with OA [3-10]. Most of these studies performed the measurements in a dedicated gait laboratory using reflective markers placed on the skin at predefined anatomical positions captured by high speed cameras [4, 5, 7, 8, 11-13]. These measurements have a considerable need of resources since they require specialized personnel and equipment and are time consuming [14]. Not surprisingly, the number of studies reporting on gait analysis in patients with hip OA is in no way comparable to the number of studies reporting on other functional outcome measures despite of the obvious relevance of ambulatory mechanics in the disease process [15]. Moreover, these studies typically report on small cohorts because of the time and cost associated with assessments with marker and camera-based systems in gait laboratories. A systematic review examining gait analysis as an outcome measure for hip OA concluded that one of the main limitations of the existent literature is the insufficient number of patients in the studies [3].

Inertial sensors have risen in popularity as an affordable, time efficient, practical way of performing gait analysis [16]. Inertial sensor systems do not require a dedicated laboratory and hence are feasible in an outpatient clinic setting and in large cohorts. Several inertial sensor systems have been described in the last decade [16]. While most studies on OA using inertial sensor systems have focused on knee OA, a few studies performing measurements with inertial sensor systems in patients with hip OA have reported spatiotemporal parameters [6, 9, 10, 17, 18], but none of these captured joint kinematics. Among inertial sensor systems, the RehaGait® system has been shown to provide reliable data that are comparable to an instrumented treadmill and camera-based system for measuring spatiotemporal parameters and lower limb kinematics in younger and older healthy subjects as well as in patients with knee OA and lumbar spinal stenosis [19-23].

The purpose of this study was to investigate the feasibility of using the RehaGait® for gait analysis in patients with hip OA. We hypothesized that known spatiotemporal and kinematic differences between patients with hip OA and age matched asymptomatic control subjects can be measured using the inertial sensor system RehaGait®.

2. Methods

2.1 Participants

Twenty-two patients with severe hip OA were included in this study. Inclusion criteria were: age ≥ 30 years; diagnosed unilateral hip OA scheduled for total hip arthroplasty (THA). Exclusion criteria were: body mass index (BMI) > 35 kg/m^2; use of walking aids; neuromuscular disorders affecting gait. Patients were recruited through our outpatient clinic as well as through cooperating external orthopaedic clinics. Forty-five control subjects were included meeting the inclusion criteria: age ≥ 30 years; and no clinical diagnosis of OA, rheumatoid arthritis or history of knee or hip trauma or pain at the time of the measurement. Exclusion criteria were: Hip Osteoarthritis Outcome Score (HOOS) < 90 in the pain subcategory; BMI > 35 kg/m^2; use of walking aids; neuromuscular disorders affecting gait; and inability to follow procedures due to psychological disorders or dementia. Control subjects were recruited from the local community through advertisements on our internet page. All subjects gave written informed consent prior to participation. This study was approved by the regional review board and conducted in accordance with the Declaration of Helsinki.

2.2 Demographic and clinical parameters

Demographic data including age, sex, body mass, height, and BMI were recorded for each subject. The HOOS score was used as subjective measure of the patients' symptoms [24]. The HOOS is composed of a total of 40 questions further divided in five subscales consisting of 10 questions for pain (HOOS Pain), five for symptoms (HOOS Symptoms), 17 for activities of daily living (HOOS ADL), four for sport and recreation (HOOS Sport/Rec) and four for hip related quality of life (HOOS QOL). A total score is calculated for each subcategory with a range from 0-100, higher scores representing better conditions. Anteroposterior pelvic x-rays and axial hip x-rays were used to determine the Kellgren/Lawrence (K/L) radiographic severity scale of the patients [25]. A K/L grade of 1 on the contralateral side was accepted as long as the hip was asymptomatic. The combination of a K/L Grade 3 or 4 and symptoms leading to the decision to perform a THA was defined as severe hip OA [26].

2.3 Measurements

The measurements were performed using the RehaGait® (Hasomed, Magdeburg, Germany) inertial sensor system. The system consists of seven sensors, each comprising three accelerometers, three gyroscopes and a magnetometer. Three sensors were placed at each lower extremity (lateral foot, lateral lower leg and lateral thigh) and one on the pelvis overlying the 5^{th} lumbar vertebra (Fig. 1). The calibration of the system took place with the subject standing for 10 s and then flexing the trunk and each hip alternating. Each subject walked for 20 m at a self-selected speed. Spatiotemporal and kinematic parameters for the hip, knee and ankle were computed by the manufacturer's proprietary software (Hasomed, Magdeburg, Germany) according to Seel et al. [27]. Spatiotemporal parameters (walking

speed, cadence, stride length and duration as well as duration of stance/swing phase and single/double support phase as percentage of the gait cycle) as well as time series of hip, knee and ankle kinematics were exported. Spatiotemporal and ankle, knee and hip kinematic data obtained using this system are comparable to those obtained using a state-of-the-art camera-based system and is reliable [19, 21, 28].

