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ABBREVIATIONS AND DEFINITIONS OF TERMS

AE	Adverse event
IDL	Innovative Design Labs
CHOP	Children's Hospital of Philadelphia
IR	Infrared

ABSTRACT

Context:

With the rise in competitive sports participation in pediatric and adolescent populations, there has also been an increase in overuse injuries. Current methods of overuse injury prevention, such as pitch-counting, fail to account for differing techniques or effort and often ignore the elevated risk for children participating in two or more sports emphasizing the same body part. This wearable device seeks to more accurately monitor overuse to prevent and aid rehabilitation of overuse injuries.

Objectives:

The primary objective of this study is to collect motion-capture data on movements common to baseball play in order to develop an algorithm for a wearable device for the prevention and rehabilitation of sports-related overuse injuries. Secondary objectives include evaluating the feasibility of wearing the throwing device during simulated baseball play.

Study Design:

Prospective reliability study.

Setting/Participants:

- Males and female baseball pitchers age 8-14 years old at the time of consent will be included
- Children with an existing injury in their throwing arm will be excluded

Data collection for the Pilot Phase will occur at sports medicine/physical therapy sessions at the Children's Hospital of Philadelphia, including satellite locations. Participants may be approached at the start of their physical therapy sessions at CHOP. Data collection for Phase 1 will occur at the Epic Sports Biomechanics research facility. Participants will be recruited via solicitation from letters sent to local youth sport organizations, fliers placed in the Sports Medicine Centers throughout CHOP, or personal solicitation via email, phone, or in-person contact.

Study Interventions and Measures:

Subjects will be asked to fill out a short survey about their athletic activities. They will wear a prototype of a minimal risk throwing device during simulated baseball play in a sports medicine session or at the Epic Sports Biomechanics research facility. Various motion data from the device and from the Motion Lab analysis will be collected to create and refine an algorithm to quantify workload and throwing movements.

TABLE 1: SCHEDULE OF STUDY PROCEDURES

Study Phase	Screening Pilot Phase	Screening Phase 1	Pilot Phase: Physical Therapy Data Collection	Phase 1: Epic Sports Collection
Visit Number			1	1
Informed Consent/Assent	X	X		
Review Inclusion/Exclusion Criteria	X	X		
Medical Record Review			X	
Athletic History Survey		X	X	
Demographics Survey		X		
Height/Weight			X	X
Physical Examination			X	X
Throwing Exercises with Device			X	X
Epic Sports Biomechanics Evaluation				X

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1 BACKGROUND INFORMATION AND RATIONALE

1.1 Introduction

Overuse injuries in youth athletes are commonplace. Current methods of prevention and progressive loading during rehabilitation are rudimentary (e.g. baseball pitch count) and fail to account for the subtleties of differing player technique or effort. A system capable of quantifying biomechanical loads associated with sports movements would substantially aid physicians, therapists, guardians, and coaches in prevention and rehabilitation efforts.

Study team partners at Innovative Design Labs (IDL) in collaboration with Reality Works Inc. have developed a prototype for an advanced wearable device that has potential to track cumulative exposure to injurious forces, monitor adherence to sport-specific overuse standards and rehab regimens, and identify improper throwing technique. The purpose of this study is to collect preliminary and advanced motion data from youth athletes in order to create and refine an algorithm to quantify throwing movements, numbers, and injury associations among youth baseball players for use in this wearable throwing monitor. The Pilot Phase of the study will occur in the CHOP rehabilitation clinic while wearing the prototype device and aims to test and refine rudimentary throwing algorithms using simple throwing and movement tasks. Phase 1 of the study will occur at the Epic Sports Biomechanics research facility and will collect advanced motion-capture data during simulated baseball play in order to improve system hardware, firmware, and algorithms.

1.2 Name and Description of Investigational Product

This sports injury performance monitoring device aims to 1) track exposure to injurious forces 2) monitor adherence to sport specific overuse standards and prescribed rehab regimens, 3) identify improper technique, and 4) meet the practical requirements of a youth-sports monitoring system (e.g. cost, aesthetics, ease-of-use, etc.). An accompanying smart phone application and web interface will be developed as part of the study for use in future product development. More information on the electronic hardware and software can be found in the Appendix, page 20.

As the comfort, ease-of-use, robustness, and appearance of any wearable device is of critical importance to its acceptance, significant effort will be put into analyzing the requirements and testing concepts for the device design in this study phase. Perfecting design and manufacturability will occur in a future study. The sensors will be sealed in soft, hypoallergenic foam to provide resistance to sweat, dirt, and physical impact. Multiple form-factors including arm-bands, elbow compression sleeves, and wrist straps will be investigated, optimizing the combination of easy donning and doffing, maximal comfort, aesthetics, and to accurate motion transfer. The system will include a “zero touch” interface where no user interaction is required to utilize the device. Study team members will be responsible for setting up, powering up, and charging the device.The case will be hermetically sealed creating a dust-tight and waterproof device (IP68 rated).

