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Assessing Pelvic Tilt in Patients Undergoing Total Hip Arthroplasty Using Sensor Technology

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ABSTRACT

Background: The purpose of our study was to assess the accuracy of a commercially available wearable sensor in replicating pelvic tilt movement in both the sitting and standing position in patients before total hip arthroplasty.

Methods: This prospective study evaluated patients undergoing a primary unilateral total hip arthroplasty by a single surgeon. Patients were excluded if they had a body mass index (BMI) greater than 40 kg/m^2. Two sensors were adhered directly to patients' skin at S2 and T12. The S2 angle was recorded on the sensor at maximum flexion and extension angles and compared with pelvic tilt measurements on both sitting and standing radiographs. The primary outcomes recorded were patients' pelvic tilts measured using radiographs (PT-RAD) and sensors (PT-SEN), with Pearson correlation coefficients and intraclass correlation coefficients (ICCs) calculated.

Results: Sixty-one patients (35 males and 26 females) with an average age of 61.5 ± 8.5 years and BMI of 26.9 ± 4.1 kg/m^2 were analyzed. The mean prestanding PT-RAD and PT-SEN were 1.5 ± 8.3 and 1.0 ± 8.1, respectively, with an ICC of 0.98 (95% confidence interval, 0.96-0.99). The mean presitting PT-RAD and PT-SEN were -21.9 ± 12.5 and -20.9 ± 11.7, respectively, with an ICC of 0.97 (95% confidence interval, 0.95-0.98). The multiple R^2 was 0.95 for the prestanding and presitting comparisons. The R^2 for all comparisons between PT-RAD and PT-SEN was >0.85, regardless of BMI or sex.

Conclusions: Although the use of wearable technology may have limitations, based on our results, a wearable sensor is accurate in replicating pelvic tilt movement.

Introduction

Abnormal spinopelvic mobility is increasingly being recognized as a contributing factor to postoperative complications such as impingement and dislocation after total hip arthroplasty (THA). Recent studies have demonstrated the significance of the hip-spine relationship and how it affects the dynamic spine-pelvic-hip kinetic chain during movement [1-7]. Pathologic alterations to this coordinated motion as a result of spinopelvic stiffness have implications on functional acetabular cup positioning [8-11]. Traditionally, the Lewinnek safe zone (LSZ) of 40 ± 10 degrees of inclination and 15 ± 10 degrees of anteversion has been described as a safe target for acetabular cup positioning, based on supine anteroposterior radiographs [12]. However, this safe zone is a static safe zone and does not account for changes in cup position that occur with pelvic motion during functional activity. Additionally, with mounting evidence that the majority of THA dislocations occur within the LSZ, greater emphasis is now being placed on identifying functional cup positioning that accounts for patient-specific spinopelvic mobility [13,14]. Functional inclination and anteversion of the acetabular component are dynamic parameters that vary according to pelvic tilt and motion, and understanding pelvic tilt in patients undergoing THA is crucial to component positioning and stability of the hip implants.

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Assessing pelvic tilt changes with static based radiographs is important for determining optimized acetabular component positioning and orientation [15-18]. Posterior pelvic tilt with standing as occuring with sagittal spinal imbalance, for instance, increases functional inclination and anteversion of a cup relative to the supine position, and a posterior rotation that is large enough would take a well-positioned cup out of the LSZ [1-4,19]. Conversely, an anterior pelvic tilt when standing will decrease functional inclination and anteversion of a cup relative to supine [1-4,19]. Such functional cup malorientation has been theorized to initiate a cascade of events including subluxation, edge-loading, and impingement, leading to accelerated wear, aseptic loosening, and dislocation ultimately resulting in the need for revision THA.