2.4 Data processing and statistical analyses

Discrete kinematic parameters including dynamic joint range of motion (ROM), minimum and maximum hip, knee and ankle angles during stance and swing were computed using a custom algorithm written in Matlab (MathWorks Inc., Natick, MA, USA) from the kinematic time series and used for further analyses. Because we were interested in the clinical relevance of group and side differences, 95% confidence intervals (CI) were calculated for within-subject and between-subject differences in spatiotemporal and kinematic parameters. In addition, paired and independent sample t-tests were performed to detect statistically significant within-subject and between-subject differences, respectively. The significance level was set a priori to 0.05 with a Bonferroni correction to account for multiple comparisons resulting in a significance level of 0.025.

The required number of subjects was calculated based on group differences reported in the literature [11]. Sample size estimation revealed that 9 participants per group were required to detect an expected difference in hip ROM with an effect size of at least 1.33 with 80% power at a 5% significance level. We aimed at enrolling 20 participants per group.

3. Results

3.1 Clinical evaluation

The demographic parameters of the two groups are presented in Table 1. Each subcategory of the HOOS score was significantly lower in the hip OA group, the greatest differences were observed in the HOOS QOL (quality of life) subcategory. Nine patients had a K/L grade of 3, and 13 patients had a K/L grade of 4.

3.2 Spatiotemporal differences between patients with hip OA and controls

Patients with hip OA had a slower walking speed (-0.18 m/s, P<0.001) and shorter stride length than the control subjects (-0.16m, P<0.001; Table 2). While not statistically significant, the cadence in patients was lower than in the control group (-4.13 steps/min, P=0.116). There was no notable difference in stride duration between groups (+0.05 s, P=0.079). Furthermore, the single support phase of the affected leg of the patients, expressed as a percentage of the gait cycle, was shorter than that of the healthy group (-2.9%, P<0.001). The comparison between legs in patients revealed that the stance phase of the affected side was shorter than that of the unaffected side (-2.3%, P=0.019).

3.3 Kinematic differences between the affected leg of the patients and controls

The two legs of the control subjects did not differ in any kinematic parameters (P>0.05, Fig.2). Therefore, the left lower extremity parameters were used for further analyses. The affected side of the patients had less maximum hip flexion during stance and swing (-8.0°, P<0.001 and -7.8°, P=0.001, respectively) and less maximum hip extension (-3.5°, P<0.001; Table 3). Accordingly, hip ROM in the patients was lower during stance (-11.6°, P<0.001) and swing (-11.3°, P<0.001) compared to the control group. The knee of the

affected side in patients had a smaller ROM during terminal stance and swing (-9.0° and -11.5°, P<0.001, respectively) and a higher minimum flexion angle in the terminal stance phase (+7.2°, P<0.001). Lastly, the ankle of the affected side had a higher maximum dorsiflexion angle than the control group (+3.5°, P=0.001; Fig.2 and Fig.3).

3.4 Kinematic differences between the affected and the unaffected hip of the patients

The affected side in patients had a smaller hip ROM during stance and swing (-9.3° P=0.002 and -9.3°, P=0.004, respectively) and smaller maximum hip flexion during stance and swing (-8.1°, P=0.007, and -8.1°, P=0.017, respectively) compared to the unaffected side. Furthermore, the affected side had a smaller knee ROM during terminal stance and swing (-7.5° and -6.8°, P<0.001, respectively) and a higher minimum knee flexion in the terminal stance phase (+4.8°, P<0.001). Lastly, the ankle of the affected side had a higher maximum dorsiflexion angle than the contralateral side (+2.5°, P=0.020; Fig.2 and Fig.3).

4. Discussion

We hypothesized that the known spatiotemporal and kinematic differences between patients with hip OA and asymptomatic control subjects can be measured using the inertial sensor system RehaGait®. The measured differences were in agreement with those reported in the literature for marker and camera-based gait analysis systems. To the best of our knowledge this is the first study measuring kinematic differences in the hip, knee and ankle joints in patients with hip OA with a wearable inertial sensor system.

