Medical Cyber-Physical Systems: IoMT Applications and Challenges

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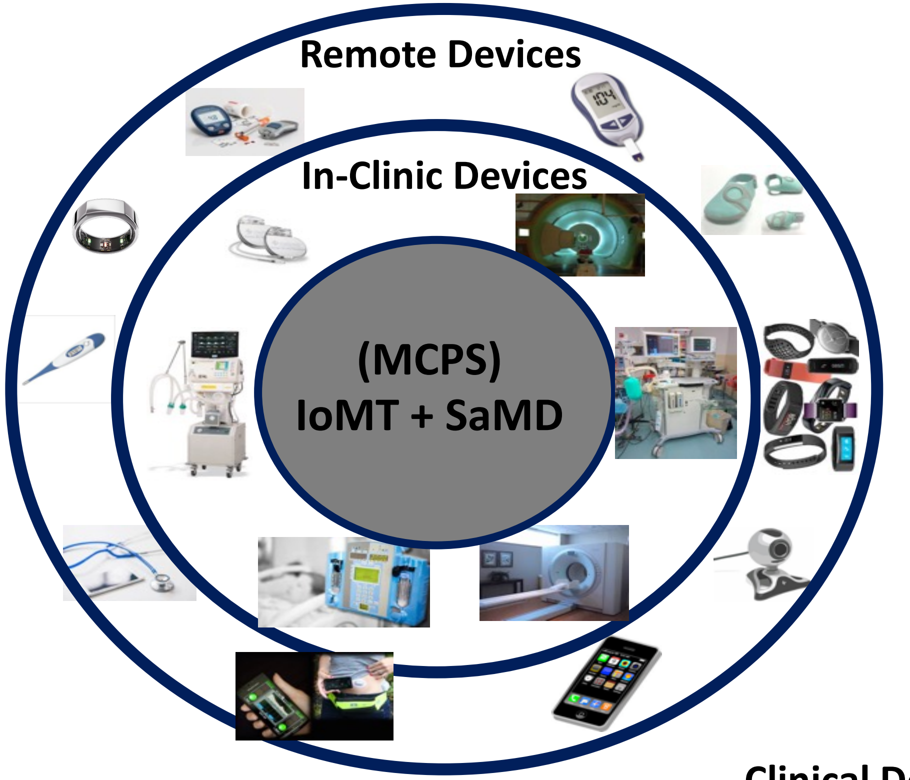
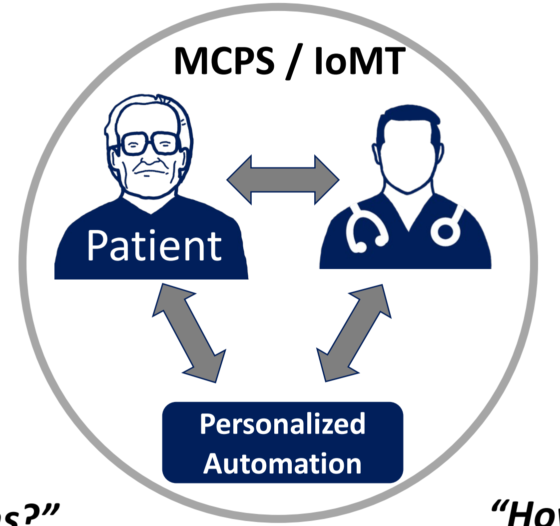
IoMT Research



Medical Device Interoperability

"How to collect/exchange the RIGHT data?"

- VitalCore: platform for medical device dashboard, anomaly detector, clinical alert apps.
- Raproto: Open-source, rapid prototyping platform for data collection via smartwatches
- Secure/tamper-proof logging



Clinical Decision Support

"How to interpret data for clinicians?"