1.3 Relevant Literature and Data

Youth sports participation in the United States has grown to 46.5 million children annually [1]. Although participation in athletics has numerous health benefits [2], sport-related overuse injuries from excessive stress and/or inadequate recovery periods represent a significant and growing health care concern [3]. Annually, 1.25 million sports-related overuse injuries are reported in emergency rooms with patients 24 years or younger [4] resulting in $2 billion of healthcare costs [3], [8]–[11]. In addition to cost and pain, these injuries result in lost participation time, numerous physician visits, and lengthy rehabilitation [2]–[5]. Further, athletes with recurrent overuse injuries may stop participating in sports, thus adding to the already increasing numbers of unhealthy sedentary and obese youths [3]. Overuse injuries are preventable through proper monitoring and education; however, adherence to guidelines is often deficient [6]. This device seeks to prevent and aid rehabilitation of such sports-related overuse injuries.

1.4 Compliance Statement

This study will be conducted in full accordance all applicable Children's Hospital of Philadelphia Research Policies and Procedures and all applicable Federal and state laws and regulations including 45 CFR 46 and 21 CFR Parts 50, 56.

The investigators will perform the study in accordance with this protocol, will obtain consent and assent, and will report unanticipated problems involving risks to subjects or others in accordance with The Children's Hospital of Philadelphia IRB Policies and Procedures and all federal requirements. Collection, recording, and reporting of data will be accurate and will ensure the privacy, health, and welfare of research subjects during and after the study.

2 STUDY OBJECTIVES

The overall purpose of the study is to create and refine an algorithm to quantify throwing movements, effort, numbers, and injury associations among youth baseball players for use in a wearable throwing monitor with the hopes of preventing and aiding in the rehabilitation of sports-related overuse injuries.

2.1 Primary Objective (or Aim)

The primary objective of this study is to collect motion-capture data on movements common to baseball play in order to develop a wearable device for the prevention and rehabilitation of sports-related overuse injuries.

2.2 Secondary Objectives (or Aim)

The secondary objectives are to:

- Develop algorithms to quantify injury associated with common baseball injures
- Evaluate the feasibility of wearing the throwing monitor during a simulated baseball game

- Validate simplistic device measurements (Pilot Phase)

3 INVESTIGATIONAL PLAN

3.1 General Schema of Study Design

This study will occur in two phases with two different subject groups. The Pilot Phase will include 10 evaluable subjects and occur in the sports medicine physical therapy clinic at the Children's Hospital of Philadelphia. Subjects will be asked to perform simple throwing movements as part of or in addition to their rehabilitation regiment. This will test the ability of the prototype device to detect basic movements.

Phase 1 will include 10 evaluable subjects and occur at the Epic Sports Biomechanics research facility. Subjects will partake in a simulated baseball game while wearing the prototype device and additional baseball-related movements while being tracked by the Epic Sports Biomechanics research facility's infrared sensors. The goal of this phase is to create and refine a more robust algorithm for the device that can track various throwing movements and track potential injurious forces or poor techniques.

This study is a prospective reliability study.

3.1.1 Screening Phase

Pilot Phase: Potential subjects will be identified from screening patient lists for CHOP sports medicine/physical therapy sessions. Potential subjects will be screened using the protocol inclusion and exclusion criteria. Subjects will be consented in-person at the start of their physical therapy session.

Phase 1: Potential subjects will be identified through recruitment strategies outlined in Section 8.5. Subjects will be screened over the phone, over email or in person using the protocol inclusion and exclusion criteria. Subjects will have the study explained to them and have opportunity to ask questions over the phone or in person and will sign a REDCap consent form sent to them via email. Once the consent form is signed, the study team will work with the subject to schedule a session at the Epic Sports Biomechanics research facility.

For both phases, parental/guardian permission (informed consent) and child assent, will be obtained prior to any study related procedures being performed.

3.1.2 Pilot Phase Cohort: Physical Therapy Throwing Session

During the Pilot Phase, subjects that have been identified, consented, and enrolled will wear a prototype of IDL's throwing monitor device during the duration of their physical therapy appointment. Subjects will wear the device somewhere on their arm and may or may not be asked to perform throwing movements as part of their rehabilitation regimen. This phase will test if the device is able to detect basic throwing movements and create an accurate pitch count.

