A Low-Cost, Wearable Magnet-Based Detection System to Assess Joint Kinematics in Humans and Large Animals

Feini Qu[1,2]
Brendan D. Stoeckl[1]
Peter M. Gebhard[1]
Robert L. Mauck[1,2]

1University of Pennsylvania
Philadelphia, PA

2Translational Musculoskeletal Research Center
Philadelphia VA Medical Center
Philadelphia, PA

Introduction

Functional outcomes such as joint kinematics and gait are important indicators of efficacy in musculoskeletal research.[1] Traditional technology to objectively assess these parameters, such as visual tracking systems and/or force plates, are challenging to deploy in long-term translational and clinical studies. To address this limitation, we previously developed a low-cost, multi-sensor device that detects animal activity and joint angle, and hypothesized that it could quantify post-operative functional recovery.[2] Here, we establish longitudinal changes in animal activity after a bilateral arthrotomy, and demonstrate the feasibility of measuring joint kinematics in both large animals and humans using a magnet-based detection system.

Methods

Device Hardware: The device consists of an enclosure containing a polymer lithium ion battery, microcontroller board, radio board, data logger, and sensor board, which integrates a triple-axis accelerometer, triple-axis gyroscope, and triple-axis magnetometer.[2] *Device Validation:* To measure changes in joint angle, the device and a neodymium magnet (1" ø, 1/4" thick) were affixed 4" distal and 4" proximal to a human knee joint on the posterior surface, respectively. The knee was moved to flexion angles of 0º, 30º, 60º, and 70º. Position was held for 5 s at each angle (n = 3-4/group) and the magnetic field strength was recorded at 40 Hz. An equation relating sensor-magnet angle as a function of magnetic field magnitude was derived to predict flexion angle. To validate that the device could capture dynamic range of motion of the knee during normal gait, a human subject (n = 1) walked at a step frequency of approximately 1 Hz, and the magnetic field strength and angular velocity were recorded. Individual steps (n = 10) were used to obtain the range of motion (ROM) during the gait cycle. *Animal Monitoring:* To evaluate general activity of a large animal, the device was attached to a harness worn by a castrated male Yucatan minipig pre- and post-surgery (n = 1, 26 kg pre-op) in an unrelated study involving bilateral arthrotomy of the stifle, with analgesics given for the first 5 days after surgery. Data was collected at 8 Hz for 30 min of unsupervised activity in a 4' × 6' pen pre-operatively on Day −1 (Baseline) and post-operatively on Day 1 and weekly thereafter until euthanasia at Week 12. Angular velocity (º/s) parallel to the dorsal plane (animal turning left or right) was recorded and the absolute values binned into four activity intensity levels: 0-5 (Rest), 5-50 (Low), 50-100 (Moderate), and > (High). On Week 11, the sensor and magnet were laterally attached to the left hindlimb 4" proximal and 5" distal to the stifle joint, respectively. The stifle was manually flexed to angles of 20º (maximum extension), 30º, 60º, and 90º. Position was held for 5 s at each angle (n = 3-4/group) and the magnetic field strength was recorded at 8 Hz. The animal was allowed to freely ambulate within the pen and the magnetic field strength was recorded. Individual steps (n = 10) were used to obtain the ROM and were visually confirmed with synchronized high-speed video. *Statistics:* Significance was assessed by one-way ANOVA with Tukey's post-hoc tests to compare magnetic field strength between groups ($p \leq 0.05$). Data are presented as the mean ± SD unless otherwise noted.

