

OPTICAL GONIOMETER DEVICE FOR
CONTINUOUS MONITORING OF THE KNEE
MOVEMENT IN PHYSIOTHERAPY
APPLICATION

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ABSTRACT

Knee joint is the most crucial among the lower limbs joints due to its exposed location and its major role which carries the entire burden of the body practically our entire life. Hence, by being able to measure the knee joint angle accurately during continuous movement, allows the physiotherapist to detect knee joint damage at early stages before it turns into an injury or permanent scar tissue. Due to the limited number of continuous monitoring devices applicable for diagnosis and treatment stage of the knee, most physicians opted for X-ray and magnetic resonance imaging (MRI) technologies to have some insight on the knee issue before suitable treatment can be recommended. Aside from being expensive for general use of MRI, X-ray on the other hand can cause short-term side effects due to radiation exposure. Knee joint angle measurement devices technologies include but are not limited to the implementation of accelerometer, electrogoniometer, torsiometer, acoustic, visual sensory, and optic fibre. There are many limitations to these technologies that require improvements before they can become clinically applicable such as accuracy issues, limited range of motion measurement, and inability to monitor continuous movement measurement of the knee joint, which have been discussed thoroughly in this research. The need for technologies with higher accuracy, reliability, able to measure the full knee range of motion, applicable for continuous motion measurement and lower cost have always been a crucial factor. The use of optical based devices provides significant contribution in this area due to their advantages such as immunity to electromagnetic interference, lightweight and possibly small sensor setup. However, the application of intensity-based optical fibre sensor for human joint motion detection resulted in limited detection angle, where most sensor are not able to detect angle variation of more than 90°. To improve this limitation, an optical sensor approach with mechanical-assisted components assembly that translates angular movement to linear movement was developed. The light detection on the photodiode array sensor at different pixels is analysed to represent the angle movement of the knee. The sensor is securely attached to a medical standard knee brace tool to ensure firm sensor placement on the knee area. Based on current study, the proposed optical sensor has a range of motion between 0 to 160°, with 0.08° resolution, has a 210.5 sampling rate per second, which allows it to present and record a real time graphical output to demonstrate the knee joint activity performance. Moreover, the proposed device was able to give an excellent internal consistency obtained by Cronbach's Alpha analysis of 0.967, and has 98.044% correlation with the gold standard goniometer.

ABSTRAK

Sendi lutut adalah yang terpenting di kalangan sendi anggota bawah badan oleh kerana lokasinya yang terdedah dan peranan utamanya yang menampung seluruh beban badan sepanjang hayat kami. Oleh itu, dengan dapat mengukur sudut sendi lutut dengan tepat semasa pergerakan berterusan, akan membolehkan ahli fisioterapi mengesan masalah sendi lutut pada peringkat awal sebelum ia bertukar menjadi kecederaan atau tisu parut kekal. Disebabkan pilihan peralatan pemantauan yang terhad yang boleh digunakan untuk peringkat diagnosis dan rawatan lutut, kebanyakan pakar perubatan memilih teknologi X-ray dan pengimejan resonans magnetik (MRI) untuk mendapatkan sedikit pandangan tentang isu lutut sebelum rawatan yang sesuai boleh disyorkan. Selain teknologi MRI mahal untuk kegunaan umum, X-ray sebaliknya boleh menyebabkan kesan sampingan jangka pendek akibat pendedahan radiasi. Teknologi peranti pengukuran sudut sendi lutut termasuk tetapi tidak terhad kepada pelaksanaan accelerometer, elektrogoniometer, torsiometer, akustik, sensor visual dan gentian optik. Terdapat banyak limitasi kepada teknologi ini yang memerlukan penambahbaikan sebelum ia boleh digunakan secara klinikal seperti isu ketepatan, julat pengukuran pergerakan terhad dan ketidakupayaan untuk memantau pengukuran pergerakan berterusan sendi lutut, yang telah dibincangkan secara menyeluruh dalam penyelidikan ini. Keperluan untuk teknologi dengan ketepatan yang lebih tinggi, kebolehpercayaan, mampu mengukur julat gerakan lutut penuh, sesuai untuk pengukuran gerakan berterusan dan kos yang lebih rendah sentiasa menjadi faktor penting. Penggunaan peranti berasaskan optik memberikan sumbangan besar dalam bidang ini kerana kelebihan seperti imuniti terhadap gangguan elektromagnet, ringan dan kebarangkalian tetapan sensor yang lebih kecil. Walau bagaimanapun, aplikasi penderia gentian optik berasaskan intensiti untuk pengesanan gerakan sendi manusia menghasilkan sudut pengesanan terhad, di mana kebanyakan penderia tidak dapat mengesan lebih daripada 90°. Untuk menambah baik had ini, pendekatan penderia optik dengan pemasangan komponen bantuan mekanikal yang menterjemahkan pergerakan sudut kepada pergerakan linear telah dihasilkan. Pengesanan cahaya pada sensor linear array fotodiod pada piksel yang berbeza dianalisis untuk mewakili pergerakan sudut lutut. Sensor dipasang pada alat pendakap lutut kelas perubatan untuk memastikan peletakan sensor yang kukuh pada kawasan lutut. Berdasarkan kajian semasa, penderia optik yang dicadangkan mempunyai julat pergerakan antara 0 hingga 160°, dengan resolusi 0.08°, mempunyai kadar pensampelan 210.5 sesaat, yang membolehkan alatan ini membentangkan dan merekodkan hasil grafik masa nyata untuk menunjukkan prestasi aktiviti sendi lutut. Dengan menggunakan alatan yang dicadangkan, ketekalan dalaman yang sangat baik dapat diperolehi oleh analisis Alpha Cronbach sebanyak 0.967, dan mempunyai korelasi 98.044% dengan goniometer standard emas.