- *Suppressing events:* smart alarms/alerts
- *Detecting events:*T1D meal ingestion
- *Estimating/modeling state*: T1D patient behavior
- *Predicting outcomes*: ACL Retear

Device Coordination / Closed-Loop

"How to automatically adjust clinical care"

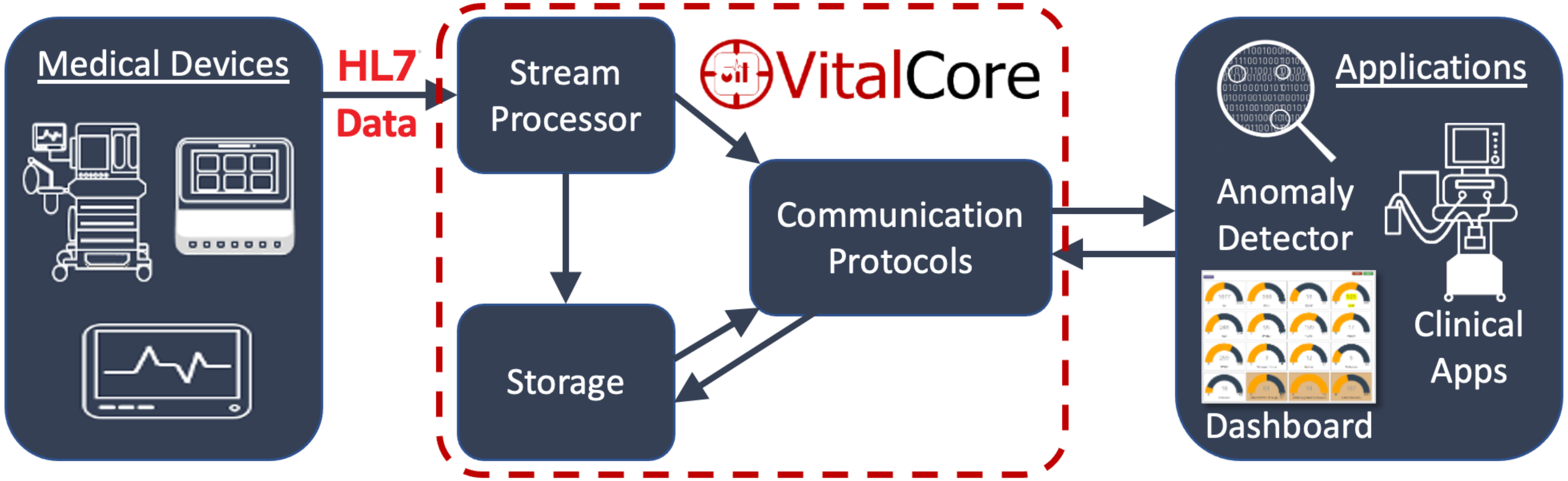
- Mechanical ventilator weaning
- Fall prediction
- Motion detector using PulseOx

Challenges

1. IoMT/MCPS should be implemented in such a manner to reduce clinician load, not add to it.
2. Because of the reliance on high-quality data the first and often the most time-consuming step in many research endeavors is to build a data collection system.
3. Medical applications require high quality data from reliable, human-safe devices. Further, they present data storage issues and need ample processing and analysis to create useful applications.