Results

A wearable device capable of sensing motion and quantifying joint kinematics was fabricated with off-the-shelf electronics for <$200. Knee flexion angle was predicted via changes in the magnetic field strength, which increased exponentially with flexion (Figure 1B, $p \leq 0.05$). Using this method, we measured the range of motion (ROM) of a human knee during a normal gait cycle. Flexion angle and angular velocity of the tibia appeared as repetitive and predictable patterns during ambulation (Figures 1C and 1D). The average ROM of the human knee during the gait cycle was 54 ± 4º, with a peak flexion angle of 55 ± 3º. Next, the device was used to monitor unsupervised large animal activity pre- and post-surgery, and to quantify stifle joint kinematics. The device was worn by a Yucatan minipig and angular velocity in the dorsal plane was recorded over 12 weeks (Figure 2). On Day −1 (Baseline), the animal had full ROM and activity was characterized by Rest and Low intensity activity, with short periods of Moderate and High intensity activity (Figure 2A). Immediately post-operative on Day 1, the animal was predominately sedentary and ambulated with a stiff, limping gait. The animal regained

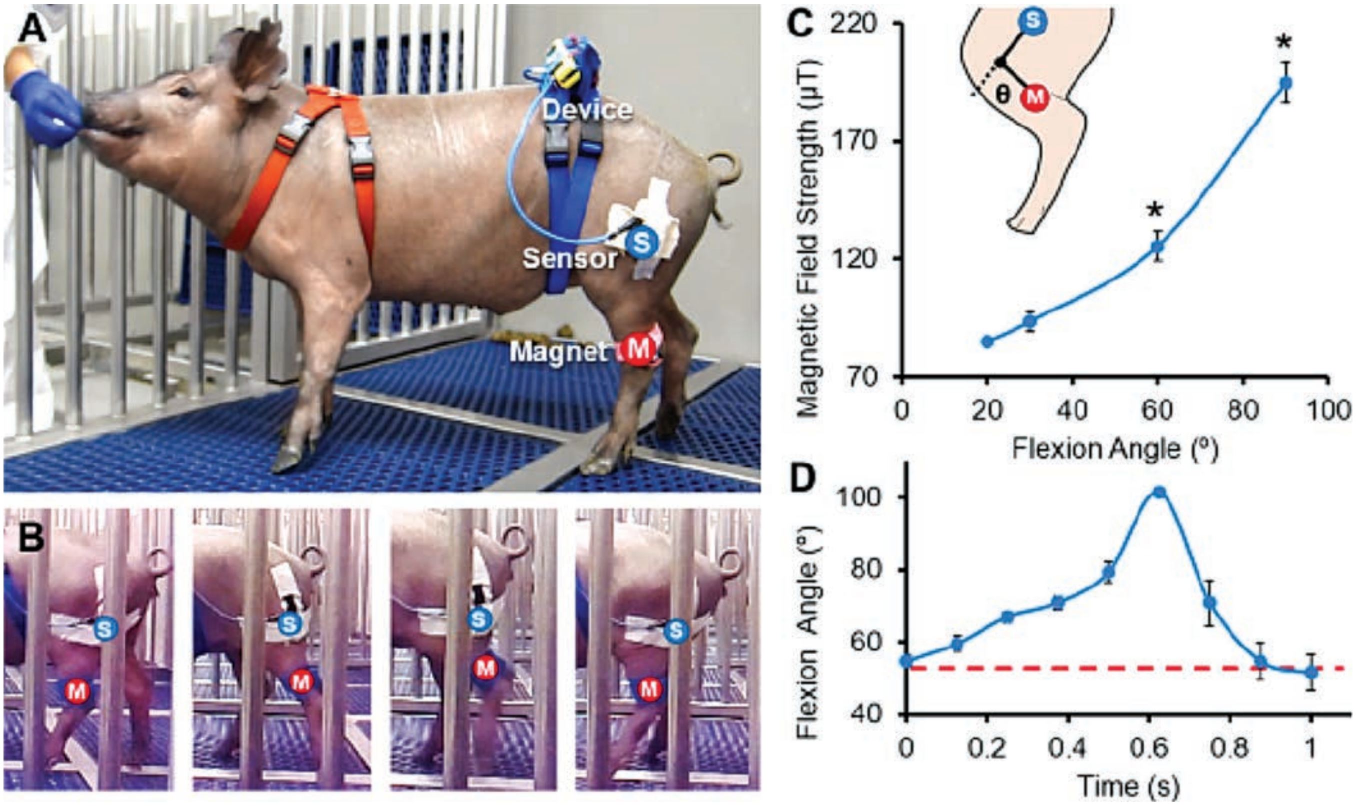

Figure 1. Magnet-based system for quantifying joint kinematics. (A) Experimental schematic. (B) Magnetic field strength as a function of flexion angle. *= $p \leq 0.05$ vs. all other angles. (C) Average flexion angle and (D) Angular velocity for a human knee during a gait cycle (mean ± SEM for 10 steps).