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REFERENCES

- [1]Anwar Zawawi, M., O’Keffe, S., & Lewis, E. (2013). Intensity-modulated fiber optic sensor for health monitoring applications: a comparative review. *Sensor Review*, 33(1), 57–67. <https://doi.org/10.1108/02602281311294351>
- [2]Adib, M. A. H. M., & Jaafar, M. F. (2013). Review: Modelling of meniscus of knee joint during soccer kicking. *IOP Conference Series: Materials Science and Engineering*, 50, 012027. <https://doi.org/10.1088/1757-899x/50/1/012027>
- [3]Kubiček, M., & Florian, Z. (2010). STRESS STRAIN ANALYSIS OF KNEE JOINT. *Engineering MECHANICS*, 16(5), 315–322. http://www.engineeringmechanics.cz/pdf/16_5_315.pdf
- [4]Sim, F. H., Choong, P. F. M., & Weber, K. L. (2012). Orthopaedic oncology and complex reconstruction. Philadelphia: *Wolters Kluwer/Lippincott Williams & Wilkins Health*.
- [5]Zhang, Y., & Jordan, J. M. (2010). Epidemiology of Osteoarthritis. *Clinics in Geriatric Medicine*, 26(3), 355–369. <https://doi.org/10.1016/j.cger.2010.03.001>
- [6]Altman, R. D. (2010). Early management of osteoarthritis. *The American Journal of Managed Care*, 16 Suppl Management(20297876), S41-47. Retrieved from <https://pubmed.ncbi.nlm.nih.gov/20297876/>
- [7]Majewski, M., Susanne, H., & Klaus, S. (2006). Epidemiology of athletic knee injuries: A 10-year study. *The Knee*, 13(3), 184–188. <https://doi.org/10.1016/j.knee.2006.01.005>
- [8]NIELSEN, A. B., & YDE, J. (1991). Epidemiology of Acute Knee Injuries: A Prospective Hospital Investigation. *The Journal of Trauma: Injury, Infection, and Critical Care*, 31(12), 1644–1648. <https://doi.org/10.1097/00005373-199112000-00014>
- [9]Lohmander, L. S., Englund, P. M., Dahl, L. L., & Roos, E. M. (2007). The Long-term Consequence of Anterior Cruciate Ligament and Meniscus Injuries. *The American Journal of Sports Medicine*, 35(10), 1756–1769. <https://doi.org/10.1177/0363546507307396>
- [10]Glaser, V. (1997). Pinpointing the cause of acute knee pain. *Patient Care*, 31(18), 100–117.
- [11]Donald Shelbourne, K., & Klootwyk, T. E. (2000). Low-velocity knee dislocation with sports injuries: Treatment principles. *Clinics in Sports Medicine*, 19(3), 443–456. [https://doi.org/10.1016/S0278-5919\(05\)70217-9](https://doi.org/10.1016/S0278-5919(05)70217-9)
- [12]Mitchell, E. L., & Furey, P. (2011). Prevention of radiation injury from medical

imaging. *Journal of Vascular Surgery*, 53(1), 22S27S.
<https://doi.org/10.1016/j.jvs.2010.05.139>

- [13] Moatshe, G., Dornan, G. J., Løken, S., Ludvigsen, T. C., Laprade, R. F., & Engebretsen, L. (2017). Demographics and injuries associated with knee dislocation: A prospective review of 303 patients. *Orthopaedic Journal of Sports Medicine*, 5(5). <https://doi.org/10.1177/2325967117706521>
- [14] Werner, B. C., Gwathmey, F. W., Higgins, S. T., Hart, J. M., & Miller, M. D. (2014). Ultra-low velocity knee dislocations: Patient characteristics, complications, and outcomes. *In American Journal of Sports Medicine* (Vol. 42, pp. 358–363). <https://doi.org/10.1177/0363546513508375>
- [15] De Loës, M., Dahlstedt, L. J., & Thomée, R. (2000). A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scandinavian Journal of Medicine and Science in Sports*, 10(2), 90–97. <https://doi.org/10.1034/j.1600-0838.2000.010002090.x>
- [16] Messier, S. P., Mihalko, S. L., Legault, C., Miller, G. D., Nicklas, B. J., DeVita, P., ... Loeser, R. F. (2013). Effects of intensive diet and exercise on knee joint loads, inflammation, and clinical outcomes among overweight and obese adults with knee osteoarthritis: The IDEA randomized clinical trial. *JAMA - Journal of the American Medical Association*, 310(12), 1263–1273. <https://doi.org/10.1001/jama.2013.277669>
- [17] Bliddal, H., & Christensen, R. (2009, August). The treatment and prevention of knee osteoarthritis: A tool for clinical decision-making. *Expert Opinion on Pharmacotherapy*. <https://doi.org/10.1517/14656560903018911>
- [18] Lespasio, M. J., Piuze, N. S., Husni, M. E., Muschler, G. F., Guarino, A., & Mont, M. A. (2017). Knee Osteoarthritis: A Primer. *The Permanente Journal*. <https://doi.org/10.7812/TPP/16-183>
- [19] Abbott, J. H., Clare, M. C., McKenzie, J. E., David, G. D., Theis, J. C., & Campbell, A. J. (2009). Exercise therapy, manual therapy, or both, for osteoarthritis of the hip or knee: A factorial randomised controlled trial protocol. *Trials*, 10. <https://doi.org/10.1186/1745-6215-10-11>
- [20] Donno, M., Palange, E., Di Nicola, F., Bucci, G., & Ciancetta, F. (2008). A new flexible optical fiber goniometer for dynamic angular measurements: Application to human joint movement monitoring. *IEEE Transactions on Instrumentation and Measurement*, 57(8), 1614–1620. <https://doi.org/10.1109/TIM.2008.925336>
- [21] Logerstedt, D., Arundale, A., Lynch, A., & Snyder-Mackler, L. (2015, September 1). A conceptual framework for a sports knee injury performance profile (SKIPP) and return to activity criteria (RTAC). *Brazilian Journal of Physical Therapy. Revista Brasileira de Fisioterapia*. <https://doi.org/10.1590/bjpt->

- [22] Mayr, H. O., Weig, T. G., & Plitz, W. (2004). Arthrofibrosis following ACL reconstruction - Reasons and outcome. *Archives of Orthopaedic and Trauma Surgery*, 124(8), 518–522. <https://doi.org/10.1007/s00402-004-0718-x>
- [23] Ingram, J. G., Fields, S. K., Yard, E. E., & Comstock, R. D. (2008). Epidemiology of knee injuries among boys and girls in US high school athletics. *American Journal of Sports Medicine*, 36(6), 1116–1122. <https://doi.org/10.1177/0363546508314400>
- [24] Shelbourne, K. D., Patel, D. V., & Martini, D. J. (1996). Classification and management of arthrofibrosis of the knee after anterior cruciate ligament reconstruction. *American Journal of Sports Medicine*, 24(6), 857–862. <https://doi.org/10.1177/036354659602400625>
- [25] Chmielewski, T. L., Stackhouse, S., Axe, M. J., & Snyder-Mackler, L. (2004). A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture. *Journal of Orthopaedic Research*, 22(5), 925–930. <https://doi.org/10.1016/j.orthres.2004.01.007>
- [26] Hancock, G. E., Hepworth, T., & Wembridge, K. (2018). Accuracy and reliability of knee goniometry methods. *Journal of Experimental Orthopaedics*, 5(1). <https://doi.org/10.1186/s40634-018-0161-5>
- [27] Hambly, K., Sibley, R., & Ockendon, M. (2012). Level of agreement between a novel smartphone application and a long arm goniometer for the assessment of maximum active knee flexion by an inexperienced tester. *International Journal of Physiotherapy & Rehabilitation*, 2(May), 1–14. Retrieved from <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Level+of+agreement+between+a+novel+smartphone+application+and+a+long+arm+goniometer+for+the+assessment+of+maximum+active+knee+flexion+by+an+inexperienced#0%5Cnhttp://scholar.google.com/scholar?>
- [28] Ng, F. Y., Wong, H. L., Yau, W. P., Chiu, K. Y., & Tang, W. M. (2008). Comparison of range of motion after standard and high-flexion posterior stabilised total knee replacement. *International Orthopaedics*, 32(6), 795–798. <https://doi.org/10.1007/s00264-007-0409-7>
- [29] Ahmadi, A., Mitchell, E., Richter, C., Destelle, F., Gowing, M., O'Connor, N. E., & Moran, K. (2015). Toward automatic activity classification and movement assessment during a sports training session. *IEEE Internet of Things Journal*, 2(1), 23–32. <https://doi.org/10.1109/JIOT.2014.2377238>
- [30] Shyr, T. W., Shie, J. W., Jiang, C. H., & Li, J. J. (2014). A textile-based wearable sensing device designed for monitoring the flexion angle of elbow and knee movements. *Sensors (Switzerland)*, 14(3), 4050–4059.

