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Promoting global clinical care and research for children with orthopaedic disabilities through motion analysis technology

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Abstract
Human motion analysis is a tool used to understand orthopaedic disabilities in children and to plan and monitor treatment strategies. It enables clinicians to quantitatively describe rehabilitative progress, plan surgeries, and conduct research. While this technology is prevalent in major academic medical centers, access is lacking in many regions throughout the world. This paper presents a novel approach to offer more accessible technology at greatly reduced cost. Current applications are underway in the Philippines, Mexico, and Colombia. Through international partnerships, improvements in clinical care, medical education, and research have been observed.

Keywords: human motion analysis; gait analysis; paediatric orthopaedics; rehabilitation; international collaboration

Introduction
Motion analysis systems are designed to track and analyse human movement, and provide information to clinicians to improve treatment planning and follow-up care (Harris & Smith, 1996). A typical laboratory system consists of reflective markers placed on the patient's anatomic landmarks, which are detected by cameras while the patient walks. Analysis of this gait data can show motion of individual body joints, which can be readily compared with established normal patterns to identify the cause of mobility abnormalities (Krzak et al., 2011). Patients with cerebral palsy and other disabilities are frequently assessed using motion analysis to identify gait patterns, such as crouch gait, as well as specific deformities, such as planovalgus and equinovarus of the foot and ankle.

Orthopaedic surgeons can use the results of a gait analysis session to better plan surgeries to improve patient mobility. The breadth of data provided by this analysis allows the surgeon to plan single-event, multi-level surgeries to speed patient progress and reduce the number of surgeries needed. Similarly, physical medicine and rehabilitation physicians can plan interventions based on a gait analysis session, targeted to specific patient needs. Gait analysis also provides capacity for quantitative outcome assessment, enabling physicians to track patient outcomes and improve the quality of interventions (Graf et al., 2009).

The Orthopaedic and Rehabilitation Engineering Center (OREC) at Marquette University has significant history in orthopaedic and motion analysis research in the United States, including many local collaborations. This has led to several postdoctoral fellows, students and colleagues identifying needs outside the U.S., specifically in international settings of need. Typical motion analysis laboratory technologies were far too expensive and complex for use in global health applications, and a strong interest was observed in reducing their cost and complexity. This paper describes the development of accessible technology and the formation of international partnerships to impact clinical care, medical education, and research for children with orthopaedic disabilities.

Technology
Development History
Prior to this program, the high cost of motion analysis systems and associated technical complexity severely restricted implementation and support. Only well-funded research clinics and institutions with substantial resources and staff were able to utilize

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these systems. Our group has been able to integrate and evaluate a system that enabled gait analysis at a fraction of the cost of commercial systems (Kertis et al., 2010). The system, completed and first installed in 2010, includes low-cost, high-resolution cameras, reflective markers, calibration devices, and software to process the results. The camera system provides data on kinematics, the motion of the joints. That system has since been installed and continuously upgraded in facilities in Asia, South America, and Mexico.

In 2014, further needs and outreach opportunities were identified for manual wheelchair users. To address these needs and promote cost-effective and simplified technology, a wheelchair assessment system was developed (Rammer et al., 2017). The system includes a roll-in-place wheelchair platform and simplified camera technology, enabling easy to use and quick assessments of manual wheelchair users.

In 2015, based on the success of our outreach efforts with the kinematics technology, the system was upgraded to include a force plate, which assesses kinetics, the forces within the body. The patient steps on the force plate while walking, and data is recorded and compared with normal patterns.

In 2017, the system was upgraded further to include an 8-channel wireless electromyography (EMG) system, which measures the activation of muscles. Again, this data can be compared with normal patterns to determine when each muscle is active during gait, giving the clinicians valuable insight to assist in care planning.

Current Components

The current motion analysis system uses 18 OptiTrack [NaturalPoint Inc., Corvallis, OR, USA] cameras positioned around the laboratory, an AMTI [Advanced Mechanical Technology, Inc., Watertown, MA, USA] force plate integrated into the laboratory floor, and a DelSys [DelSys Inc., Natick, MA, USA] Trigno Wireless EMG System, with 8 individual wireless muscle sensors. In a typical motion analysis session, the patient would walk back-and-forth 10 times while being recorded by all three systems.