Infrastructure: VitalCore

Analytics & Support Dashboard for Medical Device Integration

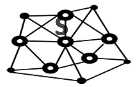


3000+
Integrated Medical Devices

36
HL7 & Application Servers

13
Facilities

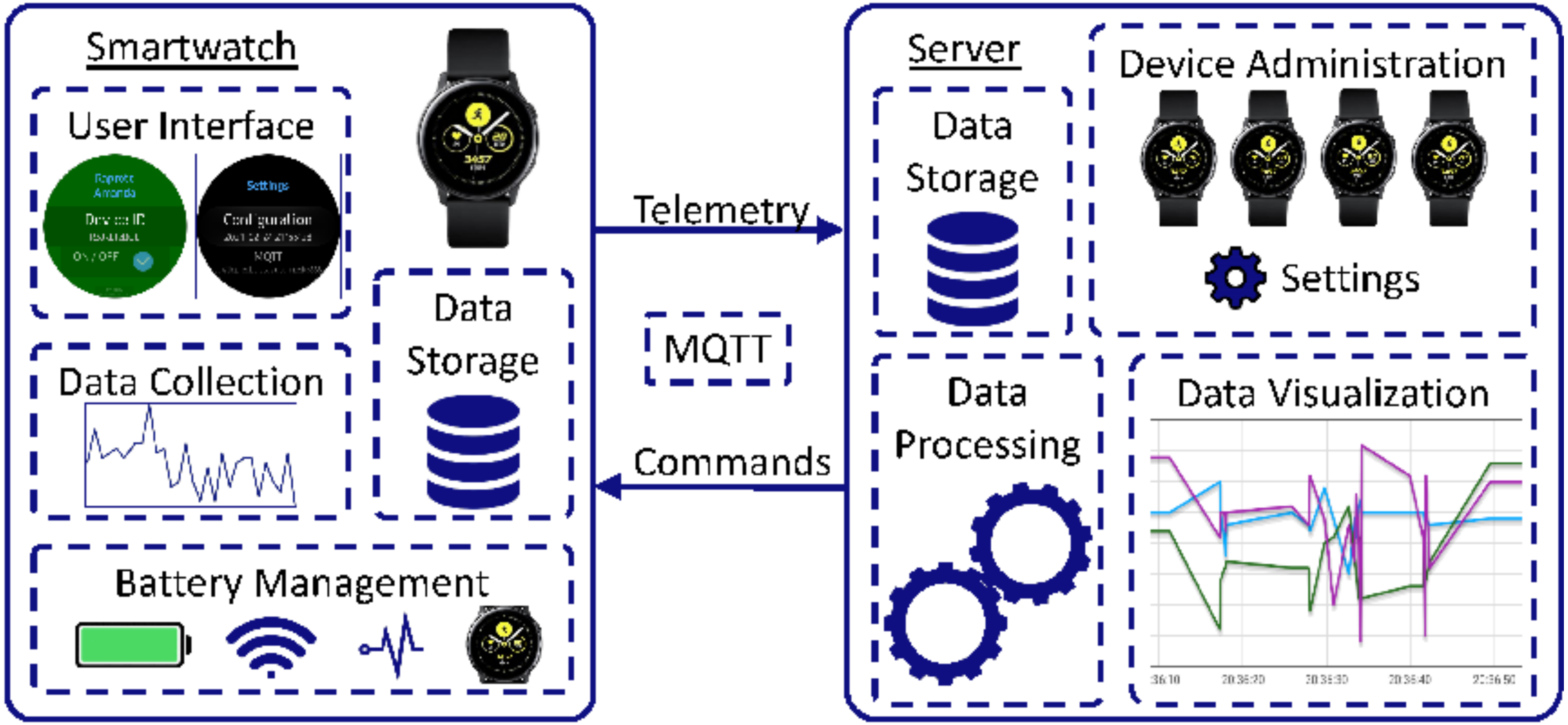
7
Vendor Network



And growing...

Infrastructure: Raproto

Open-source, rapid prototyping platform for data collection via smartwatches



Applications: SmartAlarms

- Medical device alarms are non-informative
  - between 80% and 99% of all alarms are false
- Clinicians have developed **alarm fatigue** and may not respond to alarms
  - A top 10 health technology hazard since 2007
- Solution: Smart alarm suppression
  - Maximally suppress alarms non-informative alarms without suppressing actionable alarms
- Initially consider low SpO2 alarms
  - “Reducing Pulse Oximetry False Alarms Without Missing Life-Critical Events” (CHASE 2018)
  - ECRI 2019 #7 Health Tech Hazard: Improper Customization of Physiologic Monitor Alarm Settings May Result in Missed Alarms

Human-in-the-loop MCPS/IoMT

- Clinicians and/or patients operate and coordinate medical devices
- Analysis of safety and effectiveness needs to take operator behavior into consideration
  - How much the operator trusts the system
  - When and how operator interferes with automation
- Case study: patient-operated insulin pump
  - Smart pump suggest doses
    - Patients input carb intake
    - Patients can accept or adjust dose
  - How does behavior affect treatment?

RT-ACL: Identification of High-Risk Youth Patients and their Most Significant Risk Factors to Reduce Anterior Cruciate Ligament Reinjury Risk

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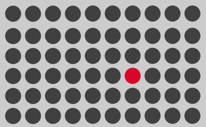
Motivation