<https://doi.org/10.3390/s140304050>

- [31] Zawawi, M. A., O’Keeffe, S., & Lewis, E. (2015). An Extrinsic Optical Fiber Bending Sensor: A Theoretical Investigation and Validation. *IEEE Sensors Journal*, 15(9), 5333–5339. <https://doi.org/10.1109/JSEN.2015.2436898>
- [32] Brukner and Khan’s Clinical Sports Medicine—Volume 1: Injuries, 5th Edition. (2018). *Medicine & Science in Sports & Exercise*, 50(6), 1344–1344. <https://doi.org/10.1249/01.mss.0000534155.50241.67>
- [33] Bucholz, R. W., Heckman, J. D., Court-Brown, C. M., Rockwood, C. A., & Green, D. P. (2006). *Rockwood and Green's fractures in adults*. ([Fractures], 1-2.) Philadelphia: Lippincott Williams & Wilkins.
- [34] Smyth MP, Koh JL. A review of surgical and nonsurgical outcomes of medial knee injuries. *Sports Med Arthrosc Rev*. 2015 Jun;23(2):e15-22. doi: 10.1097/JSA.000000000000063. PMID: 25932882.
- [35] In Court-Brown, C. M., In Heckman, J. D., In McQueen, M. M., In Ricci, W. M., In Tornetta, P., & In McKee, M. D. (2015). *Rockwood and Green's fractures in adults*.
- [36] Hughston, J. C., & Eilers, A. F. (1973). The role of the posterior oblique ligament in repairs of acute medial (collateral) ligament tears of the knee. *Journal of Bone and Joint Surgery - Series A*, 55(5), 923–940. <https://doi.org/10.2106/00004623-197355050-00002>
- [37] Cui A, Li H, Wang D, Zhong J, Chen Y, Lu H. Global, regional prevalence, incidence and risk factors of knee osteoarthritis in population-based studies. *EClinicalMedicine*. 2020 Nov 26;29-30:100587. doi: 10.1016/j.eclinm.2020.100587. PMID: 34505846; PMCID: PMC7704420.
- [38] Hughston, J. C., Andrews, J. R., Cross, M. J., & Moschi, A. (1976). Classification of knee ligament instabilities. Part I. The medical compartment and cruciate ligaments. *Journal of Bone and Joint Surgery - Series A*, 58(2), 159–172. <https://doi.org/10.2106/00004623-197658020-00001>
- [39] Hughston, J. C. (1994). The importance of the posterior oblique ligament in repairs of acute tears of the medial ligaments in knees with and without an associated rupture of the anterior cruciate ligament. *Results of long-term follow-up. Journal of Bone and Joint Surgery*, 76(9), 1328–1344. <https://doi.org/10.2106/00004623-199409000-00008>
- [40] Turkiewicz, A., De Verdier, M. G., Engström, G., Nilsson, P. M., Mellström, C., Stefan Lohmander, L., & Englund, M. (2014). Prevalence of knee pain and knee OA in southern Sweden and the proportion that seeks medical care. *Rheumatology (United Kingdom)*, 54(5), 827–838. <https://doi.org/10.1093/rheumatology/keu409>

- [41] Fredericson, M., & Yoon, K. (2006, March). Physical examination and patellofemoral pain syndrome. *American Journal of Physical Medicine and Rehabilitation*. <https://doi.org/10.1097/01.phm.0000200390.67408.f0>
- [42] Näslund, J., Näslund, U. B., Odenbring, S., & Lundeberg, T. (2006). Comparison of symptoms and clinical findings in subgroups of individuals with patellofemoral pain. *Physiotherapy Theory and Practice*, 22(3), 105–118. <https://doi.org/10.1080/09593980600724246>
- [43] Odensten, M., & Gillquist, J. (1985). Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. *Journal of Bone and Joint Surgery - Series A*, 67(2), 257–262. <https://doi.org/10.2106/00004623-198567020-00012>
- [44] Trent, P. S., Walker, P. S., & Wolf, B. (1976). Ligament length patterns, strength, and rotational axes of the knee joint. *Clinical Orthopaedics and Related Research*, 117, 263–270. <https://doi.org/10.1097/00003086-197606000-00034>
- [45] Dale, K. M., Bailey, J. R., & Moorman, C. T. (2017, January 1). Surgical Management and Treatment of the Anterior Cruciate Ligament/Medial Collateral Ligament Injured Knee. *Clinics in Sports Medicine*. W.B. Saunders. <https://doi.org/10.1016/j.csm.2016.08.005>
- [46] Lind, M., Jakobsen, B. W., Lund, B., Hansen, M. S., Abdallah, O., & Christiansen, S. E. (2009). Anatomical reconstruction of the medial collateral ligament and posteromedial corner of the knee in patients with chronic medial collateral ligament instability. *American Journal of Sports Medicine*, 37(6), 1116–1122. <https://doi.org/10.1177/0363546509332498>
- [47] Pandey, V., Khanna, V., Madi, S., Tripathi, A., & Acharya, K. (2017). Clinical outcome of primary medial collateral ligament-posteromedial corner repair with or without staged anterior cruciate ligament reconstruction. *Injury*, 48(6), 1236–1242. <https://doi.org/10.1016/j.injury.2017.03.021>
- [48] Milenkovic, M., Jovanov, E., Chapman, J., Raskovic, D., & Price, J. (2002). An accelerometer-based physical rehabilitation system. In Proceedings of the Annual Southeastern Symposium on System Theory (Vol. 2002-January, pp. 57–60). *Institute of Electrical and Electronics Engineers Inc*. <https://doi.org/10.1109/SSST.2002.1027005>
- [49] Legnani, G., Zappa, B., Casolo, F., Adamini, R., & Magnani, P. L. (2000). A model of an electro-goniometer and its calibration for biomechanical applications. *Medical Engineering and Physics*, 22(10), 711–722. [https://doi.org/10.1016/S1350-4533\(01\)00009-1](https://doi.org/10.1016/S1350-4533(01)00009-1)
- [50] Gibbs, P.T., Asada, H. (2005). Wearable Conductive Fiber Sensors for Multi-Axis Human Joint Angle Measurements. *J NeuroEngineering Rehabil* 2, 7. <https://doi.org/10.1186/1743-0003-2-7>