To prevent such component malorientation, meticulous and dynamic preoperative analysis of patients is warranted. In the current standard of care, 2 radiographs are taken: one in the standing lateral position and one in the sitting lateral position. These radiographs, however, represent 2 static snapshots in time and thus may not fully characterize changes in pelvic tilt between the sitting and standing positions owing to spinal deformity and stiffness, which are parameters better evaluated with a dynamic assessment [1,2,7,17]. Unfortunately, such dynamic analysis has traditionally necessitated costly and time-consuming imaging studies as well as exposing the patient to additional radiation. In lieu of this equipment, wearable devices can be considered for use in the preoperative setting as well as for postoperative evaluation of patients. Recent literature has demonstrated that the utilization of such technology has been exponentially expanding in orthopedic surgery as well as all areas of medicine [20-30]. Continued innovation in this sector has allowed for a variety of uses in providing both patients and surgeons with data to optimize treatment, and orthopedic surgeons may be able to capitalize on these clinical tools to facilitate simpler and more cost-efficient methods to obtaining vital patient information. This study evaluates the use of one such wearable device, a commercially available sensor, that can be utilized to track pelvic tilt. The purpose of this study was to assess the accuracy of a commercially available wearable sensor in replicating pelvic tilt movement in both the sitting and standing position in patients before THA.

Patients and methods

We prospectively enrolled patients who were undergoing a primary unilateral THA by a single surgeon. Patients were excluded if they had a body mass index (BMI) greater than 40 kg/m^2. Two sensors (dorsaVi Ltd) were placed, one at S2 and the other at T12, using a standardized measurement guide to ensure proper location, with sticky pads adhered directly to patients' skin (Fig. 1). The sensors were reusable and sticky pads replaced before placement on each patient. After calibration of the sensors, patients underwent a full-body biplanar standing and sitting radiograph (EOS Imaging, Paris, France). The S2 angle was recorded on the sensor with the patient standing and sitting and compared with pelvic tilt measurements on the radiographs in both standing and sitting (Fig. 2). There were 80 patients enrolled in this study. Nineteen patients were excluded for the following reasons: sensor adhesive issues (7), sensor movement (3), connectivity (7), and calibration issues (2). The primary outcomes recorded were patients' pelvic tilts measured using radiographs (PT-RAD) and the sensors (PT-SEN).

Statistical analysis

Baseline characteristics were assessed using means and percentages. Patients were categorized into BMI (kg/m^2) according to CDC guidelines as follows: underweight (<18.5), normal weight (≥18.5 to <25), overweight (≥25 to <30), class 1 obesity (≥30 to <35), and class 2 obesity (≥35 to <40). Linear relationships between PT-RAD and PT-SEN were assessed with the smoothing method for linear models and 95% confidence intervals (CIs). Pearson correlation coefficients and intraclass correlation coefficients (ICCs) were calculated to measure association and agreement, respectively, for prestanding and presitting measures. A high correlation between modalities indicates reproducibility and internal consistency between the sensor technology and radiograph measurement of pelvic tilt [31]. ICC is an appropriate test for studying repeatability of 2 sets of pelvic tilt data, obtained using 2 different modalities. Criteria for ICC conventionally used in the literature are as follows: values ≥0.75, excellent reproducibility; values 0.4-0.74, adequate reproducibility; and values ≤ 0.40, poor reproducibility [31-35].

In addition to analyses of the full cohort, measures of correlation and agreement were also used to assess each of the BMI groups. All analyses were performed in R, version 4.0 (R Foundation for Statistical Computing, Vienna, Austria).

Figure 1. Two sensors were placed, one at S2 and the other at T12, with sticky pads adhered directly to patients' skin.

Results

From July 2019 to December 2019, a total of 61 patients undergoing unilateral primary THA were prospectively enrolled. Of the 61 patients, 35 (57.4%) were male. The mean age of patients was 61.5 ± 8.4 years, and the mean BMI was 27.0 ± 4.1 kg/m^2. The majority (n = 57, 93.4%) of patients had degenerative joint disease of the hip. Three patients had avascular necrosis, and one patient had severe erosion of the acetabulum due to rheumatoid arthritis. Thirty-three patients underwent a THA of the left hip, and 28 patients underwent a THA of the right hip.