4.1. Spatiotemporal and kinematic differences in patients with hip OA

We measured a slower walking speed and shorter stride length in patients with hip OA compared to the asymptomatic individuals. There is strong and consistent evidence in the literature, including two systematic reviews [3, 29], that speed and stride length are lower in patients with hip OA compared to healthy individuals. Furthermore, we found a shorter single support phase in the affected leg of patients with hip OA compared to the control group, which is in agreement with all studies reporting on single/double support duration included in the systematic review of Constantinou et al [29]. Moreover, the observed shorter stance phase in the affected side compared to the unaffected side agrees with earlier studies and indicates gait asymmetry [29].

Furthermore, we detected smaller hip ROM during stance and swing in the affected hip compared to controls. Although some inconsistency exists regarding the terminology – previous studies reported ROMs for the entire gait cycle or in distinct phases of the gait cycle – several studies have described similar kinematic changes in patients with hip OA compared to controls. For instance, Ornetti et al. [7], Eitzen et al. [11] and Zeni et al. [8] all reported a reduction in hip ROM with less maximum flexion and extension of the OA hip. Bejek et al [5] confirmed these findings at different walking speeds while Ardestani et al.[4] used statistical parametric mapping analysis to explore the kinematic changes over the entire gait cycle and reported a reduction in the hip extension angle in early stance and in the hip flexion angle between 30 and 70% of the gait cycle. In addition, we observed kinematic changes at the knee and ankle of the affected leg. The knee of the affected side in patients had a smaller flexion/extension ROM during terminal stance and swing, and the ankle of the affected side had a higher peak dorsiflexion angle. While some studies measuring kinematics in patients with hip OA did not report data for the knee [8] or ankle [5, 8] and others found the reduction

in knee ROM to be not significant [7], several studies already described a reduction in ROM of the affected knee in patients with hip OA [4, 5, 11]. In addition, Ornetti et al. [7] reported an increased peak ankle dorsiflexion angle in the affected leg. Altogether the kinematic differences between patients with OA and control, despite the differences in the terminology, analysis and way of presentation, are reported consistently in the literature of camera-based systems. This study confirms these findings using a wearable sensor system.

Regarding side to side differences, we found smaller hip ROM and a lower maximum hip flexion during stance and swing in the affected compared to the unaffected side. The hip extension was less affected, which may be explained by a more symmetrical mechanism of compensation with pathologic motion in the pelvis as suggested Bejek et al. [5] although pelvic motion was not measured in the present study. Many studies reporting on gait in hip OA either did not focus only on unilateral hip OA [11, 12] or did not report direct comparisons between the affected and the unaffected side [4, 13]. Therefore, it is not possible to draw clear conclusions about the side to side kinematic differences occurring in unilateral hip OA. Nonetheless, our results regarding side to side kinematic differences are in agreement with the few studies reporting corresponding data. For instance, Zeni et al. [8] reported lower maximum hip flexion and extension angles, and Bejek et al. [5] reported lower peaks in hip and knee flexion and extension as well as in the ROM. Although side to side differences are possibly more difficult to detect because patients with unilateral disease are needed and the differences are smaller than those compared to healthy subjects, they are equally interesting since they are a clear sign of asymmetry. The similarities in the results of different studies

investigating unilateral OA – the present study included – shows that these differences characterize the gait pattern of unilateral hip OA.

4.2 Wearable inertial sensor applications in patients with hip OA

There is a clear need for an inexpensive, simple and time efficient method of gait analysis in patients with hip OA. Marker and camera-based systems have been used in many previous studies [4, 5, 7, 8, 11]. Yet, the associated great need for resources has prevented gait analysis from being established as standardized quantitative functional assessment to supplement clinical and radiological scores in clinical studies. To solve this problem, researchers have tried to apply inertial sensor systems in the gait analysis of patients with hip OA. Although several similar efforts in patients with knee OA have been successful [14], to date in hip OA kinematic measurements of the hip, knee and ankle joints using wearable inertial sensor systems have not been reported. Bolink et al.[6] used a single inertial measurement unit (MicroStrain® Inertia-Link®) for measuring spatiotemporal parameters and pelvic tilt angles. Aminian et al. [9] used a 4-sensor inertial sensor system placed at each shank and thigh (Physilog ®) and reported spatiotemporal parameters as well as thigh and shank rotations but no sagittal kinematic parameters. Barrois et al. [10] used a system comprising four inertial sensors attached to the head, the lower back (L3-L4) and both feet (XSens®) measuring acceleration signals and identified parameters discriminating between different severity stages of OA. However, they did not report spatiotemporal or joint kinematics during gait. Lastly, Rapp et al. [30] measured spatiotemporal parameters in patients who received a THA for hip OA.