200,000 ACL Tears Annually in the US

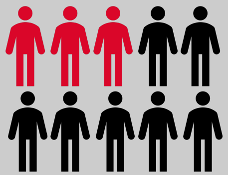


1 in 60 Youth Athletes

>6 Months Recovery

$2 Billion Annually in Medical Costs

30% Retear their ACL

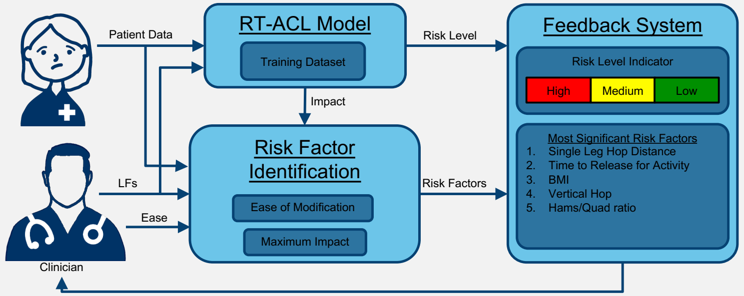


Conclusion

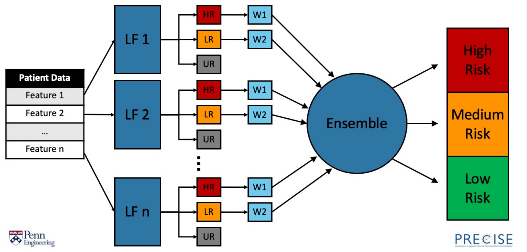
- The RT-ACL system identifies high-risk patients and determines their most significant risk factors to reduce ACL reinjury risk: High risk patients are 4.6x as likely to retear as low risk patients
- Evaluation on 441 youth patients, 8-21 years of age that underwent an ACL reconstruction at the Children's Hospital of Philadelphia
- Next Steps:
- Multi-year Clinical Validation at Children's Hospital of Philadelphia
- Generalized System Development
- Integration into the EHR

Research Overview

Aim: Identify patients at high risk for ACL Retear



Our approach: Leverage expert knowledge to intelligently design features that a predictive of risk. Combine these features using machine learning algorithms. Classify patient risk of retear as high medium or Low.



Data Collection

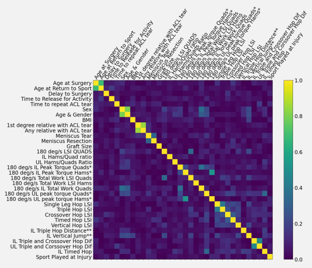
Dataset: Analyzed Clinical Notes

Category	#	Missing	Example
Demographics	6	5%	Age, DOB
Injury Inforation	2	2%	Date, Sport Played
Family History	2	43%	Relative with ACL Tear?
Surgery Information	20	9%	Type of Reconstruction
Recovery Information	2	14%	Date of Release to Activity
Re-tear Information	7	59%	Time to Repeat ACL Tear
Rehab Information	213	79%	Triple Hop LSI

Risk Factor Evaluation

Training Dataset
441 Patients

$$w_{f_h} = \frac{\sum_{x \in X_1} \mathbf{1}(f_h(x) = high \wedge f_{gt}(x) = 1)}{\sum_{x \in X_1} \mathbf{1}(f_h(x) = high)}$$

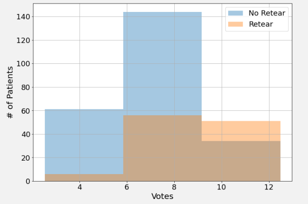


Risk Factor	High Risk W	High Risk #	Low Risk W	Low Risk #	Unlabeled #
Age at Return to Sport	37	188	11	27	139
Delay to Surgery	32	31	14	14	323
Time to Release for Activity	33	227	23	51	76
Time to repeat ACL tear	92	36	69	22	296
Age and Sex	29	193	37	161	0
BMI	32	284	25	8	62
1st Degree Relative ACL Tear	23	40	31	87	227
Any relative ACL tear	26	31	30	96	227
Meniscus tear	28	226	37	71	57
Meniscus resection	23	92	33	205	57
Graft Size	18	11	38	126	57
180 deg/s LSI Quads	31	101	41	130	123
IL Hams/Quads Ratio	32	307	34	44	3
UL Hams/Quads Ratio	32	304	36	47	3
180 deg/s IL PT Quads*	28	110	35	241	3
180 deg/s IL PT Hams*	26	109	36	242	3
180 deg/s Ttl Work LSI Quads	28	139	36	129	86
180 deg/s Ttl Work LSI Hams	34	173	29	80	101
180 deg/s IL Ttl Work Quads	36	110	31	240	4
180 deg/s UL PT Quads*	26	221	43	131	2
180 deg/s UL PT Hams*	33	109	32	242	3
Single Leg Hop LSI	19	32	43	129	193
Triple Hop LSI	31	29	36	140	185
Crossover Hop LSI	54	13	53	69	272
Timed Hop LSI	18	11	53	86	257
Vertical Hop LSI	34	62	40	111	181
IL Triple Hop Distance(cm)**	43	101	39	106	147
IL Vertical Jump(cm)**	44	18	47	82	254
IL Triple & Crossover Hop Dif	52	42	54	82	230
UL Triple & Crossover Hop Dif	54	46	53	78	230
IL Timed Hop	49	102	55	45	207
Sport Played at Injury	37	253	11	34	67

