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

Amanda Watson*, Pengyuan Lu*, Elliot Greenberg+, J. Todd R. Lawrence+, Theodore J. Ganley+, Insup Lee*, James Weimer*

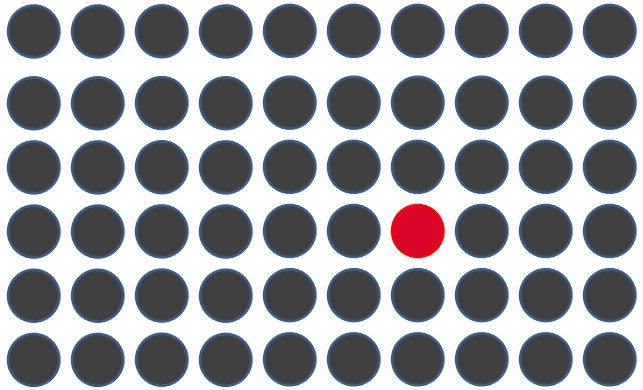
*University of Pennsylvania, +Children's Hospital of Philadelphia

Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

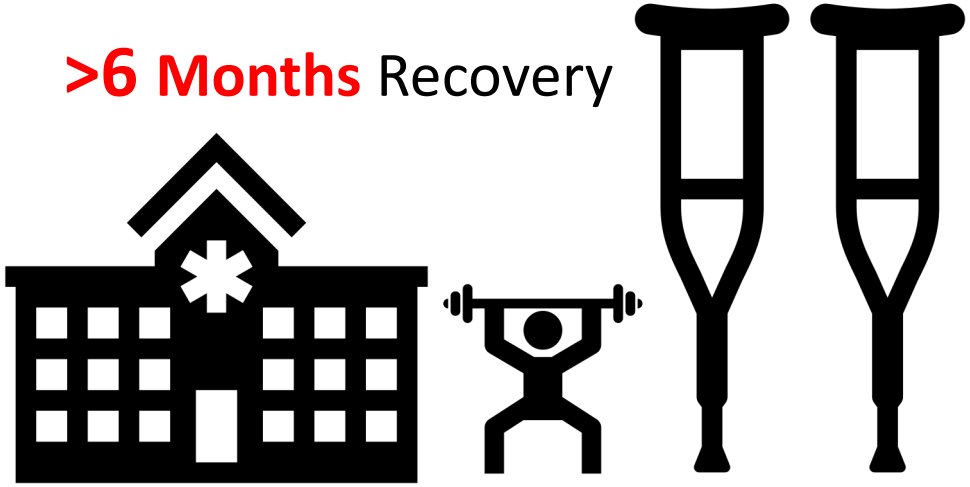
Introduction

200,000 ACL Tears Annually in the US



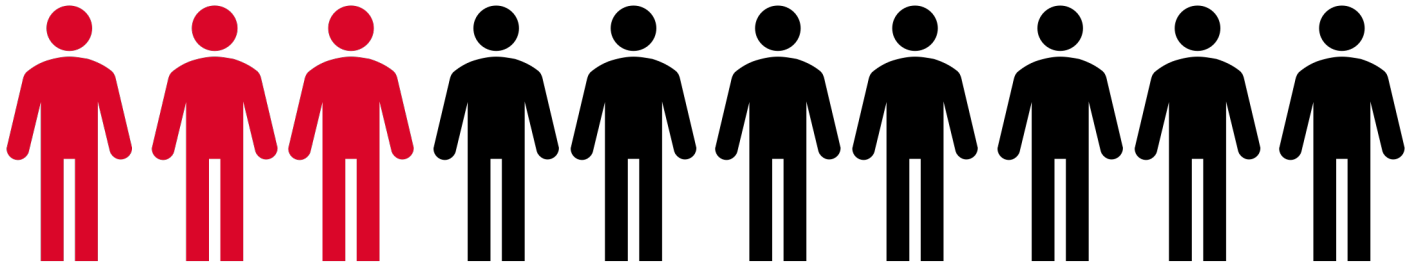
1 in 60
Youth
Athletes

>6 Months Recovery



$2 Billion Annually in Medical Costs

30% Retear their ACL



Penn Engineering

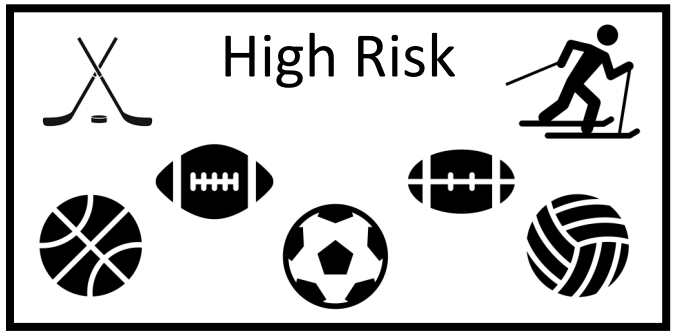
PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