3.1.3 Phase 1 Cohort: Epic Sports Biomechanics Throwing Session

During Phase 1, subjects that have been recruited, consented, and enrolled will come to the Epic Sports Biomechanics research facility on the day of their appointment. Subjects will be asked to wear the prototype device during a simulated baseball game (approximately 30-45 pitches), and then will perform a set of other baseball-specific movements while fitted with infrared markers for throwing analysis. This data will be used to develop and refine the algorithm for the prototype.

3.2 Study Duration, Enrollment and Number of Sites

3.2.1 Duration of Study Participation

The study duration per subject will be 1 day for screening, and 1 day for throwing evaluation for both the Pilot and Phase 1 groups.

3.2.2 Total Number of Study Sites/Total Number of Subjects Projected

The study will be conducted at approximately 3 investigative site in the United States: The Children's Hospital of Philadelphia, Epic Sports Biomechanics, and the University of Pennsylvania. Data will also be transferred to and analyzed at the University of Pennsylvania.

Recruitment will stop when approximately 40 total subjects are recruited. It is expected that approximately 40 subjects will be enrolled to produce 20 evaluable subjects, with 10 in the Pilot Group and 10 in the Phase 1 Group.

3.3 Study Population

3.3.1 Inclusion Criteria

Pilot Phase

1) Males or females age 8 to 14 years
2) Presenting to CHOP Physical Therapy Clinic for rehabilitation of injury that does not impede their ability to perform basic throwing movements.

Phase 1

1) Males or females age 8 to 14 years
2) Involved in official baseball team and primarily plays as the pitcher

3.3.2 Exclusion Criteria

Pilot Phase

1) Injury of any aspect of the throwing arm
2) Unwillingness to perform all requested motions

3) Parents/guardians or subjects who, in the opinion of the Investigator, may be non-compliant with study procedures.

Phase 1

1) Injury or disability impeding ability to perform normal baseball-related movements

2) Inability/unwillingness to schedule and/or travel to the Epic Sports Biomechanics research facility

3) Parents/guardians or subjects who, in the opinion of the Investigator, may be non-compliant with study schedules or procedures.

Subjects that do not meet all of the enrollment criteria may not be enrolled. Any violations of these criteria must be reported in accordance with IRB Policies and Procedures.

4 STUDY PROCEDURES

4.1 Screening Visit

4.1.1 Pilot Phase

The screening visit will occur on the day of clinic and any screening procedures (e.g. informed consent) will happen in-person. Procedures include:

- Review of inclusion/exclusion criteria
- Medical Record Review

4.1.2 Phase I cohort

For the Phase 1 cohort, the screening visit will occur over the phone or in-person. Screening procedures include:

- Informed consent (via electronic consent on REDCap distributed through email)
    - Study explanation and time for the potential subject to ask questions will occur over the phone or in person with a member of the study team
    - Subjects will be emailed an electronic consent form through REDCap, which will contain all consent-form language for their review and space for an electronic signature
- Demographics survey (on REDCap, distributed through email after consent form is received and verified)
- Complete athletic history survey (on REDCap, distributed through email after consent form is received and verified)
- Review of inclusion/exclusion criteria

4.2 Study Treatment Phase

4.2.1 Pilot Phase Study Visit

- Informed consent and assent

Subjects will be asked to put on the throwing monitor device prototype at the beginning of their physical therapy session and will wear the device for the duration of the visit or until asked by a member of the study team to remove the device. Subjects will be asked to do the following tasks while wearing the device:

- Complete any physical therapy rehabilitation exercises given by their physical therapist as part of their care
- Complete a limited number of additional throwing exercises within in the limits of the rehabilitation regimen
- Complete athletic history survey (not required to wear device for survey completion)
- Medical record review
- Height and weight measurements if not collected as part of clinical care
- Physical exam if not collected as part of clinical care
- Return throwing device at end of session or earlier if requested by study team

No subject will be asked to complete any motions or tasks that may hinder their rehabilitation regimen.

4.2.2 Phase 1 Study Visit

At the Epic Sports Biomechanics research facility, subjects will be asked to do the following activities:

- Height and weight measurements
- Physical Exam
- Wear the prototype device and participate in a simulated game
    - Pitch approximately 30-45 times using varying pitch types (fastball, change-up, etc.)
- Complete additional baseball-related movements with full the Epic Sports Biomechanics research facility monitors in a random order, including
    - Field-based overhand throws
    - Runs

- Bat swings
- Catching balls

- Return throwing device at end of session or earlier if requested by study team

4.3 Subject Completion/Withdrawal

Subjects may withdraw from the study at any time without prejudice to their care (if applicable). They may also be discontinued from the study at the discretion of the Investigator for lack of adherence to study protocols (i.e. wearing the device at appropriate times), failure to follow visit schedules, injury that prevents the subject from throwing or participating in the study, or any AEs. The Investigator may also withdraw subjects who violate the study plan, or to protect the subject for reasons of safety or for administrative reasons. It will be documented whether or not each subject completes the clinical study. If the Investigator becomes aware of any serious, related adverse events after the subject completes or withdraws from the study, they will be recorded in the source documents and on the CRF.