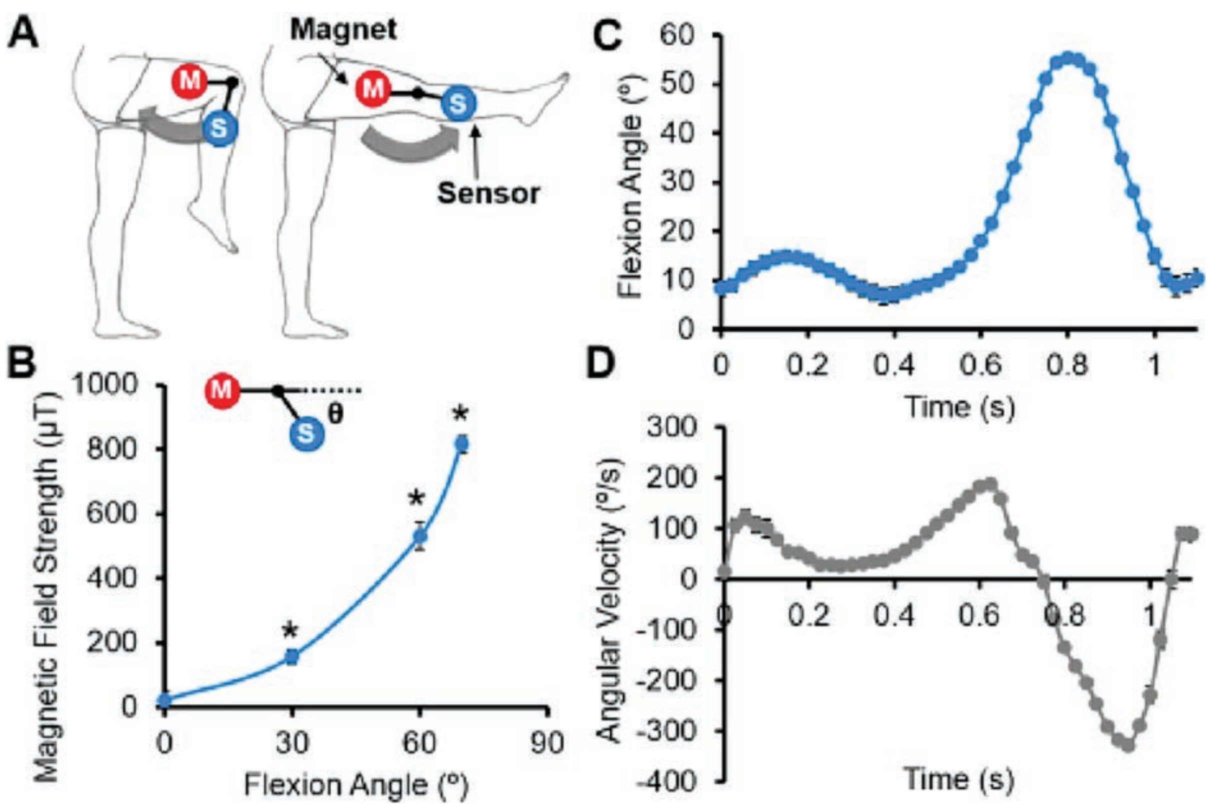

Figure 2. Unsupervised activity monitoring demonstrates time course of recovery in a porcine model. (A) Distribution of activity intensity pre- and post-surgery. (B) Non-Rest Activity normalized to the pre-operative Baseline value (red dashed line) and animal weight over 12.