To date, hip kinematics during gait have not been reported for inertial sensor systems. Contrary to knee joint, capturing hip kinematics requires sensors placed at the pelvis and at

the legs. Clearly, our results demonstrate that assessing hip kinematics using the sensors of the RehaGait® system is feasible. Technical improvements are expected in all inertial sensor systems, and hence further studies on hip OA using wearable inertial sensor systems are expected to emerge in the following years. The results of our study are promising and may serve as comparison for future studies that are needed to confirm these results. Building upon our study, data on changes in spatiotemporal parameters and lower extremity kinematics after THA can now be generated. Because wearable inertial sensor systems are easy to use and time efficient, the use of inertial sensors should increase the number of subjects included in studies reporting on hip OA kinematics allowing for using ambulatory mechanics as outcome of large clinical trials and facilitate capturing gait data as measures for monitoring quality and success of conservative or surgical treatment. Moreover, large data sets on ambulatory mechanics in patients with hip and knee OA and other orthopaedic conditions affecting the lower extremities will allow to identify specific gait parameters that are characteristic not only for the specific condition but also for its severity.

4.3. Strengths and limitations

The strengths of this study include the homogeneity of the patient group because we included only patients with severe unilateral hip OA. Furthermore, participants in the control group in our study were matched for age to our patient group. In this first study on the use of wearable inertial sensors for measuring spatiotemporal and kinematic difference in gait between patients with hip OA and control subjects, we only included a rather small sample size. However, in line with our a priori sample size estimation, we found clear and clinically relevant spatiotemporal and kinematic differences. The results presented in our study apply only to the inertial sensor system RehaGait® and would have to be confirmed for other inertial sensor systems. While most inertial sensors comprise similar technology (accelerometers, gyroscopes, magnetometers), existing systems differ largely with respect to

the underlying computational algorithms and wireless data transfer protocols, and hence the comparability among these systems has yet to be shown.

5. Conclusion

Spatiotemporal and kinematic gait parameters characteristic of patients with hip OA can be measured with the RehaGait® inertial sensor system. This system is inexpensive, practical, time efficient and requires no specific expertise in the field of biomechanics. Therefore, this system is suitable for routine application in clinical practice and for large cohort studies. This study clearly showed that the utilization of wearable inertial sensor systems for gait analysis in hip OA is feasible.

Conflict of interest statement

The authors declare no conflict of interest.

Acknowledgements
Funding was received from the Department of Orthopaedics and Traumatology of the University Hospital Basle, the Foundation for Funding Science and Education at the Department of Surgery at the University of Basel, Swiss Orthopaedics, Merian Iselin Foundation and Deutsche Arthrose-Hilfe e.V. The funding sources had no involvement in any aspect of this study.

References

[1] L.B. Murphy, C.G. Helmick, T.A. Schwartz, J.B. Renner, G. Tudor, G.G. Koch, et al., One in four people may develop symptomatic hip osteoarthritis in his or her lifetime, Osteoarthritis Cartilage 18(11) (2010) 1372-9.
[2] A. Turkiewicz, I.F. Petersson, J. Bjork, G. Hawker, L.E. Dahlberg, L.S. Lohmander, et al., Current and future impact of osteoarthritis on health care: a population-based study with projections to year 2032, Osteoarthritis Cartilage 22(11) (2014) 1826-32.
[3] P. Ornetti, J.F. Maillefert, D. Laroche, C. Morisset, M. Dougados, L. Gossec, Gait analysis as a quantifiable outcome measure in hip or knee osteoarthritis: a systematic review, Joint Bone Spine 77(5) (2010) 421-5.
[4] M.M. Ardestani, M.A. Wimmer, Can a linear combination of gait principal component vectors identify hip OA stages?, J Biomech 49(10) (2016) 2023-2030.
[5] Z. Bejek, R. Paroczai, A. Illyes, R.M. Kiss, The influence of walking speed on gait parameters in healthy people and in patients with osteoarthritis, Knee Surg. Sports Traumatol. Arthrosc. 14(7) (2006) 612-22.
[6] S.A. Bolink, L.R. Brunton, S. van Laarhoven, M. Lipperts, I.C. Heyligers, A.W. Blom, et al., Frontal plane pelvic motion during gait captures hip osteoarthritis related disability, Hip Int. 25(5) (2015) 413-9. http://www.ncbi.nlm.nih.gov/pubmed/26351120.