The mean prestanding PT-RAD was 1.5 ± 8.3, and the mean prestanding PT-SEN was 1.0 ± 8.1. The ICC comparing the 2 measures was 0.98 (95% CI, 0.96-0.99), indicating excellent internal consistency and repeatability between the wearable sensors and radiograph evaluation of pelvic tilt measurement. The mean presitting PT-RAD was -21.9 ± 12.5 and the mean presitting SPT-SEN

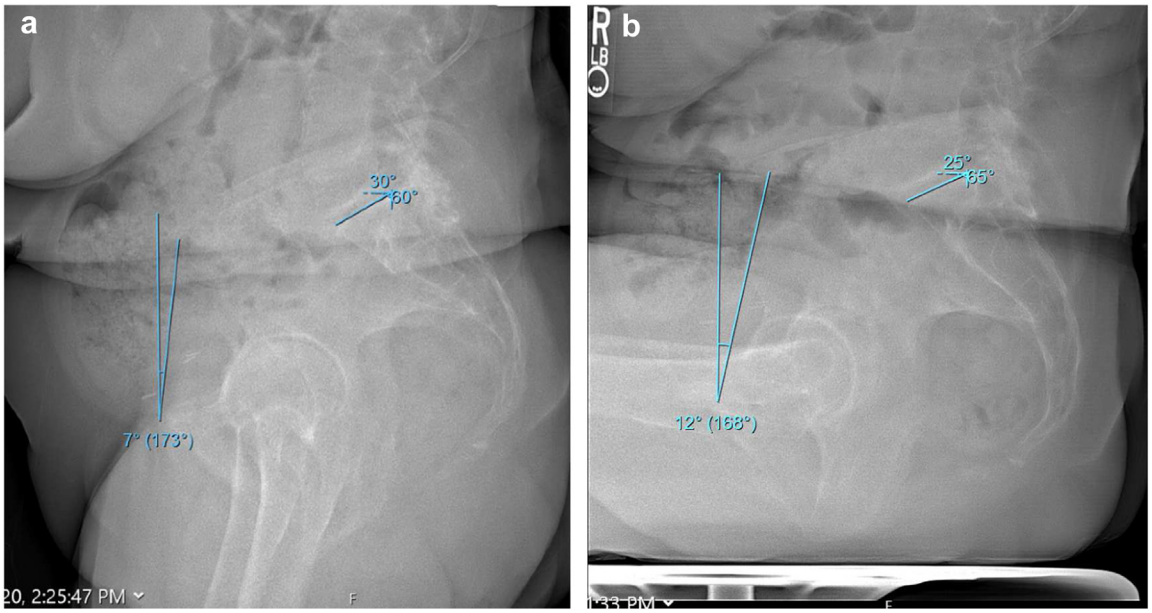

Figure 2. Pelvic tilt measurements on (a) standing and (b) sitting biplanar EOS images.

was -20.9 ± 11.7, with an ICC of 0.97 (95% CI, 0.95-0.98). PT-SEN was significantly different from presitting to prestanding ($P < .001$). The multiple R^2 was 0.95 for both the prestanding and presitting comparisons (Figs. 3-6).

There was little evidence to suggest that the correlation of PT-RAD with PT-SEN changed by either BMI or sex (R^2 for all comparisons >0.85) in patients with BMI <40 kg/m^2. For prestanding pelvic tilt, the R^2 value was 0.96 for patients with a normal BMI and was 0.92 for patients with class 1 obesity. For presitting pelvic tilt, the R^2 value was 0.93 for patients with a normal BMI and 0.88 for those with class 1 obesity.

Discussion

Increasing use of wearable technology in orthopedic surgery results in a rapid improvement of sensor technology that can be utilized for preoperative evaluation of patients as well as intraoperative guidance and postoperative monitoring and follow-up [20,23-28]. The use of wearable sensors is a safe, rapid, and efficient way to detect pelvic mobility in patients, including those with low back pain or those requiring spinopelvic evaluation [36-38]. Given the importance of spinopelvic motion on THA stability and survival, appropriate evaluation of the functional dynamic between the spine, pelvis, and hip in the preoperative setting is necessary to determine patient-specific acetabular cup position and orientation as a function of pelvic orientation [1,2,7,17]. In this study, an evaluation of patients' functional pelvic position in the standing and seated positions was performed using wearable sensors. The PT-SEN recorded using the sensors was compared with the conventional PT-RAD, determined from biplanar radiographs, to assess pelvic tilt measurement efficacy and consistency between the 2 modalities. Based on the results of this study, the wearable sensors were accurate in measuring pelvic tilt movement with an ICC comparing the measures of 0.98 for standing pelvic tilt and 0.97 for seated pelvic tilt, suggesting excellent consistency between measurement modalities. Additionally, the sensors are capable of detecting changes in pelvic tilt in both the standing and seated positions, with results indicating significantly different PT-SEN measurements between the 2 positions and consistency with PT-RAD in both cases. These findings suggest that the wearable sensors could be reliably utilized while assessing for spinopelvic pathology during preoperative evaluation of patients before THA. Patient data on changes in pelvic tilt when transitioning from the standing to seated position as well as functional pelvic plane information in the standing position could be recorded with the sensors and used as part of a hip-spine workup and risk determination protocol.