- [51] Stupar, D. Z., Bajic, J. S., Manojlovic, L. M., Slankamenac, M. P., Joza, A. V., & Zivanov, M. B. (2012). Wearable low-cost system for human joint movements monitoring based on fiber-optic curvature sensor. *IEEE Sensors Journal*, 12(12), 3424–3431. <https://doi.org/10.1109/JSEN.2012.2212883>
- [52] Tao, W., Liu, T., Zheng, R., & Feng, H. (2012, February). Gait analysis using wearable sensors. *Sensors*. <https://doi.org/10.3390/s120202255>
- [53] Yang, C. C., & Hsu, Y. L. (2010, August). A review of accelerometry-based wearable motion detectors for physical activity monitoring. *Sensors*. <https://doi.org/10.3390/s100807772>
- [54] Sharma, P., Arora, R. K., Pardeshi, S., & Singh, M. (2013). Fibre Optic Communications : An Overview. *International Journal of Emerging Technology and Advanced Engineering*, 3(5), 474–479.
- [55] Kub, M. (2009). Stress strain analysis of knee joint. *Engineering MECHANICS*, 16(5), 315–322. Retrieved from http://www.engineeringmechanics.cz/pdf/16_5_315.pdf
- [56] Pathak, N. (2017). Evaluation of Patients Presenting with Knee Pain: Part I. History, Physical Examination, Radiographs, and Laboratory Tests. *WebMD*. <https://www.webmd.com/nehathathak-md>
- [57] Viradia, N. (2011). Knee Injuries in Collegiate Athletes, a Review of Literature, and a Study of the Effects of Pre vs. Post Collegiate ACL Reconstruction in Division 1 Collegiate Athletes on Subsequent Knee Surgeries and Sports Career Length. <https://doi.org/10.17615/18s8-6x30>
- [58] Thiem, U., Lamsfuß, R., Günther, S., Schumacher, J., Bäker, C., Endres, H. G., ... Pientka, L. (2013). Prevalence of Self-Reported Pain, Joint Complaints and Knee or Hip Complaints in Adults Aged ≥ 40 Years: A Cross-Sectional Survey in Herne, Germany. *PLoS ONE*, 8(4). <https://doi.org/10.1371/journal.pone.0060753>
- [59] Piriyaarasarth, P., Morris, M. E., Winter, A., & Bialocerowski, A. E. (2008). The reliability of knee joint position testing using electrogoniometry. *BMC Musculoskeletal Disorders*, 9. <https://doi.org/10.1186/1471-2474-9-6>
- [60] Ibeachu, C., Selfe, J., Sutton, C. J., & Dey, P. (2019). Knee problems are common in young adults and associated with physical activity and not obesity: The findings of a cross-sectional survey in a university cohort. *BMC Musculoskeletal Disorders*, 20(1). <https://doi.org/10.1186/s12891-019-2487-2>
- [61] Dejnabadi, H., Jolles, B. M., & Aminian, K. (2005). A new approach to accurate measurement of uniaxial joint angles based on a combination of accelerometers and gyroscopes. *IEEE Transactions on Biomedical Engineering*, 52(8), 1478–1484. <https://doi.org/10.1109/TBME.2005.851475>

- [62] Chi, C. Y., & Cheny, T. L. (2009). MEMS gyroscope control systems for direct angle measurements. *In Proceedings of IEEE Sensors* (pp. 492–496). <https://doi.org/10.1109/ICSENS.2009.5398283>
- [63] Sudin. S. (2012). Wireless knee joint angle measurement system using gyroscope [*master thesis, university tun hussein onn Malaysia*]. <https://core.ac.uk/download/pdf/12007861.pdf>
- [64] Bakhshi, S., Mahoor, M. H., & Davidson, B. S. (2011). Development of a body joint angle measurement system using IMU sensors. *In Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS* (pp. 6923–6926). <https://doi.org/10.1109/IEMBS.2011.6091743>
- [65] Dipietro, L., Sabatini, A. M., & Dario, P. (2003). Evaluation of an instrumented glove for hand-movement acquisition. *Journal of Rehabilitation Research and Development*, 40(2), 179–189. <https://doi.org/10.1682/jrrd.2003.03.0181>
- [66] Khayani S. B. (2011). Development of Wearable Sensors for Body Joint Angle Measurement. [*Master thesis, University of Denver*]. <https://digitalcommons.du.edu/cgi/viewcontent.cgi?article=1048&context=etd>
- [67] R., B. E., Xiaoping, Y., & Anne, B. (2007). An Investigation of the Effects of Magnetic Variations on Inertial/Magnetic Orientation Sensors Eric. *Contract*, 298(0704), 107. Retrieved from <http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA455390>
- [68] Bortz, J. E. (1971). A New Mathematical Formulation for Strapdown Inertial Navigation. *IEEE Transactions on Aerospace and Electronic Systems*, AES-7(1), 61–66. <https://doi.org/10.1109/TAES.1971.310252>
- [69] El-Gohary, M., & McNames, J. (2012). Shoulder and elbow joint angle tracking with inertial sensors. *IEEE Transactions on Biomedical Engineering*, 59(9), 2635–2641. <https://doi.org/10.1109/TBME.2012.2208750>
- [70] Mahmoud Ahmed El-Gohary M. A. (2013). Joint Angle Tracking with Inertial Sensors. [*Doctorate research, Portland State University*] https://pdxscholar.library.pdx.edu/open_access_etds/661/
- [71] Szelitzky, E., Kuklyte, J., Mândru, D., & O'Connor, N. (2014). Low Cost Angular Displacement Sensors for Biomechanical Applications - A Review. *Journal of Biomedical Engineering and Technology*, 2(2), 21–28. <https://doi.org/10.12691/JBET-2-2-3>
- [72] Roduit, R., Besse, P. A., & Micallef, J. P. (1998). Flexible angular sensor. *IEEE Transactions on Instrumentation and Measurement*, 47(4), 1020–1022. <https://doi.org/10.1109/19.744661>