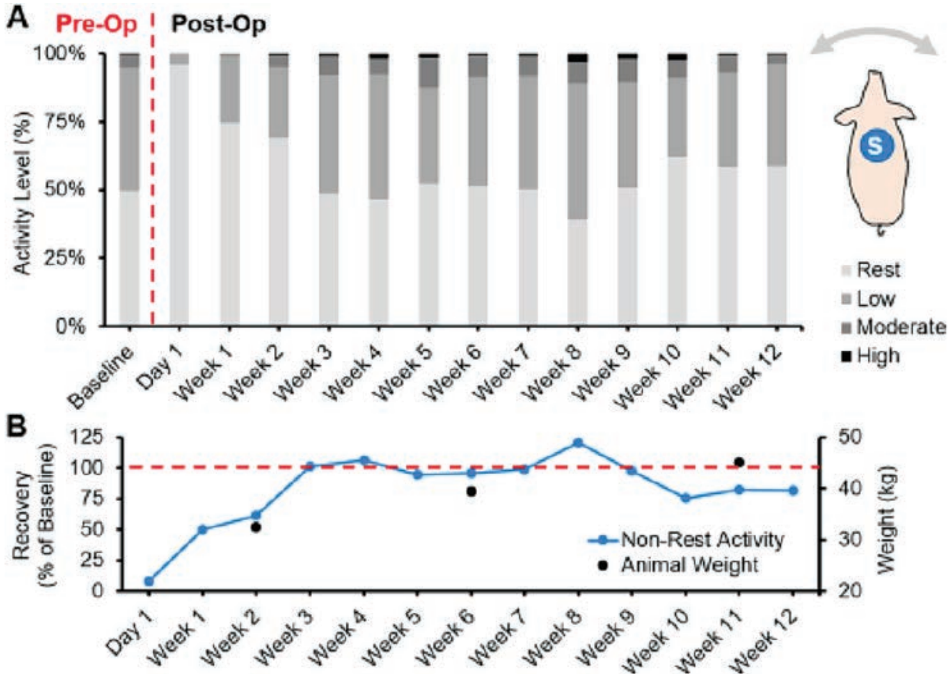

Figure 3. Dynamic range of motion during unprovoked ambulation. (A) Image of animal wearing the device. (B) Sensor and magnet positions during gait cycle. (C) Magnetic field as a function of flexion angle. * = $p \leq 0.05$ vs. all other angles. (D) Average flexion angle during a gait cycle at Week 11 (mean ± SEM for 10 steps). Red line indicates neutral stance.

50% of its pre-operative Non-Rest activity level by Week 1, and was fully recovered by Week 3. Non-Rest activity levels were maintained until Week 10, when it slightly declined (Figure 2B). The average ROM of the porcine stifle during the gait cycle was 55 ± 13º at Week 11, with a peak flexion angle of 101 ± 4º (Fig. 3).

Discussion

Wearable motion sensors have the potential to provide objective, individualized data on physical activity and locomotion for animal models. However, basic accelerometer-based monitors cannot assess the type or quality of movement,[3] whereas more complicated analytical systems are costly and often require the use of multiple sensor components in a supervised environment.[4,5] To that end, we developed a low-cost device using a single integrated sensor that quantifies both joint kinematics and activity in an unsupervised manner. Using this system, we tracked the time course of recovery of a pig after arthrotomy and found that return to baseline activity occurred 3 weeks after surgery. Monitoring also revealed a slight decline in activity in the long term, which may indicate behavioral changes due to increasing weight or age. By placing a magnet opposite the articulating joint, we identified discrete steps and calculated the dynamic ROM during unprovoked ambulation in both the human knee and the porcine stifle. Importantly, the measured ROM for the porcine stifle was consistent with previously reported values for healthy swine,[6] indicating functional joint recovery by 3 months. Standard gait parameters, such as cadence and swing/stance phase ratio, may also be derived from this data. Simple and inexpensive, this magnet-based system will facilitate the longitudinal assessment of joint abnormalities and functional recovery for animal and human subjects in orthopaedic research.

Significance

This device allows inexpensive quantification of joint kinematics and activity levels in research subjects using a single integrated sensor.

Acknowledgments

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