With an increased interest in noninvasive wearable technology for research and clinical use, there remains a need to validate and

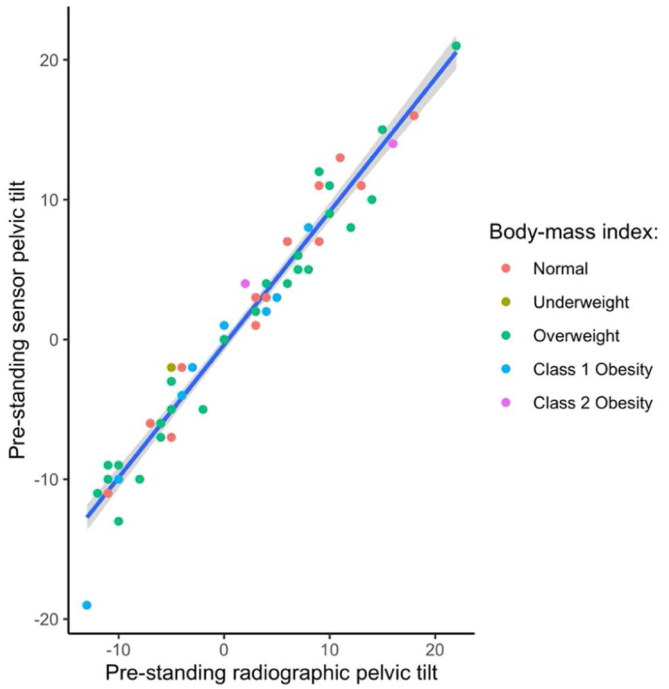

Figure 3. Correlation of prestanding sensor pelvic tilt with prestanding radiographic pelvic tilt stratified by body mass index. Equation: AA = 0.95 *Y -0.37; R-squared: 0.95.

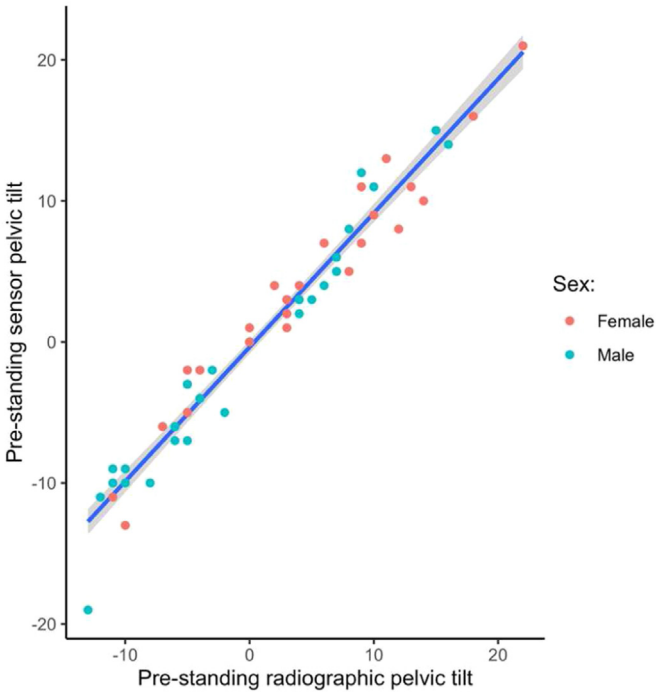

Figure 4. Correlation of prestanding sensor pelvic tilt with prestanding radiographic pelvic tilt stratified by sex. Equation: AA = 0.95 *Y -0.37; R-squared: 0.95.