- [73] Gentner, R., & Classen, J. (2009). Development and evaluation of a low-cost sensor glove for assessment of human finger movements in neurophysiological settings. *Journal of Neuroscience Methods*, 178(1), 138–147. <https://doi.org/10.1016/j.jneumeth.2008.11.005>
- [74] Mat, S., Jaafar, M. H., Ng, C. T., Sockalingam, S., Raja, J., Kamaruzzaman, S. B., Tan, M. P. (2019). Ethnic differences in the prevalence, socioeconomic and health related risk factors of knee pain and osteoarthritis symptoms in older Malaysians. *PLoS ONE*, 14(11). <https://doi.org/10.1371/journal.pone.0225075>
- [75] K.M. Venu K. M. (2003). Clinical Examination, MRI or Arthroscopy: Which is the gold standard in the diagnosis of significant internal derangement in the knee. *Orthopaedic Proceedings*. Vol. 85-B, No. SUPP II. https://doi.org/abs/10.1302/0301-620X.85BSUPP_II.0850167a
- [76] Orengo, G., Saggio, G., Bocchetti, S., & Giannini, F. (2011). Evaluating strain sensor performance for motion analysis. In *BIODEVICES 2011 - Proceedings of the International Conference on Biomedical Electronics and Devices* (pp. 244–249). <https://doi.org/10.5220/0003168402440249>
- [77] Kuriyama, S., Ding, M., Kurita, Y., Ogasawara, T., & Ueda, J. (2009). Flexible sensor for McKibben pneumatic actuator. In *Proceedings of IEEE Sensors* (pp. 520–525). <https://doi.org/10.1109/ICSENS.2009.5398292>
- [78] Cochrane, C., Koncar, V., Lewandowski, M., & Dufour, C. (2007). Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite. *Sensors*, 7(4), 473–492. <https://doi.org/10.3390/s7040473>
- [79] Kramer, R. K., Majidi, C., Sahai, R., & Wood, R. J. (2011). Soft curvature sensors for joint angle proprioception. In *IEEE International Conference on Intelligent Robots and Systems* (pp. 1919–1926). <https://doi.org/10.1109/IROS.2011.6048270>
- [80] Lin, J. T., Walsh, K. W., Jackson, D., Aebbersold, J., Crain, M., Naber, J. F., & Hnat, W. P. (2007). Development of capacitive pure bending strain sensor for wireless spinal fusion monitoring. *Sensors and Actuators, A: Physical*, 138(2), 276–287. <https://doi.org/10.1016/j.sna.2007.04.069>
- [81] Dobrzynska, J. A., & Gijs, M. A. M. (2010). Capacitive flexible force sensor. In *Procedia Engineering* (Vol. 5, pp. 404–407). Elsevier Ltd. <https://doi.org/10.1016/j.proeng.2010.09.132>
- [82] Lee, H. K., Chung, J., Chang, S. I., & Yoon, E. (2008). Normal and shear force measurement using a flexible polymer tactile sensor with embedded multiple capacitors. *Journal of Microelectromechanical Systems*, 17(4), 934–942. <https://doi.org/10.1109/JMEMS.2008.921727>

- [83] Zhang, Q., Saraf, L. V., Smith, J. R., Jha, P., & Hua, F. (2009). An invisible bend sensor based on porous crosslinked polyelectrolyte film. *Sensors and Actuators, A: Physical*, 151(2), 154–158. <https://doi.org/10.1016/j.sna.2009.02.034>
- [84] Nishijima, T., Yamamoto, A., & Higuchi, T. (2009). A flexible sensor measuring displacement and bending. *Measurement Science and Technology*, 20(4). <https://doi.org/10.1088/0957-0233/20/4/045205>
- [85] Mendes, J. J. A., Vieira, M. E. M., Pires, M. B., & Stevan, S. L. (2016, September 1). *Sensor fusion and smart sensor in sports and biomedical applications. Sensors (Switzerland)*. MDPI AG. <https://doi.org/10.3390/s16101569>
- [86] Takeda, H., Nakagawa, T., Nakamura, K., & Engebretsen, L. (2011). Prevention and management of knee osteoarthritis and knee cartilage injury in sports. *British Journal of Sports Medicine*. <https://doi.org/10.1136/bjism.2010.082321>
- [87] Jeethendria A., Senthilmuguran S. (2014). Monitoring Human Joint Movement Using Wearable Computing. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 3, Issue 4. https://www.ijareeie.com/upload/2014/april/44_Monitoring.pdf
- [88] Kam, W., O’Keeffe, M., O’Sullivan, K., Mohammed, W. S., O’Keeffe, S., Lewis, E., & Viphavakit, C. (2019). A validation study of a polymer optical fiber sensor for monitoring lumbar spine movement. *Materials*, 12(5). <https://doi.org/10.3390/ma12050762>
- [89] Gibbs, P. T., & Asada, H. H. (2005). Wearable conductive fiber sensors for multi-axis human joint angle measurements. *Journal of NeuroEngineering and Rehabilitation*, 2. <https://doi.org/10.1186/1743-0003-2-7>
- [90] Teague, C. N., Hersek, S., Toreyin, H., Millard-Stafford, M. L., Jones, M. L., Kogler, G. F., Inan, O. T. (2016). Novel methods for sensing acoustical emissions from the knee for wearable joint health assessment. *IEEE Transactions on Biomedical Engineering*, 63(8), 1581–1590. <https://doi.org/10.1109/TBME.2016.2543226>
- [91] Culshaw, B., & Kersey, A. (2008). Fiber-optic sensing: A historical perspective. *Journal of Lightwave Technology*, 26(9), 1064–1078. <https://doi.org/10.1109/JLT.0082.921915>
- [92] Kam, W., Mohammed, W. S., Leen, G., O’Keeffe, M., O’Sullivan, K., O’Keeffe, S., & Lewis, E. (2017). Compact and low-cost optical fiber respiratory monitoring sensor based on intensity interrogation. *Journal of Lightwave Technology*, 35(20), 4567–4573. <https://doi.org/10.1109/JLT.2017.2749499>
- [93] Ziemann, O. (2008). POF Handbook. Berlin, Germany: *Springer-Verlag Berlin*

Heidelberg.

- [94] Mitsubishi Rayon CO. LTD. Eska Optical Fiber Division (GH-4001-P) [*Specification Sheet*]. Tokyo, Japan: Eska Optical Fiber Division.
- [95] Thiel F. L. & Hawk R. M. (1976). Optical waveguide cable connection: erratum. *Appl. Opt.* 16, 1468-1468. <https://opg.optica.org/ao/abstract.cfm?uri=ao-16-6-1468>
- [96] Rocha, R. P., Silva, A. F., Carmo, J. P., & Correia, J. H. (2011). FBG in PVC foils for monitoring the knee joint movement during the rehabilitation process. *In Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS* (pp. 458–461). <https://doi.org/10.1109/IEMBS.2011.6090064>
- [97] Bergmann, J. H. M., Anastasova-Ivanova, S., Spulber, I., Gulati, V., Georgiou, P., & McGregor, A. (2013). An attachable clothing sensor system for measuring knee joint angles. *IEEE Sensors Journal*, 13(10), 4090–4097. <https://doi.org/10.1109/JSEN.2013.2277697>
- [98] Saggio, G., Quitadamo, L. R., & Albero, L. (2014). Development and evaluation of a novel low-cost sensor-based knee flexion angle measurement system. *Knee*, 21(5), 896–901. <https://doi.org/10.1016/j.knee.2014.04.014>
- [99] Kim, S., Lee, J., & Bae, J. (2017). Analysis of Finger Muscular Forces using a Wearable Hand Exoskeleton System. *Journal of Bionic Engineering*, 14(4), 680–691. [https://doi.org/10.1016/S1672-6529\(16\)60434-1](https://doi.org/10.1016/S1672-6529(16)60434-1)
- [100] Saggio, G., & Orenco, G. (2018). Flex sensor characterization against shape and curvature changes. *Sensors and Actuators, A: Physical*, 273, 221–231. <https://doi.org/10.1016/j.sna.2018.02.035>
- [101] Abro, Z. A., Zhang, Y. F., Hong, C. Y., Lakho, R. A., & Chen, N. L. (2018). Development of a smart garment for monitoring body postures based on FBG and flex sensing technologies. *Sensors and Actuators, A: Physical*, 272, 153–160. <https://doi.org/10.1016/j.sna.2018.01.052>
- [102] Umesh, S., Padma, S., Srinivas, T., & Asokan, S. (2018). Fiber bragg grating goniometer for joint angle measurement. *IEEE Sensors Journal*, 18(1), 216–222. <https://doi.org/10.1109/JSEN.2017.2770176>
- [103] Rezende, A., Alves, C., Marques, I., Silva, M. A., & Naves, E. (2018). Polymer optical fiber goniometer: A new portable, low cost and reliable sensor for joint analysis. *Sensors (Switzerland)*, 18(12). <https://doi.org/10.3390/s18124293>
- [104] Azahari, A., Siswanto, W. A., Ngali, M. Z., Salleh, S. M., & Yusup, E. M. (2017). Dynamic Simulation and Analysis of Human Walking Mechanism. *In IOP Conference Series: Materials Science and Engineering* (Vol. 166). Institute of