Clinical Decision Support

Aim: Develop a decision support system that is easy-to-use and is trusted by clinicians to aid in decision making for ventilation weaning

Based on votes from the expert created features and labeling functions. A risk stratification is applied that features an increasing retear rate as patients move through the bins.



Binning

Group patents by how likely they are to retear

High	Medium	Low

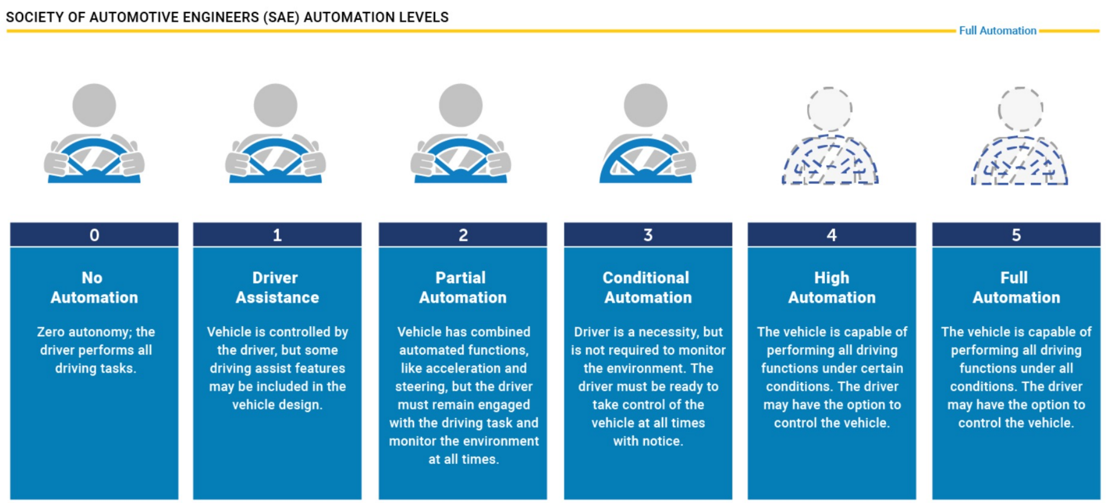
High risk patients are 4.6x as likely to retear as low risk patients

Feedback System

```
Patient #:  607.0
Risk Level:  High        Votes:  10.532917410200376
Votes to lower risk level:  1.2061838279777248

Highest Risk Features:
Involved Limb Timed Hop_final                                   0.555556
Difference between triple and corssover hop Uninvolved_final    0.543478
Difference between triple and crossover hop Involved_final      0.543210
Crossover Hop LSI_final                                         0.538462
Timed Hop LSI_final                                             0.529412
Name: 173, dtype: float64
```

Levels of Autonomy



Increasingly human-performed tasks

Increasingly machine-performed tasks

Caregiver(s) performs the task

No autonomy

Caregiver(s) is involved in task and technology aids and enhances effectiveness

Technology Assistance

Caregiver(s) initiates a task and has discrete control over technology that executes it

Task Autonomy

Caregiver(s) defines and initiates a task & technology executes the task with caregiver supervision

Conditional Autonomy

Technology decides course of action and executes it with caregiver supervision

High Autonomy

Technology decides course of action and executes it without supervision

Full Autonomy

Conclusion

- We are pushing towards a vision of the future in which technology autonomously provides comprehensive medical care.
- As we strive towards this reality, we have developed the IoMT and MCPS, but we still have many more challenges to surpass.