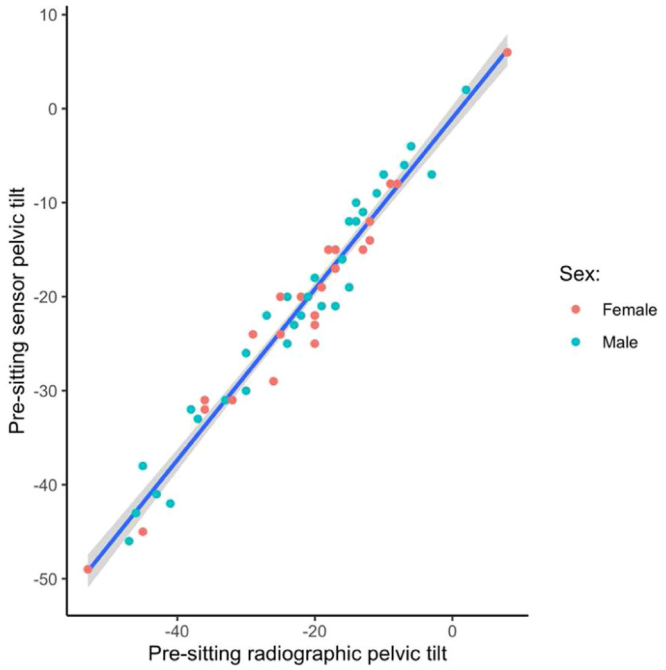

Figure 6. Correlation of presitting sensor pelvic tilt with presitting radiographic pelvic tilt stratified by sex. Equation: AB = 0.91*Z-1.00; R-squared: 0.95.

determine the most effective, efficient, and accurate devices [29]. Not only can wearable technology be utilized during the preoperative evaluation process to help guide surgical decision-making, but such devices can be used for direct monitoring of postoperative outcomes and follow-up as well as for evaluation of functional biomechanics [20,23-28]. Studies in the literature evaluating wearable technology for spinopelvic motion analysis report promising results. Chhikara et al. evaluated the use of a wearable device in tracking lumbar spine and pelvic dynamic motion during daily activities, with a mean average orientation error ranging from 0.1 ± 2.3 degrees to 4.2 ± 2.6 degrees indicating high levels of consistency between the sensor technology and validated optical tracking [36]. Similarly, Zhang et al. report on a nanomaterial-based electronic skin-wearable sensor for lumbar-pelvic movement monitoring in patients with lower back pain, demonstrating repeatability in the measurements and suggesting an improved method of real-time monitoring and evaluation of movement for patients with lower back pain [37]. Another study reports strong correlation (r = 0.60-0.72) between a wearable sheet sensor and an optical motion capture system in tracking lumbar movement, concluding that the wearable system demonstrated significant promise in monitoring lower back motion [38].

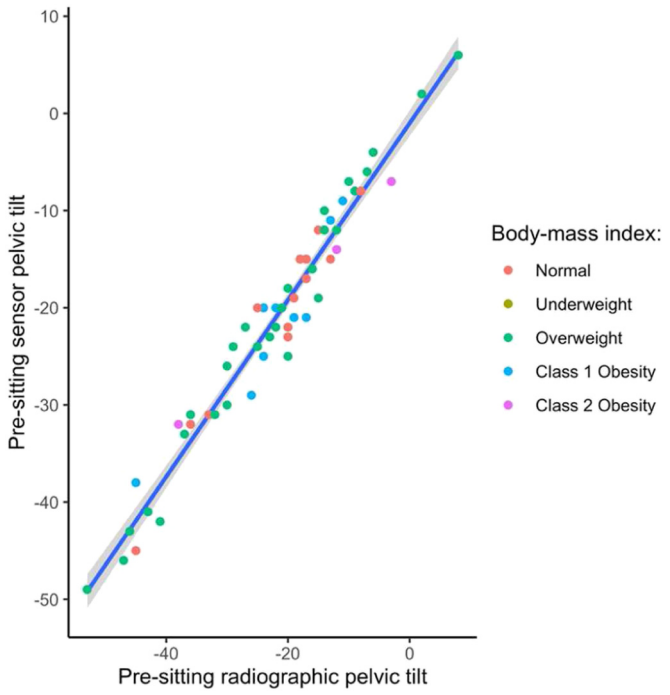

Figure 5. Correlation of presitting sensor pelvic tilt with presitting radiographic pelvic tilt stratified by body mass index. Equation: AB = 0.91*Z-1.00; R-squared: 0.95.