Physics Publishing. <https://doi.org/10.1088/1757-899X/165/1/012027>

- [105] Fotoohabadi, M. R., Tully, E. A., & Galea, M. P. (2010). Kinematics of rising from a chair: image-based analysis of the sagittal hip-spine movement pattern in elderly people who are healthy. *Physical Therapy*, 90(4), 561–571. <https://doi.org/10.2522/ptj.20090093>
- [106] Tanaka, S., & Ohtsuka, Y. (1991). Fiber-optic strain sensor using a dual Mach-Zehnder interferometric configuration. *Optics Communications*, 81(5), 267–272. [https://doi.org/10.1016/0030-4018\(91\)90613-I](https://doi.org/10.1016/0030-4018(91)90613-I)
- [107] Kersey, A. D., Davis, M. A., Patrick, H. J., LeBlanc, M., Koo, K. P., Askins, C. G., ... Friebele, E. J. (1997). Fiber grating sensors. *Journal of Lightwave Technology*, 15(8), 1442–1462. <https://doi.org/10.1109/50.618377>
- [108] Taffoni F, Formica D, Saccomandi P, Di Pino G, Schena E. Optical fiber-based MR-compatible sensors for medical applications: an overview. *Sensors (Basel)*. 2013 Oct 18;13(10):14105-20. doi: 10.3390/s131014105. PMID: 24145918; PMCID: PMC3859111.
- [109] Hemmerich A, Brown H, Smith S, Marthandam SS, Wyss UP. Hip, knee, and ankle kinematics of high range of motion activities of daily living. *J Orthop Res*. 2006 Apr;24(4):770-81. doi: 10.1002/jor.20114. PMID: 16514664.
- [110] Hamamatsu. (2017). CMOS Linear Image Sensor (KMPD1163E06) [Datasheet]. Japan: Hamamatsu Photonics K. K. <https://www.hamamatsu.com/jp/en/product/type/S12706/index.html>
- [111] Lee, B. (2003). Review of the present status of optical fiber sensors. *Optical Fiber Technology*, 9(2), 57–79. [https://doi.org/10.1016/S1068-5200\(02\)00527-8](https://doi.org/10.1016/S1068-5200(02)00527-8)
- [112] Engebretsen, L., Risberg, M. A., Robertson, B., Ludvigsen, T. C., & Johansen, S. (2009). Outcome after knee dislocations: A 2-9 years follow-up of 85 consecutive patients. *Knee Surgery, Sports Traumatology, Arthroscopy*, 17(9), 1013–1026. <https://doi.org/10.1007/s00167-009-0869-y>
- [113] Texas instruments. (2019). Tiva C TM4c123GH6PM (SPMS376E) [Datasheet]. Texas: Texas Instruments.
- [114] T. Wheeler. (2020). your guide to knee pain. *WebMD*, p. 2. <http://www.webmd.com/pain-management/knee-pain/knee-problemsand-injuriestopic-overview>
- [115] Edmund Optics. (2017). Fundamentals of Lasers. Centre for Devices and Radiological Health. [Laser Products and Instruments]. *U S Food and Drug Administration Home Page*.
- [116] Industrial Fiber optics. (2000). Plastic Fiber Optic Green Led (IF-E93)

[Datasheet]. USA: Industrial Fiber Optics Inc.

- [117] Massa, N. (2009). Fiber Optic Telecommunication. *In Fundamentals of Photonics* (pp. 293–347). SPIE. <https://doi.org/10.1117/3.784938.ch8>
- [118] Igwele, Minabai, M. (2019). Comparison of Signal Losses in Fibre Optic Cables. *Optical Fiber Sensor and Communication 1*: 1-9, ISSN 2516-3671. DOI: 10.23977/ofsc.2019.11001
- [119] Thorat, P. V. (2014). Plastic Optical Fiber. *International Journal of Engineering Research and Reviews*, Vol. 2, Issue 4, pp: (95-105). ISSN 2348-697X.
- [120] Mohapatra, B. N. (2017). Audio Transmitter and receiver System using Fiber Optic Cable. *International Journal of Emerging Technologies in Engineering Research (IJETER)* Volume 5, Issue 5.
- [121] The fiber optics association, “optical fiber”, [online], *the international professional association of fiber optics*, California, USA. February 2020. <https://www.thefoa.org/tech/ref/basic/fiber.html>
- [122] Bühner, M., Stampanoni, M., Rochet, X., Büchi, F., Eller, J., & Marone, F. (2019). High-numerical-aperture microscope optics for time-resolved experiments. *Journal of Synchrotron Radiation*, 26, 1161–1172. <https://doi.org/10.1107/S1600577519004119>
- [123] Avago technologies, September 1, 2015, HFBR-R/EXXYYYZ plastic optic fiber cable, *datasheet*.
- [124] Corning Incorporated, 2006, 62.5µm optical fibers, *datasheet*.
- [125] Chew, K. T. L., Lew, H. L., Date, E., & Fredericson, M. (2007, September). Current evidence and clinical applications of therapeutic knee braces. *American Journal of Physical Medicine and Rehabilitation*. <https://doi.org/10.1097/PHM.0b013e318114e416>
- [126] Paluska, S. A., & McKeag, D. B. (2000, January 15). Knee braces: Current evidence and clinical recommendations for their use. *American Family Physician*.
- [127] Riskowski, J. L., Mikesky, A. E., Bahamonde, R. E., & Burr, D. B. (2009). Design and validation of a knee brace with feedback to reduce the rate of loading. *Journal of Biomechanical Engineering*, 131(8). <https://doi.org/10.1115/1.3148858>
- [128] Singer, J. C., & Lamontagne, M. (2008). The effect of functional knee brace design and hinge misalignment on lower limb joint mechanics. *Clinical Biomechanics*, 23(1), 52–59. <https://doi.org/10.1016/j.clinbiomech.2007.08.013>