5 STUDY EVALUATIONS AND MEASUREMENTS

5.1 Screening and Monitoring Evaluations and Measurements

5.1.1 Medical Record Review

Patients enrolled in the Pilot Phase will undergo limited electronic medical record review of the following variables:

- Date of birth
- Height and weight
- Demographics including sex and race
- Primary diagnosis
- Prescribed physical therapy
- Medical history of current and previous injuries

Patients enrolled in Phase 1 will not necessarily be CHOP patients and thus will not undergo medical record review, but will instead be given a brief demographic survey.

5.1.2 Physical Examination

Subjects in both phases will be asked about current and past injuries. Subjects in the Pilot Phase will undergo a physical examination if not part of clinical care. The subjects in Phase 1 will also undergo a physical examination by the team prior to engaging in throwing activities. For both phases, we will be assessing height and weight as well as range of motion, strength, balance and other physical assessment measures involving the kinetic

chain that may lead to alterations in throwing technique and correspond to an increased risk of injury. Specific measurements may include range of motion of shoulder, elbow, spine, hip, and ankle; assessment for scapular dyskinesis; strength assessment through the shoulder, elbow, trunk and hip and lower extremities; single leg balance; humeral retrotorsion using musculoskeletal US will also be assessed using validated techniques.

5.1.3 LifeIMAGE/iSite

Any imaging records associated with the subjects in the Pilot Phase will be reviewed.

5.1.4 Other Evaluations, Measures

Subjects in both phases will be asked to complete a brief survey on their athletic history. The survey will ask about their athletic team involvement and injury history and should take no more than five minutes to complete. Subjects will not have to answer any questions that make them uncomfortable. This may be completed on REDCap or on paper for the Pilot Phase. Paper forms will then be entered into REDCap by a member of the study team and hard copies will be destroyed. Subjects in Phase 1 will receive the survey via email after the completed consent form has been received.

Subjects in Phase 1 will be asked to complete a brief demographic survey on REDCap, which will be sent to them via email after the study team has received their signed consent form. This survey will ask basic demographic information such as date of birth, race, and ethnicity.

5.1.5 Pilot Phase Throwing Evaluations

Subjects will wear the throwing monitor device prototype during a physical therapy session unless asked by a member of the study team to remove it. They will go through all of their normal physical therapy exercises. In addition, subjects may be asked to do a limited number of additional throwing movements during their physical therapy session. Subjects will not have to interact with the device other than donning and doffing the device. The device will collect motion data for the duration of the session. Subjects will not be asked to complete any additional exercises that could hinder their rehabilitation program. Subjects will be asked to return the throwing monitor device by the end of the study visit.

5.1.6 Phase 1 Throwing Evaluations

At the Epic Sports Biomechanics research facility, subjects will wear the throwing monitor device prototype during a simulated baseball game, pitching approximately 30-45 times using varying pitch types (fastball, change-up, etc.) as they would within a typical game. In addition, each player will perform a set of other baseball-specific movements (field-based overhand throw, run, bat swing, catch ball) typically seen in baseball play. Participants will be fitted with 51 infrared reflective markers to enable tracking of limb, torso, and head movement while actions are performed. Movement data will be video recorded and recorded with 12 Motion Analysis Raptor IR cameras encompassing a capture volume of 26ft length x 7ft width x 8ft height. A minimum of 3 time-synchronized video cameras placed at different viewing perspectives will also record participants as they perform movements. Subjects will be asked to return the throwing monitor device by the end of the study visit.

5.2 Efficacy Evaluations

5.2.1 Diagnostic Tests, Scales, Measures, etc.

Movement Data Processing: The first step in the processing chain is to apply calibrations and filters to correct intrinsic errors (e.g. sensor bias, scale factor, non-linearity) and extrinsic errors (e.g. sensor mounting, movement artifacts, external magnetic fields). This will be done using an Error-State Extended Kalman Filter (EKF) fusing the accelerometer, gyroscope, magnetometer, and a physical motion model together in a statistically valid fashion. Anomalous movements well outside of the expected range (e.g. a player bumping the sensor) are flagged by the sensor to avoid corrupting data interpretation. The filtered sensor data is then used to estimate time-series quantities such as short-time window 3-D motion paths, orientation stability, velocity vectors, and tangential and centripetal accelerations.