Software used in the system includes C-Motion [C-Motion Inc., Germantown, MD, USA] AMASS software for calibration of the capture volume and data collection, and Visual3D software for kinematics and kinetics processing. This software package is state-of-the-art but also turnkey for the user with minimal training required for operation. The data output consists of three distinct pages (Figure 1), the kinematic, kinetic, and EMG data. This data is plotted alongside average normal ranges for each parameter for ready identification of deficits. Integration of OpenSim [NCSRR, Stanford, CA, USA] advanced musculoskeletal modelling is ongoing and would further support use of the system in advanced research projects.

The wheelchair propulsion assessment system consists of a roll-in-place wheelchair platform two Microsoft [Microsoft Corporation, Redmond, WA, USA] Kinect sensors, and custom software which integrates with OpenSim musculoskeletal models. In a typical analysis session, the patient would push their wheelchair on the stationary roller system several times while arm and hand motion is recorded by the sensors. The Milwaukee Foot Model (Harris & Smith, 2008; Long et al., 2011; Canseco et al., 2012; Kruger et al., 2017) extends the capabilities of the motion analysis system by providing detailed foot kinematics, enabling research and patient assessment of foot abnormalities.

Collaborators of our group have developed a database for managing and sharing motion analysis research data (http://motionlabresources.org/Information.htm). The database simplifies sorting and processing of patient data, and in multi-institutional collaborative use, can increase research output and statistical power. Currently, the database can process gait analysis data and standardized outcome tools and enables secure sharing of this data. The motion lab database is being installed in outreach laboratories to enable participation in these multi-institutional studies.

Recent developments have also led to research in activity monitoring (Kurapati et al., 2017). Consumer-grade sensors have been implemented in outreach settings to study daily mobility in the home and community. Our implementation currently includes Fitbit [Fitbit, San Francisco, CA, USA] sensors given to patients over a 1-week period. A major study was completed in Manila, using the motion analysis laboratory and Fitbit sensors to study osteogenesis imperfecta, a rare disorder causing brittle bones, in the community (Kurapati et al., 2017). In this case, the laboratory data were used as a baseline measure to correlate sensor-derived activity levels at home and in the community. It is expected that this work could lead to new information on fracture risk and activity participation in this population.

Implementation Strategy

Thus far, initial contacts with outreach institutions have been obtained through research collaborators and current/former students and fellows. Key personnel from interested institutions are invited to OREC for two weeks of proficiency training in motion analysis. The first week is for technical training in setup and operation of the equipment, and the second week is for clinical interpretation of the results. This provides the necessary background to use the system clinically. Following the training, the facilities requirements of the outreach institution are determined. Typically, a room with minimum dimensions 3.5 m by 9 m, non-reflective floor surface for camera compatibility, sufficient electrical service, and reliable internet connection are required. It is also necessary to have at least a half-time employee dedicated to the laboratory, typically an engineer or physical therapist.

The system is transported and installed by OREC staff in phases to minimize the learning curve, and ensure that each technological upgrade is effectively being used to improve patient care and medical education. OREC covers the cost of all travel, equipment, and supplies for each laboratory, and the institutions are responsible for providing the necessary facilities and personnel. The current phases of implementation are as follows:

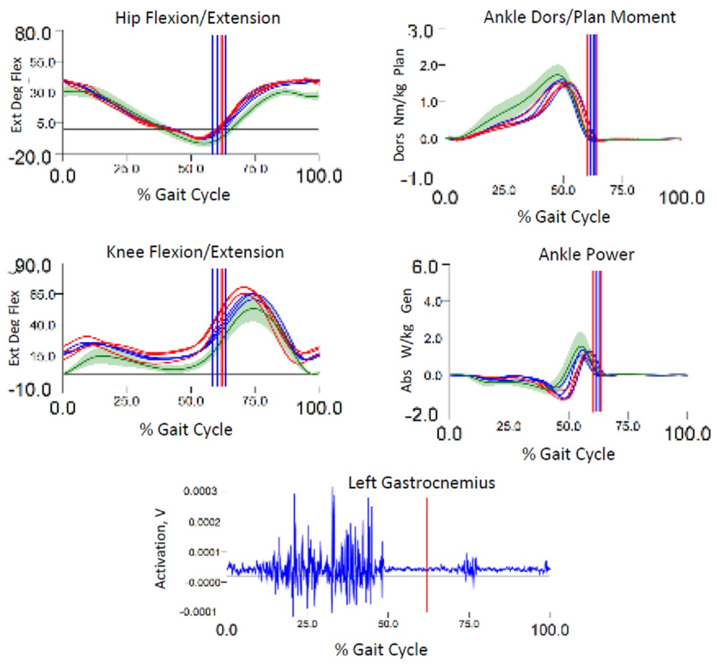

Figure 1. Example clinical outputs; kinematics (left), kinetics (right), and EMG (bottom). Green shaded areas represent normal values for population. Vertical lines represent the transition from stance to swing phase in gait. Data presented from IRB-Approved Study (Marquette University IRB Protocol HR-2948).

- Phase I: Camera system (kinematics)
- Phase II: Force plate (kinetics)
- Phase III: EMG (muscle activation)
- Phase IV: Wheelchair assessment system
- Phase V: Research-specific tools and database integration
- Phase VI: Self-sufficiency

Ongoing technical support and research stimulation is provided by OREC personnel both remotely (via video call and/or screen-sharing) and in-person during two visits yearly.

Clinical Partnerships

Over the past several years, we have developed three international clinical partnerships.

Cali, Colombia

Our colleagues in the Silver Service Foundation have a 25-year history of clinical outreach to Colombia, and originally identified the need there for motion analysis to improve orthopaedic care. In 2012, our first outreach collaboration was initiated with the Fundacion Clinica Infantil Club Noel, a specialty hospital for children in Cali, Colombia. Over the years, the lab has gradually developed its clinical output and is currently evaluating at least one child with cerebral palsy on a weekly basis.

Manila, Philippines

Manila, Philippines, is a massive population center with very high needs in medical care and clinical education. Colleagues recommended Philippine General Hospital (PGH) in Manila as a potential outreach location, and a collaboration was developed to implement a motion analysis system there in 2014. The lab had a very high impact almost immediately on clinical care and research at PGH, being used for orthopaedics and rehabilitation medicine patient care, medical education, and research. Due to high patient and research demand, the system was rapidly upgraded to include kinetics, EMG, and the wheelchair assessment system. Currently there are several research projects and university collaborations ongoing, including activity monitoring in children with osteogenesis imperfecta (Smith, Rauch, and Harris 2015). Recently, a manuscript was published by colleagues at PGH on a study of paraplegic wheelchair athletes with the system (Constantino et al., in press). Figures 2 and 3 show activity in Manila.

Mexico City, Mexico

Most recently, an outreach program was established at Shriners Hospital for Children, Mexico City, to accommodate an ever-increasing clinical need for quantitative motion analysis and specialty orthopaedic care. As our third outreach effort, the installation in Mexico City was guided by our past experiences. The initial kinematics system was installed in 2016, and upgraded to kinetics in 2017. Interest in the program has led to a residency training program in mobility, affiliations being developed with engineering programs in Mexico City, and a high patient volume. The outreach effort and collaboration will continue to progress toward maximizing clinical care and research for children in need.

Figure 2. Paediatric patient being prepared for motion analysis, Manila, Philippines

Figure 3. Wheelchair propulsion assessment system, Manila, Philippines

Future Directions

Through this effort, we have gained experience in developing effective technology, establishing collaborative international relationships, and providing impactful resources to communities of great need. The technology developed through the effort is sufficient to produce quality clinical and research data, and effective in global outreach settings. Our group will continue to find opportunities for further outreach, and strengthen the collaborative network that makes the project possible, while continuing to support clinical, education, and research efforts at all current outreach locations. The long-term goal of the project is to enable each outreach laboratory to become self-sufficient. We encourage each outreach institution to participate in collaborative research efforts and develop the capacity to seek extramural funding, which will promote self-sufficiency.

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