- [129] Tomal, A. N. M. A., Saleh, T., & Khan, M. R. (2017). Improvement of Dimensional Accuracy of 3-D Printed Parts using an Additive/Subtractive Based Hybrid Prototyping Approach. *In IOP Conference Series: Materials Science and Engineering* (Vol. 260). Institute of Physics Publishing. <https://doi.org/10.1088/1757-899X/260/1/012031>
- [130] Dey, A., & Yodo, N. (2019, September 1). A systematic survey of FDM process parameter optimization and their influence on part characteristics. *Journal of Manufacturing and Materials Processing*. MDPI Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/jmmp3030064>
- [131] Kotake, T., Dohi, N., Kajiwara, T., Sumi, N., Koyama, Y., & Miura, T. (1993). An analysis of sit-to-stand movements. *Archives of Physical Medicine and Rehabilitation*, 74(10), 1095–1099. [https://doi.org/10.1016/0003-9993\(93\)90068-L](https://doi.org/10.1016/0003-9993(93)90068-L)
- [132] Onishi, H., Yagi, R., Oyama, M., Akasaka, K., Ihashi, K., & Handa, Y. (2002). EMG-angle relationship of the hamstring muscles during maximum knee flexion. *Journal of Electromyography and Kinesiology*, 12(5), 399–406. [https://doi.org/10.1016/S1050-6411\(02\)00033-0](https://doi.org/10.1016/S1050-6411(02)00033-0)
- [133] Myles, C. M., Rowe, P. J., Walker, C. R. C., & Nutton, R. W. (2002). Knee joint functional range of movement prior to and following total knee arthroplasty measured using flexible electrogoniometry. *Gait and Posture*, 16(1), 46–54. [https://doi.org/10.1016/S0966-6362\(01\)00198-9](https://doi.org/10.1016/S0966-6362(01)00198-9)
- [134] Rowe, P. J., Myles, C. M., Walker, C., & Nutton, R. (2000). Knee joint kinematics in gait and other functional activities measured using flexible electrogoniometry: How much knee motion is sufficient for normal daily life? *Gait and Posture*, 12(2), 143–155. [https://doi.org/10.1016/S0966-6362\(00\)00060-6](https://doi.org/10.1016/S0966-6362(00)00060-6)
- [135] Tully, E. A., Fotoohabadi, M. R., & Galea, M. P. (2005). Sagittal spine and lower limb movement during sit-to-stand in healthy young subjects. *Gait and Posture*, 22(4), 338–345. <https://doi.org/10.1016/j.gaitpost.2004.11.007>
- [136] Devers, B. N., Conditt, M. A., Jamieson, M. L., Driscoll, M. D., Noble, P. C., & Parsley, B. S. (2011). Does Greater Knee Flexion Increase Patient Function and Satisfaction After Total Knee Arthroplasty? *Journal of Arthroplasty*, 26(2), 178–186. <https://doi.org/10.1016/j.arth.2010.02.008>
- [137] Trappler, R., Smith, E., Goldberg, G., Parvizi, J., and Hozack, W.J. (2018). Knee Range of Motion: Can we believe the Goniometer Reading. *Orthopaedic Proceedings*, Vol 91-B, SUPP_I, 6-6. https://online.boneandjoint.org.uk/doi/abs/10.1302/0301-620X.91BSUPP_I.0910006a
- [138] Clapper, M. P., & Wolf, S. L. (1988). Comparison of the reliability of the

Orthoranger and the standard goniometer for assessing active lower extremity range of motion. *Physical Therapy*, 68(2), 214–218.
<https://doi.org/10.1093/ptj/68.2.214>

- [139] Ochi, A., Ohko, H., Ota, S., Shimoichi, N., Takemoto, T., & Mitsuke, K. (2018). Custom-made hinged knee braces with extension support can improve dynamic balance. *Journal of Exercise Science and Fitness*, 16(3), 94–98.
<https://doi.org/10.1016/j.jesf.2018.08.002>
- [140] Cotton, R. J., & Rogers, J. (2019). Wearable monitoring of joint angle and muscle activity. In IEEE International Conference on Rehabilitation Robotics (Vol. 2019-June, pp. 258–263). *IEEE Computer Society*.
<https://doi.org/10.1109/ICORR.2019.8779538>
- [141] Nazarahari, M., Noamani, A., Ahmadian, N., & Rouhani, H. (2019). Sensor-to-body calibration procedure for clinical motion analysis of lower limb using magnetic and inertial measurement units. *Journal of Biomechanics*, 85, 224–229. <https://doi.org/10.1016/j.jbiomech.2019.01.027>
- [142] Jaimes, J. C., Leal-Junior, A. G., Siqueira, A. A. G., & Frizzera, A. (2019). Instrumentation and validation of polymer optical fiber sensor technology on a knee exoskeleton. In *2019 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference, IMOC 2019*. Institute of Electrical and Electronics Engineers Inc. <https://doi.org/10.1109/IMOC43827.2019.9317420>
- [143] Watson, A., Sun, M., Pendyal, S., & Zhou, G. (2020). TracKnee: Knee angle measurement using stretchable conductive fabric sensors. *Smart Health*, 15. <https://doi.org/10.1016/j.smhl.2019.100092>
- [144] Resta, P., Lo Presti, D., Schena, E., Massaroni, C., Formica, D., Kim, T., & Shin, D. (2020). A wearable system for knee flexion/extension monitoring: Design and assessment. In *2020 IEEE International Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2020 - Proceedings* (pp. 273–277). Institute of Electrical and Electronics Engineers Inc. <https://doi.org/10.1109/MetroInd4.0IoT48571.2020.9138192>
- [145] Leal-Junior, A. G., Theodosiou, A., Díaz, C. A. R., Avellar, L. M., Kalli, K., Marques, C., & Frizzera, A. (2020). FPI-POFBG Angular Movement Sensor Inscribed in CYTOP Fibers with Dynamic Angle Compensator. *IEEE Sensors Journal*, 20(11), 5962–5969. <https://doi.org/10.1109/JSEN.2020.2974931>
- [146] Teague, C. N., Heller, J. A., Nevius, B. N., Carek, A. M., Mabrouk, S., Garcia-Vicente, F., ... Etemadi, M. (2020). A Wearable, Multimodal Sensing System to Monitor Knee Joint Health. *IEEE Sensors Journal*, 20(18), 10323–10334. <https://doi.org/10.1109/JSEN.2020.2994552>
- [147] Vargas-Valencia, L. S., Schneider, F. B. A., Leal-Junior, A. G., Caicedo-Rodriguez, P., Sierra-Arevalo, W. A., Rodriguez-Cheu, L. E., ... Frizzera-Neto,