Movement Classification: The system is only interested in analyzing a subset of the movements executed during play hence the next step in the processing chain is detection / classification of movements of interest. This process begins with separation of processed time-series data into portions containing movements of unknown type. This is done with a classifier trained to discriminate fixed sized windows into either start of movement, end of movement, or other classes. This separation process is important as different actions will on average take differing amounts of time. Attempting to classify actions directly with fixed window sizes results in diminished discriminative power as the timeseries values used to produce these features will likely be taken from a period where the system is in multiple states [39], [40]. After action segmentation, a secondary feature set will be calculated over the movement timeseries and used to classify the movement to a known class of actions in the given sport (e.g. forehand swing, backhand swing, serve in tennis). IDL has had success with the decision tree classifier in previous efforts and will begin our research efforts with this algorithm. The tree is trained offline using the C4.5 algorithm with data acquired in the research facility [41]. The resulting decision trees are then used for real-time classification on the sensor hardware.

Movement Phase Segmentation: After detection and classification, movements are further segmented into constituent phases. The true phase of the movement is modeled as a hidden Markov model where time series data or windowed feature data derived from the time series data are used as emissions of the Markov process. Using the set of emissions recorded, the optimal set of series of states is calculated using the Viterbi algorithm [2]. Emissions distributions for the phases of a movement are determined from truth data gathered in the Epic Sports Biomechanics research facility.

Biomechanical interpretations: Pseudo Biomechanical Variables (PBVs) related to the true biomechanical values such as torques on joints and forces applied to ligaments are estimated at the final stage in the processing pipeline. This is accomplished using a combination regression analysis and a phase-specific simplified inverse biomechanical model. Since movement phases are associated with specific biomechanical configuration and displacements of the body segments within a phase are constrained by design, the inverse mapping is determined over a smaller problem subspace. Regression analysis is used offline to calculate a mapping between biomechanical values of interest (e.g. torque in shoulder) and sensor measurements (e.g. x dimension acceleration). The regression is simplified through use of the least absolute shrinkage and selection operator (LASSO) to determine the

minimum set of active joint variables to improve computational performance when executed on sensor hardware in real-time [42].

These values are then used to determine the probability of injury as well as calculate performance estimates such as pitch velocity. PBVs are also paired with movement phase information, stored, and available for viewing by the player, parents, and coaches to aid in quick identification of problems with form or opportunities to improve performance. Injury estimation cost functions will score actions based on the potential for accumulated overuse injury risk. For example, large forces on the UCL during the stride phase of a baseball pitch due to an excessive rotation of the forearm from the horizon to the vertical plane would accumulate a higher cost than a similar pitch with proper form [43].

5.3 Safety Evaluation

This is a minimal risk study. The Principal Investigator will be responsible for monitoring the safety of study subjects and complying with all reporting requirements. Members of the study team who perform the motion analysis will monitor subjects throughout to ensure that they do so safely. The PI and study investigators will monitor data accuracy and identify ways to resolve any problem areas.

6 STATISTICAL CONSIDERATIONS

6.1 Primary Endpoint

- The primary endpoint of this study is to quantify motion capture data on movements common to baseball play.

6.2 Secondary Endpoints

Secondary endpoints will include the following:

- Quantify injury associated with different baseball movement using the proposed system.
- Development of algorithms to quantify workloads associated with injury during common baseball movements.
- Validation of basic device measurements (Pilot Phase)

6.3 Statistical Methods

6.3.1 Baseline Data

Data will be analyzed with the goal of determining the feasibility of the approach. The accuracy of movement classification, movement phase segmentation, mapping of sensor reading to biomechanical values, and movement detection will all be quantified. K-fold cross validation will be used to estimate the performance of regressors and classifiers. Regressor performance will be quantified via the mean and standard deviation of error values between predicted biomechanical variable values and actual values as determined from motion capture data. Biomechanical value prediction models will be considered successful if error distributions have mean and standard deviation of less than 5% and 10% respectively of the nominal value. Sensitivity and specificity will be used to quantify the

performance of movement detection and classification algorithms. Movement segment detection will be considered correct if the algorithm identifies 90% of time occupied by the movement. Detection algorithms will be considered successful if they are able to operate with specificity and sensitivity of 95%.

6.3.2 Efficacy Analysis

Data recorded from the motion capture system will be analyzed with C-Motion Research Visual 3D v5 Professional and used to derive biomechanical variables of interest when performing movements associated with overuse injuries or of interest for performance monitoring. Analysis will calculate a time series of torques, compression forces, and tension forces on joints, ligaments, and muscles of interest. A biomechanist at the Epic Sports Biomechanics research facility familiar with baseball will review video of each movements of interest (e.g. pitches) and segment movements into their constituent phases. Additionally, the biomechanist will flag any abnormalities in data such as aborted movements and instances of improper form or technique.