Cost savings is another potential advantage with wearable devices, whether for investigative or clinical purposes. Further research is needed to demonstrate cost-effectiveness or neutrality in consideration of overall clinical outcomes with the use of wearable technology, although the theoretical benefits of less imaging requirements and in-person visits, for instance, suggest the potential for cost reduction while maintaining or improving patient outcomes [29]. The development of this technology from the industry standpoint and adoption of this technology from the provider standpoint, however, is not without significant cost [39]. Nevertheless, the idea that a short- and intermediate-term cost increase lending to a long-term decrease in utilization and outcomes-related costs driven by improvements in patient satisfaction and outcomes is a decision that must be weighed by healthcare providers and hospital systems [39,40].

Additionally, despite existing safety measures in place, concerns about data monitoring, security, and patient privacy with mobile technology are valid, as information security issues associated with various mobile devices can theoretically occur [41]. Patients need to be fully aware of the information being tracked and evaluated by

their providers, and full transparency is important to ensure patients are in agreeance before the initiation of data monitoring [41].

Our study has some notable limitations. Despite having a smaller sample size, the data from the sensor and radiograph measurements were examined for each subject and demonstrated high internal validity and a strong correlation across measurement modalities. Future studies will evaluate this technology on a larger scale. Additionally, 19 patients were excluded for the following reasons: sensor adhesive issues (7), sensor movement (3), connectivity (7), and calibration issues (2). These are preventable, sensor-related issues that led to a higher-than-anticipated patient exclusion rate and will be troubleshooted with the development team before clinical deployment. Further analysis into BMI restrictions will be performed, and the design of sensors will continue to be optimized to ensure adequate adhesive capability, particularly for patients with greater amounts of body hair, and sensitivity on patient skin. In addition, even though there is a preponderance of evidence suggesting that the spinopelvic relationship affects implant positioning and stability, there is no universal agreement on how pelvic orientation should be managed. Wearable sensors are evaluated for use in the preoperative setting in this study, but future investigations should examine the intraoperative benefit of such technology in helping guide component positioning. Despite these limitations, the promising results and radiographic validation of the sensors' specificity in detecting pelvic mobility and tilt in the patients that were studied warrant future investigation.

Conclusions

This study evaluates the use of wearable sensors on the pelvis and lumbar spine to ascertain whether this technology could be utilized as a convenient and accessible tool during the systematic evaluation of pelvic tilt in patients undergoing THA. The ability to detect pelvic mobility during the transition from the standing to seated positions was validated with radiographic measurement, with the results showing a strong correlation between the sensor and radiographic modalities. Additionally, the wearable sensors are sensitive and reliable in detecting changes in pelvic tilt between the standing and seated positions. This promising outcome suggests the validity of sensor technology as a tool to add to the surgeon's armamentarium during preoperative examination of pelvic tilt and mobility in patients before THA. Further work evaluating the efficacy of this sensor technology in functional pelvic positions such as a forward flexion position (ie, bending down to tie shoelaces or rising out of a deep chair) and a step-up position (ie, climbing a flight of stairs) needs to be performed to validate this technology on a broader scale.

Conflicts of interests

Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jonathan M. Vigdorchik, M.D., reports stock ownership in Intellijoint Surgical and Motion Insights, receiving fees and research funding from Corin Group, and receiving fees from Intellijoint Surgical, Medacta, and Zimmer; Seth Jerabek, M.D., reports having stock ownership in Stryker and Imagen and receiving IP royalties, personal fees, and research funding from Stryker; the other authors declare no potential conflicts of interest.