[7] P. Ornetti, D. Laroche, C. Morisset, J.N. Beis, C. Tavernier, J.F. Maillefert, Three-dimensional kinematics of the lower limbs in hip osteoarthritis during walking, J. Back Musculoskelet. Rehabil. 24(4) (2011) 201-8. http://www.ncbi.nlm.nih.gov/pubmed/22142708.
[8] J. Zeni, Jr., F. Pozzi, S. Abujaber, L. Miller, Relationship between physical impairments and movement patterns during gait in patients with end-stage hip osteoarthritis, J. Orthop. Res. 33(3) (2015) 382-9.
[9] K. Aminian, C. Trevisan, B. Najafi, H. Dejnabadi, C. Frigo, E. Pavan, et al., Evaluation of an ambulatory system for gait analysis in hip osteoarthritis and after total hip replacement, Gait Posture 20(1) (2004) 102-107.
[10] R. Barrois, T. Gregory, L. Oudre, T. Moreau, C. Truong, A. Aram Pulini, et al., An Automated Recording Method in Clinical Consultation to Rate the Limp in Lower Limb Osteoarthritis, PLoS One 11(10) (2016) e0164975. http://www.ncbi.nlm.nih.gov/pubmed/27776168.
[11] I. Eitzen, L. Fernandes, L. Nordsletten, M.A. Risberg, Sagittal plane gait characteristics in hip osteoarthritis patients with mild to moderate symptoms compared to healthy controls: a cross-sectional study, BMC Musculoskelet. Disord. 13 (2012) 258.
[12] R.J. Leigh, S.T. Osis, R. Ferber, Kinematic gait patterns and their relationship to pain in mild-to-moderate hip osteoarthritis, Clin. Biomech. (Bristol, Avon) 34 (2016) 12-7.
[13] C.A.G. Meyer, M. Wesseling, K. Corten, A. Nieuwenhuys, D. Monari, J.P. Simon, et al., Hip movement pathomechanics of patients with hip osteoarthritis aim at reducing hip joint loading on the osteoarthritic side, Gait Posture 59 (2018) 11-17.
[14] R. van der Straaten, L. De Baets, I. Jonkers, A. Timmermans, Mobile assessment of the lower limb kinematics in healthy persons and in persons with degenerative knee disorders: A systematic review, Gait Posture 59 (2018) 229-241.
[15] H. Tateuchi, Y. Koyama, H. Akiyama, K. Goto, K. So, Y. Kuroda, et al., Daily cumulative hip moment is associated with radiographic progression of secondary hip osteoarthritis, Osteoarthritis Cartilage 25(8) (2017) 1291-1298. https://www.ncbi.nlm.nih.gov/pubmed/28232145.
[16] R. Caldas, M. Mundt, W. Potthast, F. Buarque de Lima Neto, B. Markert, A systematic review of gait analysis methods based on inertial sensors and adaptive algorithms, Gait Posture 57 (2017) 204-210.
[17] S. Bolink, E. Lenguerrand, L.R. Brunton, N. Hinds, V. Wylde, I.C. Heyligers, et al., The association of leg length and offset reconstruction after total hip arthroplasty with clinical outcomes, Clin. Biomech. (Bristol, Avon) 68 (2019) 89-95. http://www.ncbi.nlm.nih.gov/pubmed/31177011.
[18] S.A. Bolink, B. Grimm, I.C. Heyligers, Patient-reported outcome measures versus inertial performance-based outcome measures: A prospective study in patients undergoing primary total knee arthroplasty, Knee 22(6) (2015) 618-23. http://www.ncbi.nlm.nih.gov/pubmed/26032657.
[19] C. Nüesch, E. Roos, G. Pagenstert, A. Mündermann, Measuring joint kinematics of treadmill walking and running: Comparison between an inertial sensor based system and a camera-based system, J. Biomech. 57 (2017) 32-38. http://www.ncbi.nlm.nih.gov/pubmed/28366438

https://www.sciencedirect.com/science/article/abs/pii/S0021929017301641?via%3Dihub.
[20] S. Loske, C. Nüesch, K.S. Byrnes, O. Fiebig, S. Schären, A. Mündermann, et al., Decompression surgery improves gait quality in patients with symptomatic lumbar spinal stenosis, Spine J 18(12) (2018) 2195-2204. https://www.ncbi.nlm.nih.gov/pubmed/29709554.
[21] L. Donath, O. Faude, E. Lichtenstein, G. Pagenstert, C. Nuesch, A. Mundermann, Mobile inertial sensor based gait analysis: Validity and reliability of spatiotemporal gait characteristics in healthy seniors, Gait Posture 49 (2016) 371-374. https://www.ncbi.nlm.nih.gov/pubmed/27494305

