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Clinically Relevant Knee Motion is Accurately Measured with a Self-calibrated Wearable Sensor

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Introduction

Total knee arthroplasty is an effective treatment for many patients suffering from end-stage osteoarthritis. However, post-operative knee stiffness often leads to flexion contracture deformities that require aggressive therapies and revision surgery. Restoring knee motion within three months following joint replacement surgery mitigates the risk of flexion contracture and poor outcomes[1]. While motion analysis accurately characterizes knee motion, such measurements are financially and logistically impractical for continuously monitoring post-operative patient progress. Recently, our group developed a wearable sensor paradigm that utilizes a low-cost motion sensor and magnet to quantify knee angle during activity[2].The purpose of this study is to develop a self-calibration procedure that (1) is simple to perform, (2) generates accurate knee flexion data, and (3) does not require any external measurements.

Methods

Seven healthy young adults (4 males, 3 females; 26 ± 4 years; BMI 23.8 ± 3.7) participated in this IRB approved study. Subjects wore standard lab attire, a low-cost wearable sensor on the knee, and retro-reflective markers. The wearable sensor[2] was based on a strong earth magnet and a 9-degree- of-freedom motion sensor (LSM9DS0, FLORA 9-DOF, Adafruit) that was secured on the distal-lateral thigh and the proximal-lateral shank of the right leg, respectively, with fabric-backed tape and self-adhesive wrap. The wearable sensor was calibrated from a series of five static knee poses between 0 and 90 degrees knee flexion while the subject sat on a treatment table (Fix 1A). A 3rd order polynomial was fit to the pitch of the shank with respect to gravity—calculated via the accelerometer—and the magnetic field strength captured throughout this calibration motion (Figure Y). Subjects then performed clinically relevant motions—seated knee extension and sit to stand—and walked on a treadmill at three different speeds (0.9, 1.2, and 1.5 m/s) and up a 10% grade (1.2 m/s). Motion capture and wearable sensor data were synchronously collected and cross-correlations and peak knee angles were calculated for all trials.

Results

Peak knee extension values during the seated-knee extension exercises were accurate within 5 degrees across all subjects ($p = 0.29$, RMS Error: 2.6 degrees). Peak knee extension measurements were less accurate during the sit to stand exercises, consistently under-approximating extension values ($p = 0.48$; RMS Error: 16.6 degrees). Peak knee flexion during both of these movements reached sensor saturation at approximately 65 degrees knee flexion (Figure 1B). Knee angles during walking strongly correlated with motion capture measurements ($0.84 \leq r_{xy} \leq 0.99$). Despite these strong similarities in waveform pattern, the wearable sensor showed an RMS Error of 10.3 degrees peak knee flexion when considering all walking conditions. Walking faster and up an incline generated smaller errors ($p = 0.47$; RMS Errors: 7.9 and 7.4 degrees, respectively) compared to

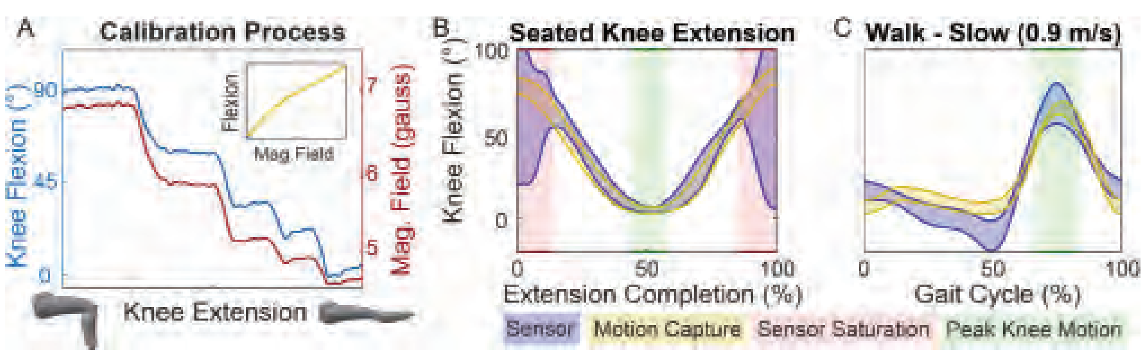

Figure 1. (A) Knee flexion and magnetic field strength are taken at 5 points and used to develop a 3rd order polynomial (inset) **(B)** Knee flexion measured by the device and motion capture throughout a seated knee extension exercise, green highlights show when peak knee extension occurs, red highlights show where sensor saturation produced non-real angle predictions by the sensor **(C)** Knee flexion plotted across a gait cycle from heel strike to heel strike, the sensor predicts a similar waveform as motion capture but exact values are much less accurate due to soft tissue artifact.

walking at slow and medium speeds generated ($p = 0.64$; RMS Errors: 12.8 and 13.2 degrees, respectively) compared to motion capture.

Discussion

This study presents a new calibration paradigm that accurately measures clinically relevant joint motions using a single low-cost sensor. Our results support the feasibility of this sensor paradigm for measuring knee extension during clinical exams. However, more functional motions—for example, walking and rising from a chair—appear to be affected by soft tissue artifact [3] and produce less accurate predictions of knee angle. Many of the issues caused by soft tissue artifact could be lessened by integrating the device into a brace and reducing its overall size, but a major limitation of the device lies in the nature of magnetic fields: the farther a magnet is from the sensor, the smaller the changes in magnetic field strength will be with respect to distance. This means that calibrating for accurate measurements at full extension will make measurements at deep flexion more prone to saturation errors. While this study focused on measuring knee motion, this paradigm can be adapted to work with other planar joints such as the elbow or ankle. Monitoring knee motion using a low-cost sensor provides new opportunities for clinicians to monitor patient progress and function outside of clinical visits, especially during the first three months following joint replacement when restoring motion is the most critical [1]. Current work is focused on developing educational material and a smartphone app to monitor patient knee motion during in-home rehabilitation protocols.

Significance

Knee extension can be accurately measured within 5 degrees using a low-cost and self-calibrating sensor, which may be used to identify patients at risk of developing knee flexion contractures.

References

1 Callahan+, *JAMA*, 1994
2 Qu+, *ORS San Diego*, 2017
3 Leardini+, *Gait & Posture*, 2005