References

[1] Pierrepont J, Hawdon G, Miles BP, et al. Variation in functional pelvic tilt in patients undergoing total hip arthroplasty. Bone Joint J 2017;99-B:184.
[2] Langston J, Pierrepont J, Gu Y, Shimmin A. Risk factors for increased sagittal pelvic motion causing unfavourable orientation of the acetabular component in patients undergoing total hip arthroplasty. Bone Joint J 2018;100-B:845.
[3] Vigdorchik JM, Sharma AK, Dennis DA, Walter LR, Pierrepont JW, Shimmin AJ. The majority of total hip arthroplasty patients with a Stiff spine Do not have an Instrumented Fusion. J Arthroplasty 2020;35(6S):S252–4.
[4] Esposito CI, Carroll KM, Sculco PK, Padgett DE, Jerabek SA, Mayman DJ. Total hip arthroplasty patients with Fixed spinopelvic Alignment are at higher risk of hip dislocation. J Arthroplasty 2018;33:1449.
[5] Innmann MM, Merle C, Gotterbarm T, Ewerbeck V, Beaulé PE, Grammatopoulos G. Can spinopelvic mobility be predicted in patients awaiting total hip arthroplasty? A prospective, diagnostic study of patients with end-stage hip osteoarthritis. Bone Joint J 2019;101-B:902.
[6] DelSole EM, Vigdorchik JM, Schwarzkopf R, Errico TJ, Buckland AJ. Total hip arthroplasty in the spinal deformity Population: does degree of sagittal deformity affect rates of safe zone placement, Instability, or revision? J Arthroplasty 2017;32:1910.
[7] Buckland AJ, Fernandez L, Shimmin AJ, Bare JV, McMahon SJ, Vigdorchik JM. Effects of sagittal spinal Alignment on Postural pelvic mobility in total hip arthroplasty Candidates. J Arthroplasty 2019;34:2663.
[8] Luthringer TA, Vigdorchik JM. A preoperative workup of a "Hip-spine" total hip arthroplasty patient: a Simplified Approach to a Complex Problem. J Arthroplasty 2019;34:S57.
[9] Lazennec JY, Riwan A, Gravez F, et al. Hip spine relationships: Application to total hip arthroplasty. HIP Int 2007;17:91.
[10] Lazennec J-Y, Brusson A, Rousseau M-A. Hip–spine relations and sagittal balance clinical consequences. Eur Spine J 2011;20:686.
[11] Malkani AL, Himschoot KJ, Ong KL, et al. Does timing of primary total hip arthroplasty prior to or after lumbar spine Fusion have an effect on dislocation and revision rates? J Arthroplasty 2019;34:907.
[12] Lewinnek GE, Lewis JL, Tarr R, Compere CL, Zimmerman JR. Dislocations after total hip-replacement arthroplasties. J Bone Joint Surg Am 1978;60:217.
[13] Abdel MP, von Roth P, Jennings MT, Hanssen AD, Pagnano MW. What safe zone? The Vast majority of dislocated THAs are within the Lewinnek safe zone for acetabular component position. Clin Orthop Relat Res 2016;474:386.
[14] Esposito CI, Gladnick BP, Lee Y, et al. Cup position Alone does not Predict risk of dislocation after hip arthroplasty. J Arthroplasty 2015;30:109.
[15] Lembeck B, Mueller O, Reize P, Wuelker N. Pelvic tilt makes acetabular cup navigation inaccurate. Acta Orthop 2005;76:517.
[16] Dorr LD, Malik A, Wan Z, Long WT, Harris M. Precision and bias of imageless computer navigation and surgeon estimates for acetabular component position. Clin Orthop Relat Res 2007;465:92.
[17] Maratt JD, Esposito CI, McLawhorn AS, Jerabek SA, Padgett DE, Mayman DJ. Pelvic tilt in patients undergoing total hip arthroplasty: when does it matter? J Arthroplasty 2015;30:387.
[18] Vigdorchik JM, Muir JM, Buckland A, et al. Undetected intraoperative pelvic movement can Lead to inaccurate acetabular cup component placement during total hip arthroplasty: a Mathematical Simulation Estimating change in cup position. J Hip Surg 2017;01:186.
[19] Innmann MM, Merle C, Phan P, Beaulé PE, Grammatopoulos G. How can patients with mobile hips and Stiff lumbar spines Be Identified prior to total hip arthroplasty? A prospective, diagnostic cohort study. J Arthroplasty 2020;35(6S):S255–61.
[20] Zarowin J, Warnick E, Mangan J, et al. Is wearable technology part of the future of Orthopedic Health care? Clin Spine Surg 2020;33:99.
[21] Slade Shantz JA, Veillette CJH. The Application of wearable technology in surgery: Ensuring the positive Impact of the wearable Revolution on surgical patients. Front Surg 2014;1:39.
[22] Kim DH, Nam KH, Choi BK, Han IH, Jeon TJ, Park SY. The Usefulness of a wearable device in daily Physical activity monitoring for the Hospitalized patients undergoing lumbar surgery. J Korean Neurosurg Soc 2019;62:561.
[23] Toogood PA, Abdel MP, Spear JA, Cook SM, Cook DJ, Taunton MJ. The monitoring of activity at home after total hip arthroplasty. Bone Joint J 2016;98-B:1450.
[24] Crizer MP, Kazarian GS, Fleischman AN, Lonner JH, Maltenfort MG, Chen AF. Stepping toward Objective outcomes: a prospective analysis of step Count after total joint arthroplasty. J Arthroplasty 2017;32:S162.
[25] Patterson JT, Wu H-H, Chung CC, Bendich I, Barry JJ, Bini SA. Wearable activity sensors and early pain after total joint arthroplasty. Arthroplast Today 2020;6:68.
[26] Chiang C-Y, Chen K-H, Liu K-C, Hsu SJ-P, Chan C-T. Data Collection and analysis using wearable sensors for monitoring knee Range of motion after total knee arthroplasty. Sensors (Basel) 2017;17(2):418.
[27] Kwasnicki RM, Ali R, Jordan SJ, et al. A wearable mobility assessment device for total knee replacement: a longitudinal feasibility study. Int J Surg 2015;18:14.
[28] Papi E, Bo YN, McGregor AH. A flexible wearable sensor for knee flexion assessment during gait. Gait Posture 2018;62:480.
[29] Bahadori S, Immins T, Wainwright TW. A review of wearable motion tracking systems used in rehabilitation following hip and knee replacement. J Rehabil Assist Technol Eng 2018;5. 2055668318771816.