- A. (2021). Sleeve for Knee Angle Monitoring: An IMU-POF Sensor Fusion System. *IEEE Journal of Biomedical and Health Informatics*, 25(2), 465–474. <https://doi.org/10.1109/JBHI.2020.2988360>
- [148] Daniel, T. M., (2016). Line Array Sensor Comparison Hamamatsu S11639 Sony ILX511B Toshiba TCD1205DG. AdvancedMEMS.
- [149] Paschotta, R. Image Sensor. Website: https://www.rp-photonics.com/image_sensors.html
- [150] Wei Chih Wang, W. C. (2008). Optical detectors [Masters dissertation]. National Tsing Hua University.
- [151] Carlson, B. S. (2002). Evaluating image sensor sensitivity by measuring camera signal-to-noise ratio. In *Electro-Optical System Design, Simulation, Testing, and Training* (Vol. 4772, p. 78). SPIE. <https://doi.org/10.1117/12.451813>
- [152] Jacquemod, G., Odet, C., Peyrin, F., & Goutte, R. (1989). IMPROVE RESOLUTION OF INDUSTRIAL X-RAY COMPUTED TOMOGRAPHIC 3D IMAGES This research has been done under contract for the Commission of the European Communities on iron and steel research. In *Non-Destructive Testing* (pp. 74–79). Elsevier. <https://doi.org/10.1016/b978-0-444-87450-4.50019-9>
- [153] Djité, I., Magnan, P., Estribeau, M., Rolland, G., Petit, S., & Saint-pé, O. (2010). Modeling and measurements of MTF and quantum efficiency in CCD and CMOS image sensors. In *Sensors, Cameras, and Systems for Industrial/Scientific Applications XI* (Vol. 7536, p. 75360H). SPIE. <https://doi.org/10.1117/12.839175>
- [154] Bulayev, Y. (2015). Advances in CMOS image sensors open doors to many applications. *Photonics Spectra*, 49(9), 41–43.
- [155] B., A., K. P., V., Alexander, A., Srivastava, V., & Namboothiry, M. A. G. (2020). Understanding the poor fill factor of solution-processed squaraine based solar cells in terms of charge carrier dynamics probed: Via impedance and transient spectroscopy. *Journal of Materials Chemistry C*, 8(42), 14748–14756. <https://doi.org/10.1039/d0tc03012k>
- [156] Wu, P. C., Liu, B. D., Tseng, S. H., Tsai, H. H., & Juang, Y. Z. (2014). Digital offset trimming techniques for CMOS MEMS accelerometers. *IEEE Sensors Journal*, 14(2), 570–577. <https://doi.org/10.1109/JSEN.2013.2284284>
- [157] Seok, G., & Kim, Y. (2019). Front-inner lens for high sensitivity of CMOS image sensors. *Sensors (Switzerland)*, 19(7). <https://doi.org/10.3390/s19071536>
- [158] Lee, S., Yasutomi, K., Morita, M., Kawanishi, H., & Kawahito, S. (2020). A time-of-flight range sensor using four-tap lock-in pixels with high near infrared

- sensitivity for lidar applications. *Sensors (Switzerland)*, 20(1).
<https://doi.org/10.3390/s20010116>
- [159] Takayanagi, I., & Nakamura, J. (2013). High-resolution CMOS video image sensors. *Proceedings of the IEEE*, 101(1), 61–73.
<https://doi.org/10.1109/JPROC.2011.2178569>
- [160] Hidalgo-López, J. A., Romero-Sánchez, J., & Fernández-Ramos, R. (2017). New Approaches for Increasing Accuracy in Readout of Resistive Sensor Arrays. *IEEE Sensors Journal*, 17(7), 2154–2164.
<https://doi.org/10.1109/JSEN.2017.2662803>
- [161] Schmidt, J., Berg, D. R., Ploeg, H. L., & Ploeg, L. (2009). Precision, repeatability and accuracy of Optotrak® optical motion tracking systems. *International Journal of Experimental and Computational Biomechanics*, 1(1), 114.
<https://doi.org/10.1504/ijecb.2009.022862>
- [162] De Luca, A., Pathirana, V., Ali, S. Z., Dragomirescu, D., & Udrea, F. (2015). Experimental, analytical and numerical investigation of non-linearity of SOI diode temperature sensors at extreme temperatures. *Sensors and Actuators, A: Physical*, 222, 31–38. <https://doi.org/10.1016/j.sna.2014.11.023>
- [163] Ohta, J. (2007). Smart CMOS image sensors and applications. Optical science and engineering; 129) *CRC Press; 1st edition*. ISBN 9781138746817.
- [164] Salazar, A. (2014). CMOS Active Column Sensor for Label-Free Biodetection in Microarrays based on Surface Plasmon Resonance (SPR). *Universite de Grenoble, Dept. of Electronics*. <https://tel.archives-ouvertes.fr/tel-00932309v1>
- [165] Ching-Chun, W. (2001). A Study of CMOS Technologies for Image Sensor Applications. [Doctoral Dissertation]. Massachusetts Institute of Technology, Dept. of Electrical Engineering and Computer Science.
<http://hdl.handle.net/1721.1/8214>
- [166] Lulé, T., Benthien, S., Keller, H., Muütze, F., Rieve, P., Seibel, K., Boöhm, M. (2000). Sensitivity of CMOS based imagers and scaling perspectives. *IEEE Transactions on Electron Devices*, 47(11), 2110–2122.
<https://doi.org/10.1109/16.877173>
- [167] Djité, I., Estribeau, M., Magnan, P., Rolland, G., Petit, S., & Saint-Pé, O. (2012). Theoretical models of modulation transfer function, quantum efficiency, and crosstalk for CCD and CMOS image sensors. *IEEE Transactions on Electron Devices*, 59(3), 729–737. <https://doi.org/10.1109/TED.2011.2176493>
- [168] Vukomanovic, A., Djurovic, A., Popovic, Z., & Ilic, D. (2014). The A-test: Reliability of functional recovery assessment during early rehabilitation of patients in an orthopedic ward. *Vojnosanitetski Pregled*, 71(7), 639–645.
<https://doi.org/10.2298/vsp130118042v>

- [169] Kappetijn, O., van Trijffel, E., & Lucas, C. (2014). Efficacy of passive extension mobilization in addition to exercise in the osteoarthritic knee: An observational parallel-group study. *Knee*, 21(3), 703–709. <https://doi.org/10.1016/j.knee.2014.03.003>
- [170] Hancock, G. E., Hepworth, T., & Wembridge, K. (2018). Accuracy and reliability of knee goniometry methods. *Journal of experimental orthopaedics*, 5(1), 46. <https://doi.org/10.1186/s40634-018-0161-5>.
- [171] Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, 15(2), 155–163. <https://doi.org/10.1016/j.jcm.2016.02.012>
- [172] Jin, W., Lee, T. K. Y., Ho, S. L., Ho, H. L., Lau, K. T., Zhou, L. M., & Zhou, Y. (2006). Structural Strain and Temperature Measurements Using Fiber Bragg Grating Sensors. *In Guided Wave Optical Components and Devices* (pp. 389–400). Elsevier Inc. <https://doi.org/10.1016/B978-012088481-0/50026-7>