6.3.3 Safety Analysis

This is a minimal risk study. The Principal Investigator will be responsible for monitoring the safety of study subjects and complying with all reporting requirements. Members of the study team who perform the motion analysis will monitor subjects throughout to ensure that they do so safely. The PI and study investigators will monitor data accuracy and identify ways to resolve any problem areas.

6.4 Sample Size and Power

This is an exploratory study so no power analysis was conducted. A total of 40 patients will be enrolled study-wide. For the pilot phase, we plan to enroll 20 patients to yield 10 evaluables. Additionally, based on previously reported literature, we plan to enroll a convenience sample of 20 youth baseball players in Phase 1 to yield 10 evaluable subjects, mainly consisting of pitchers, will be recruited to participate in this study. However, to account for subject withdrawal and attrition rates, study team plans to enroll additional 10 more subjects per phase.

7 SAFETY MANAGEMENT

7.1 Clinical Adverse Events

Clinical adverse events (AEs) will be monitored throughout the study.

7.2 Adverse Event Reporting

Since the study procedures are not greater than minimal risk, SAEs are not expected. If any unanticipated problems related to the research involving risks to subjects or others happen during the course of this study (including SAEs) they will be reported to the IRB in accordance with CHOP IRB SOP 408: Unanticipated Problems Involving Risks to Subjects. AEs that are not serious but that are notable and could involve risks to subjects will be summarized in narrative or other format and submitted to the IRB at the time of continuing review.

8 STUDY ADMINISTRATION

8.1 Treatment Assignment Methods

8.2 Data Collection and Management

1. **Confidentiality of Data**. A master list will be maintained separately from the data collection sheet and will contain identifiable data including subject ID, name, DOB and MRN (if applicable). The study team members will be the only individuals with access to the master list. All other data will be collected on a separate coded data collection sheet– only the study ID number will link the master sheet to the coded data sheet. Both the master list and coded data collection sheet will be password-protected excel files. Data will be managed and stored using the research-focused electronic data capture system REDCap, under an agreement with the software's development consortium, led by Vanderbilt University. REDCap supports two secure, web-based applications designed exclusively to support data capture for research studies. REDCap is a PHP web application served by Apache Tomcat over a 128 bit SSL connection using a signed certificate. The application relies on a study-specific data dictionary defined in an iterative self-documenting process that will be conducted by all members of the research team. The data dictionary is the foundation for custom case report form design and validated coding of variables. Authentication of research staff will be performed via LDAP using CHOP's enterprise Active Directory service. The application generates a complete audit trail of user activity, provides reporting, and has an automated export mechanism to common statistical packages (SAS, SPSS, Stata, R/S-Plus).

2. **Security**. The master sheet and data collection sheet will be password protected excel files kept in the secure storage network for the Division of Orthopaedics on the secure hospital server. The REDCap MySQL database is replicated in real time to a completely redundant instance of MySQL. The redundant instance is available for restoration of the primary database or for manual failover in the case of primary database failure. Time-stamped backup files are made from the replicated database daily by CHOP Research Information Systems using automated backup routines. Backup files are encrypted and transferred to a secure file server accessible only to designated personnel. A rolling seven-day window of backup files is maintained in an immediately available online state, with a larger window maintained in a compressed file archive available at a reduced speed of access. Daily destructive database backup files are stored on the database server and are deleted only after successful backup of the entire database to file. In the event of data error, loss or corruption, research personnel will work with CHOP Research Information Systems to determine the most appropriate recovery strategy. Data and backups are stored in the CHOP Research Information Systems Storage Area Network (SAN). Access to the SAN directories where data are stored will be limited to Research Information Systems personnel, with authentication performed using CHOP's enterprise Active Directory service. Consent forms from the Pilot Phase will be stored electronically on the secure orthopaedics hard drive or a hard-copy will be kept in a binder in the locked research office. Consent forms from Phase 1 will be stored in REDCap. All data collected from the throwing device or at the Epic Sports Biomechanics research

facility will be secured electronically or in locked cabinets only accessible to research personnel. Processed data collected in the Epic Sports Biomechanics research facility will be transferred to research staff at CHOP and the University of Pennsylvania as coded, password-protected excel files sent via secure email servers or CHOP's secure ShareFile functionality. Any processed or unprocessed data from the throwing device and/or Epic Sports Biomechanics analysis will be transferred to CHOP or the University of Pennsylvania before being sent via secure email servers, an encrypted flash drive, or CHOP's ShareFile function to collaborators outside of CHOP or the University of Pennsylvania where it will be stored securely in password-protected computers or drives.