[30] Iqbal MH, Aydin A, Brunckhorst O, Dasgupta P, Ahmed K. A review of wearable technology in medicine. J R Soc Med 2016;109:372.
[31] Yavuzer G, Oken O, Elhan A, Stam HJ. Repeatability of lower limb three-dimensional kinematics in patients with stroke. Gait Posture 2008;27:31.
[32] Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J. Issues for selection of outcome measures in stroke rehabilitation: ICF Body Functions. Disabil Rehabil 2005;27:191.
[33] Andresen EM. Criteria for assessing the tools of disability outcomes research. Arch Phys Med Rehabil 2000;81:S15.
[34] Hsueh IP, Lee MM, Hsieh CL. Psychometric characteristics of the Barthel activities of daily living index in stroke patients. J Formos Med Assoc 2001;100:526.
[35] Wolfe CD, Taub NA, Woodrow EJ, Burney PG. Assessment of scales of disability and handicap for stroke patients. Stroke 1991;22:1242.
[36] Chhikara A, Rice AC, McGregor AH, Bello F. In-House Monitoring of low back pain related disability (IMPAIRED). Conf Proc IEEE Eng Med Biol Soc 2008;2008:4507.
[37] Zhang Y, Haghighi PD, Burstein F, et al. Electronic skin wearable sensors for detecting lumbar-pelvic movements. Sensors (Basel) 2020;20(5):1510.
[38] Yamamoto A, Nakamoto H, Yamaji T, et al. Method for measuring tri-axial lumbar motion angles using wearable sheet stretch sensors. PLoS One 2017;12:e0183651.
[39] Lamiraud K, Lhuillery S. Endogenous technology adoption and medical costs. Health Econ 2016;25:1123.
[40] Suter LG, Paltiel AD, Rome BN, et al. Placing a price on medical device innovation: the example of total knee arthroplasty. PLoS One 2013;8:e62709.
[41] Cilliers L. Wearable devices in healthcare: privacy and information security issues. Health Inf Manag 2020;49:150.