https://www.sciencedirect.com/science/article/abs/pii/S0966636216304076?via%3Dihub.
[22] P. Ismailidis, C. Egloff, L. Hegglin, G. Pagenstert, R. Kernen, A. Eckardt, et al., Kinematic changes in patients with severe knee osteoarthritis are a result of reduced walking speed

rather than disease severity, Gait Posture 79 (2020) 256-261. https://www.ncbi.nlm.nih.gov/pubmed/32460135.
[23] P. Ismailidis, L. Hegglin, C. Egloff, G. Pagenstert, R. Kernen, A. Eckardt, et al., Measuring gait kinematics in patients with severe knee osteoarthritis using inertial sensors, (In review).
[24] A.K. Nilsdotter, L.S. Lohmander, M. Klassbo, E.M. Roos, Hip disability and osteoarthritis outcome score (HOOS)--validity and responsiveness in total hip replacement, BMC Musculoskelet. Disord. 4 (2003) 10.
[25] L.J. Kellgren JH, The Epidemiology of Chronic Rheumatism: Atlas of Standard Radiographs of Arthritis, Blackwell Scientific Publications1963.
[26] J.L. Astephen, K.J. Deluzio, G.E. Caldwell, M.J. Dunbar, Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity, J Orthop Res 26(3) (2008) 332-41.
[27] T. Seel, J. Raisch, T. Schauer, IMU-based joint angle measurement for gait analysis, Sensors (Basel) 14(4) (2014) 6891-909. https://www.ncbi.nlm.nih.gov/pubmed/24743160.
[28] L. Donath, O. Faude, E. Lichtenstein, C. Nüesch, A. Mündermann, Validity and reliability of a portable gait analysis system for measuring spatiotemporal gait characteristics: comparison to an instrumented treadmill, J. Neuroeng. Rehabil. 13(1) (2016) 6. https://dx.doi.org/10.1186/s12984-016-0115-z

https://jneuroengrehab.biomedcentral.com/track/pdf/10.1186/s12984-016-0115-z.
[29] M. Constantinou, R. Barrett, M. Brown, P. Mills, Spatial-temporal gait characteristics in individuals with hip osteoarthritis: a systematic literature review and meta-analysis, J. Orthop. Sports Phys. Ther. 44(4) (2014) 291-B7.
[30] W. Rapp, T. Brauner, L. Weber, S. Grau, A. Mündermann, T. Horstmann, Improvement of walking speed and gait symmetry in older patients after hip arthroplasty: a prospective cohort study, BMC Musculoskelet. Disord. 16 (2015) 291. http://www.ncbi.nlm.nih.gov/pubmed/26459628.

Fig. 1. Views of an individual wearing the RehaGait® inertial sensors. The system consists of seven sensors. Three sensors were placed at each lower extremity (lateral foot, lateral lower leg and lateral thigh) and one on the pelvis overlying the 5th lumbar vertebra.

Fig. 2. Ankle, knee and hip flexion angles during walking for individual steps for one patient with severe hip osteoarthritis (top; red–affected side; blue–unaffected side) and one asymptomatic control subject (bottom; grey–left side; black–right side).