3. **Anonymization, de-identification or destruction**. The information collected as part of this study will be retained until at least two years following final marketing approval for the device according to FDA data retention guidelines. At that time, the research information will either be destroyed or all the information that identifies the subject will be removed from the study results and the key destroyed.

8.3 Confidentiality

All data and records generated during this study will be kept confidential in accordance with Institutional policies and HIPAA on subject privacy and the Investigator and other site personnel will not use such data and records for any purpose other than conducting the study. Data will be maintained in REDCap or in password-protected data files on password-protected computers. Data transfers will be limited to within the study team and will utilize encrypted flash drive, secure email providers, and/or CHOP's secure ShareFile function.

No identifiable data will be used for future study without first obtaining IRB approval or a determination of exemption". The investigator will obtain a data use agreement between the provider (the PI) of the data and any recipient researchers (including others at CHOP) before sharing a limited dataset (PHI limited to dates and zip codes).

8.4 Regulatory and Ethical Considerations

8.4.1 Data and Safety Monitoring Plan

The principal investigator will monitor data and safety throughout the duration of the study. There is minimal safety risk associated with participation in this protocol, but the study team will immediately notify the PI if any safety issues do arise. The PI and study team will monitor data accuracy and identify ways to resolve any problem areas.

8.4.2 Risk Assessment

The risks of this study are no greater than minimal. Risks to study subjects are breach of privacy and/or breach of confidentiality. There is a minimal risk that survey questions may make subjects uncomfortable, but subjects do not have to answer any questions that make them feel uncomfortable. There is also a minimal risk that subjects may become injured while being asked to perform different throws and movements typical of physical therapy regimens or youth baseball play. However, this risk will be minimized because subjects will be under the supervision of a trained physical therapist and subjects will be able to

discontinue any throw/movement that makes them uncomfortable. Finally, there may be a risk of skin irritation from wearing the PhysSens device.

8.4.3 Potential Benefits of Trial Participation

There are no direct benefits to the subject related to this study.

8.4.4 Risk-Benefit Assessment

The risks of this study are no greater than minimal. While there is minimal risk to subjects due to accidental disclosure of PHI, this risk is minimized through the techniques outlined in the "Data Collection and Management" section.

8.5 Recruitment Strategy

Participants for the Pilot Phase will be recruited from orthopaedics physical therapy clinics at CHOP. Potential subjects will be identified by a member of the study team based on screening sports medicine physical therapy clinic schedules against the inclusion/exclusion criteria. Patients who are qualified for the study (based on the inclusion/exclusion criteria) will be approached and consented during their physical therapy visit.

Participants for Phase 1 will be recruited from multiple sources including solicitation letters sent to local youth sport organizations, fliers placed in the Sports Medicine Centers throughout CHOP organization, and or personal solicitation via email, phone, or in-person contact. Patients who are qualified for the study (based on inclusion/exclusion criteria) and who respond to solicitation or other recruitment strategies will be consented via e-consent processes using REDCap and will have the opportunity to ask questions during a phone call with a member of the study team prior to signing the eConsent. At the biomechanics laboratory for throwing performance housed at Epics Sports Biomechanics, the subjects will undergo additional data collection within the 3-D motion laboratory in order to augment training data and re-estimate the accuracy of the various algorithmic components.

For the Pilot Phase, a convenience sample of 20 youth athletes will be recruited to participate. Recruitment will stop when 10 evaluable subjects have undergone data collection.

For Phase 1, a convenience sample of 20 youth baseball pitchers, will be recruited to participate in this study. Recruitment will stop when 10 evaluable subjects have undergone data collection.

8.6 Informed Consent/Assent and HIPAA Authorization

A member of the study team will obtain consent and assent from all eligible subjects and families that agree to participate in the research. For pilot phase, the consent and assent process will take place in physical therapy setting after a member of the study team has explained the research, clearly outlined the risks and benefits of participation, and provided the subjects and their families with sufficient time to ask questions and consider participation. Similarly, the participants for Phase 1 will be recruited via methods elaborated in Section 8.5 for a study session at th Epic Sports Biomechanics research facility. Subjects

in Phase 1 will be consented and provide assent via e-consent processes using REDCap and will have the opportunity to ask questions during a phone call with a member of the study team prior to signing the eConsent. All subjects will be under 18, so parental consent and child assent will be obtained. All subjects will be provided with a hard or digital copy of the consent form, which includes a description of the research and contact information for the study team.

The Phase 1 eConsent will be administered via REDCap, and will grant parental permission/consent, child assent, and HIPPA authorization for screening procedures (questionnaires) for the main study within the same form. The consent form will be emailed to the address provided by the parent/legal guardian when discussing the study on the phone as detailed above, and a valid electronic signature will be obtained for parental consent and child assent. The subject will be able to save or print a copy of the signed as well as the unsigned consent form, and the form will have instructions on how to do so.