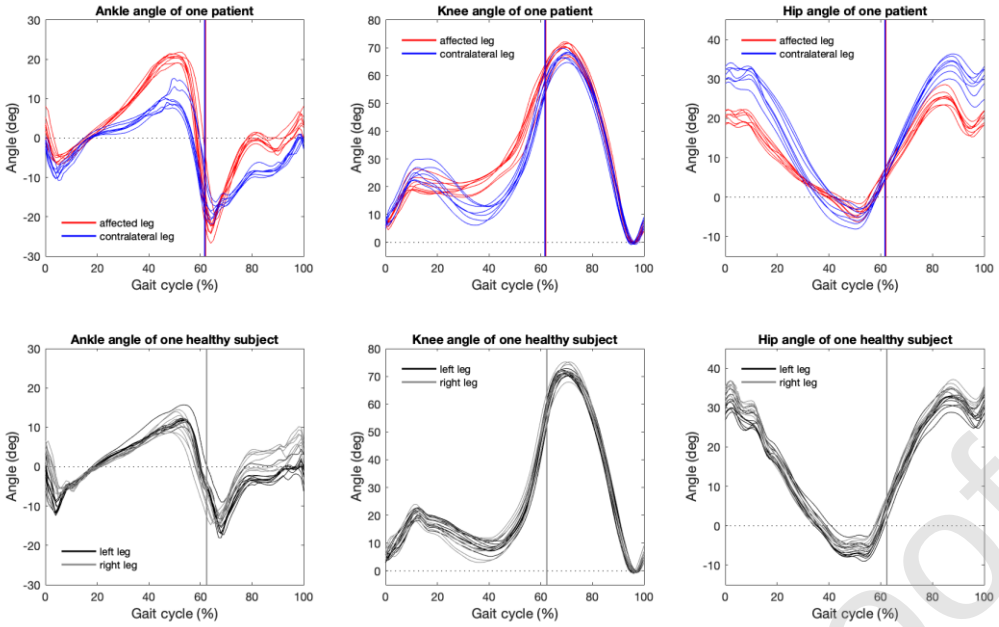

Fig. 3. Mean ankle (left), knee (middle) and hip (right) kinematics in patients with severe hip OA (N=22; affected–red line, unaffected side–blue line) and asymptomatic control subjects (N=45; black line).

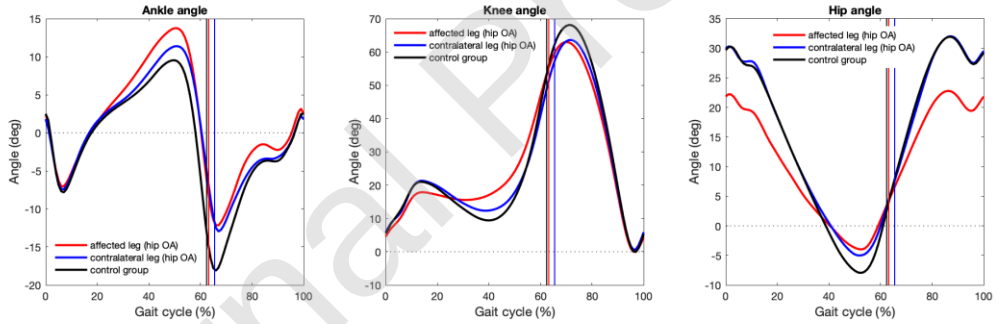

Table 1. Mean (1 standard deviation) characteristics of patients with hip OA scheduled for total hip replacement (N=22) and age-matched asymptomatic control subjects (N=45).

Parameters	*Patients*	*Asymptomatic controls*	*P-value*
Sex (male/female)	12/10	16/29	0.139[a]
Age (years)	66.3 (10.2)	66.6 (7.4)	0.867[b]
Height (m)	1.71 (0.08)	1.69 (0.08)	0.363[b]
Body mass (kg)	79.7 (13.2)	71.0 (11.9)	**0.008** [b]
BMI (kg/m^2)	27.3 (3.3)	25.0 (4.1)	0.025 [b]
HOOS Pain	98.6 (3.1)	52.3 (15.7)	< **0.001** [b]
HOOS Symptoms	97.2 (4.7)	48.3 (16.1)	< **0.001** [b]
HOOS ADL	98.6 (3.6)	53.8 (18.3)	< **0.001** [b]
HOOS Sport/Rec	98.0 (5.1)	35.1 (23.7)	< **0.001** [b]
HOOS QOL	97.0 (7.7)	27.2 (15.3)	< **0.001** [b]

[a] Chi-square test; [b] independent sample t test

BMI – body mass index; HOOS – hip injury and osteoarthritis outcome score; ADL – activities of daily living; Rec – recreation; QOL – quality of life.

Table 2. Mean (1 standard deviation) spatiotemporal gait parameters in patients with hip OA scheduled for total hip replacement (N=22) and age-matched asymptomatic control subjects (N=45).

Parameter	*Patients*	*Controls*	*95% CI patients - controls*	*P value patients - controls*
Stride duration (s)	1.12 (0.13)	1.07 (0.09)	[-0.01; 0.10]	0.079
Stride length (m)	1.16 (0.17)	1.32 (0.12)	**[-0.24; -0.09]**	**<0.001**
Walking speed (m/s)	1.06 (0.22)	1.24 (0.15)	**[-0.28; -0.09]**	**<0.001**
Cadence (steps/min)	108.68 (11.83)	112.81 (8.93)	[-9.30; 1.05]	0.116
Stance phase (%gc) (affected side)	63.2 (2.6)	62.4 (2.0)	[-0.4; 2.0]	0.174
Swing phase (%gc) (affected side)	36.8 (2.6)	37.6 (2.0)	[-2.0; 0.4]	0.174
Single support phase (%gc) (affected side)	34.7 (4.7)	37.6 (1.7)	**[-4.5; -1.3]**	**<0.001**
Double support phase (%gc) (affected side)	15.0 (4.6)	12.5 (1.6)	**[0.9; 4.0]**	**0.003**

CI—confidence interval, gc – gait cycle

Table 3. Mean (1 standard deviation) kinematic gait parameters for the ankle, knee and hip joint in patients with hip OA scheduled for total hip replacement (N=22) and age-matched asymptomatic control subjects (N=45).

Parameter	*Patients*		*Asymptomatic controls*	*95% CI patients - controls*	*95% CI affected - unaffected*	*P value patients - controls*	*P value affected-unaffected*
	Affected	Unaffected					
Ankle							
Maximum plantarflexion stance (°)	8.0 (2.9)	8.3 (2.5)	8.7 (1.9)	[-1.9; 0.5]	[-0.8; 0.6]	0.252	0.810
Maximum dorsiflexion stance (°)	14.4 (4.6)	11.9 (3.4)	10.9 (3.4)	**[1.4; 5.4]**	**[0.4; 4.1]**	**0.001**	**0.020**
Maximum plantarflexion push of (°)	14.2 (9.1)	15.1 (6.6)	19.3 (5.5)	**[-8.6; -1.4]**	[-3.3; 3.2]	**0.007**	0.966
Range of motion stance (°)	22.4 (5.8)	20.2 (4.1)	19.6 (4.0)	[0.3; 5.2]	**[0.2; 4.2]**	0.027	**0.037**
Range of motion push off (°)	28.6 (9.1)	27.0 (6.9)	30.2 (5.9)	[-5.3; 2.1]	[-1.2; 5.6]	0.391	0.188
Knee							
Initial contact (°)	4.6 (3.0)	5.9 (2.6)	5.1 (3.9)	[-2.5; 1.4]	[-2.2; 0.1]	0.602	0.061
Maximum flexion stance (°)	19.4 (6.8)	22.1 (6.7)	21.2 (5.5)	[-5.1; 1.5]	[-4.2; 0.5]	0.283	0.111
Minimum flexion terminal stance (°)	17.0 (7.0)	12.2 (4.6)	9.8 (5.3)	**[4.0; 10.5]**	**[2.3; 8.1]**	**<0.001**	**0.001**
Maximum flexion swing (°)	63.7 (11.2)	65.6 (8.6)	67.9 (5.6)	[-8.7; 0.2]	[-4.5; 1.8]	0.061	0.373
Range of motion load acceptance (°)	14.9 (4.7)	16.2 (5.6)	16.1 (4.6)	[-3.8; 1.3]	[-2.9; 1.3]	0.326	0.439
Range of motion terminal stance (°)	2.4 (3.8)	9.9 (5.6)	11.4 (5.3)	**[-11.7; -6.4]**	**[-9.1; -5.0]**	**<0.001**	**<0.001**
Range of motion swing (°)	46.6 (8.0)	53.4 (5.5)	58.1 (5.3)	**[-15.0; -8.0]**	**[-9.6; -3.5]**	**<0.001**	**<0.001**
Hip							
Maximum flexion stance (°)	22.8 (6.7)	30.9 (8.5)	30.8 (7.0)	**[-11.7; -4.4]**	**[-12.9; -2.3]**	**<0.001**	**0.007**
Maximum extension stance (°)	4.8 (2.8)	6.0 (3.1)	8.3 (3.2)	**[-5.2; -1.9]**	[-2.9; 0.7]	**<0.001**	0.221
Maximum flexion swing (°)	25.0 (6.3)	33.1 (10.5)	32.8 (8.7)	**[-12.0; -3.5]**	**[-13.8; -1.5]**	**0.001**	**0.017**
Range of motion stance (°)	27.6 (7.6)	36.9 (9.6)	39.2 (8.4)	**[-15.9; -7.2]**	**[-13.9; -3.5]**	**<0.001**	**0.002**
Range of motion swing (°)	29.8 (6.7)	39.1 (10.9)	41.1 (10.3)	**[-16.2; -6.3]**	**[-14.3; -3.2]**	**<0.001**	**0.004**

CI—confidence interval