8.6.1 Waiver of HIPAA Authorization

We believe this study qualifies for a waiver of HIPAA authorization for the screening of subjects for the Pilot Phase, as the use or disclosure of protected health information involves no more than minimal risk to the privacy of individuals. This is due to the fact that there is an adequate plan to protect identifiers and to destroy identifiers at the earliest opportunity as noted in the section entitled “Data Collection and Management.” There is also a written assurance that protected health information will not be reused or disclosed to any other person or entity, except as required by law, for authorized oversight of the research project, or for other research for which the use or disclosure of protected health information would be permitted by this subpart as noted in the section entitled “Confidentiality.” The research cannot be practicably carried out without the waiver since it is not feasible for the study team to approach all subjects coming to the Sports Medicine Center for physical therapy prior to screening for eligibility. PHI is necessary to identify our target population and review medical records; therefore, this research could not be practicably carried out without access to this information.

8.7 Payment to Subjects/Families

8.7.1 Reimbursement for travel, parking and meals

Subjects in Phase 1 only will receive free validated parking slips to cover the parking cost at the Penn Medicine University City lot near the gait lab.

8.7.2 Payments to parent for time and inconvenience (i.e. compensation)

No compensation will be provided to the parent.

8.7.3 Payments to subject for time, effort and inconvenience (i.e. compensation)

Subjects in Phase 1 only will receive $50 to compensate for time, effort, and inconvenience. Subjects in the Pilot Phase will not receive compensation as the study procedures will take

no more than 15 minutes beyond their indicated physical therapy visit for consent, surveys, and donning/doffing the device.

9 PUBLICATION

Following the completion of data collection and analysis, manuscript(s) will be written and submitted for publication in appropriate journals. Abstracts will also be prepared for submission and presentation at relevant scientific meetings. Data may also be included in future grant applications.

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11 APPENDIX

11.1 Proposed Device Overview

From Grant Application, Pages 10-11.

Starting with the IDL PhySens design, the custom electronics will swap the microSD Card holder for a solder-on eMMC memory IC to greatly reduce size and increase robustness. To sense the full dynamic range of various athletic activities (often exceeding accelerations of 60g) the updated device will include both low-range/high-resolution (ST LSM6DSL) and high-range/low-resolution (H3LIS331DL) triaxial accelerometers and gyros as well as a triaxial magnetometer (LIS2MDL) fused together through IDL's Extended Kalman Filter. This approach allows a continual, smooth estimate of the motions throughout a large dynamic range.

The sensor data will be processed by a Nordic Semiconductor nRF52840 RF SoC which includes an integrated Bluetooth Low Energy (BLE) Radio and ARM Cortex-M4F processor with floating point hardware. This processor will perform calculations, and transmit the compressed results wirelessly using a BLEv5 compatible stack. Using BLEv5 legacy features, the sensors can connect directly to nearly all smartphones produced since 2012. The new BLEv5 mesh networking capability, and "Long Range" mode of the BLEv5 network also allows sensors to communicate to the Team Communication Hub extend the range to over 200m between each player with a >110dBm link budget. When not connected to an internet enabled device (mobile phone or communication hub) data is stored locally. The sensor will provide status and activity information to the user through a segmented led "fuel bar".

It is expected that the time-averaged, total system draw when in use will be roughly 6.5mA during active play. A thin 100mAH rechargeable lithium polymer battery (2.8x2.8x1.4mm) will power the system for 15 hours of continuous use. To conserve power, the system will automatically shut off when periods of inactivity are detected. The battery will "fast-charge" through sealed contact points on a charging dock in "fast-mode" to reach 80% full charge in under 15mins.

As the comfort, ease-of-use, robustness, and appearance of any wearable device is of critical importance to its acceptance, significant effort will be put into analyzing the requirements and testing concepts (phase 1) and then perfecting its design and manufacturability (phase 2). IDL is collaborating with Mr. Scott Melanson an expert in medical, wearable, and exercise equipment industrial design including on ongoing NIH Phase 2 SBIR to monitor motions of exercises to relieve low-back pain. The sensors will be sealed in soft, hypoallergenic foam to provide resistance to sweat, dirt, and physical impact. Multiple form-factors including arm-bands, elbow compression sleeves, and wrist straps will be investigated, optimizing the combination of easy donning and doffing, maximal comfort, aesthetics, and to accurate motion transfer. The system will include a "zero touch" interface where no user interaction is required to utilize the device. Power will be automatically managed based on the user's actions—sleeping while not in use and waking up during play. The case will be hermetically sealed creating a dust tight and waterproof device (IP68 rated).