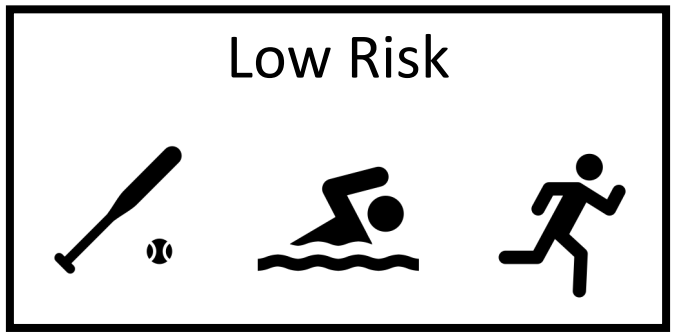
Data Collection

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

Clinician Developed Labeling Functions

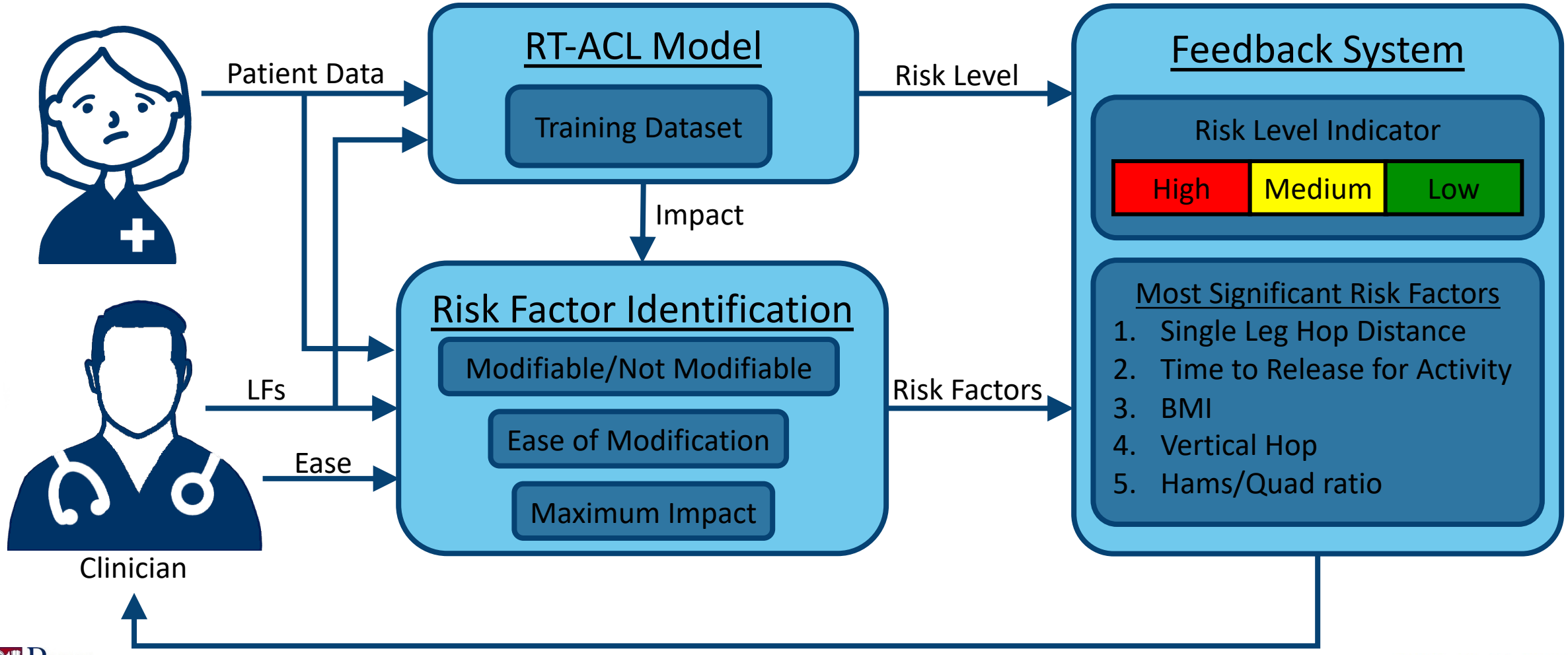




Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

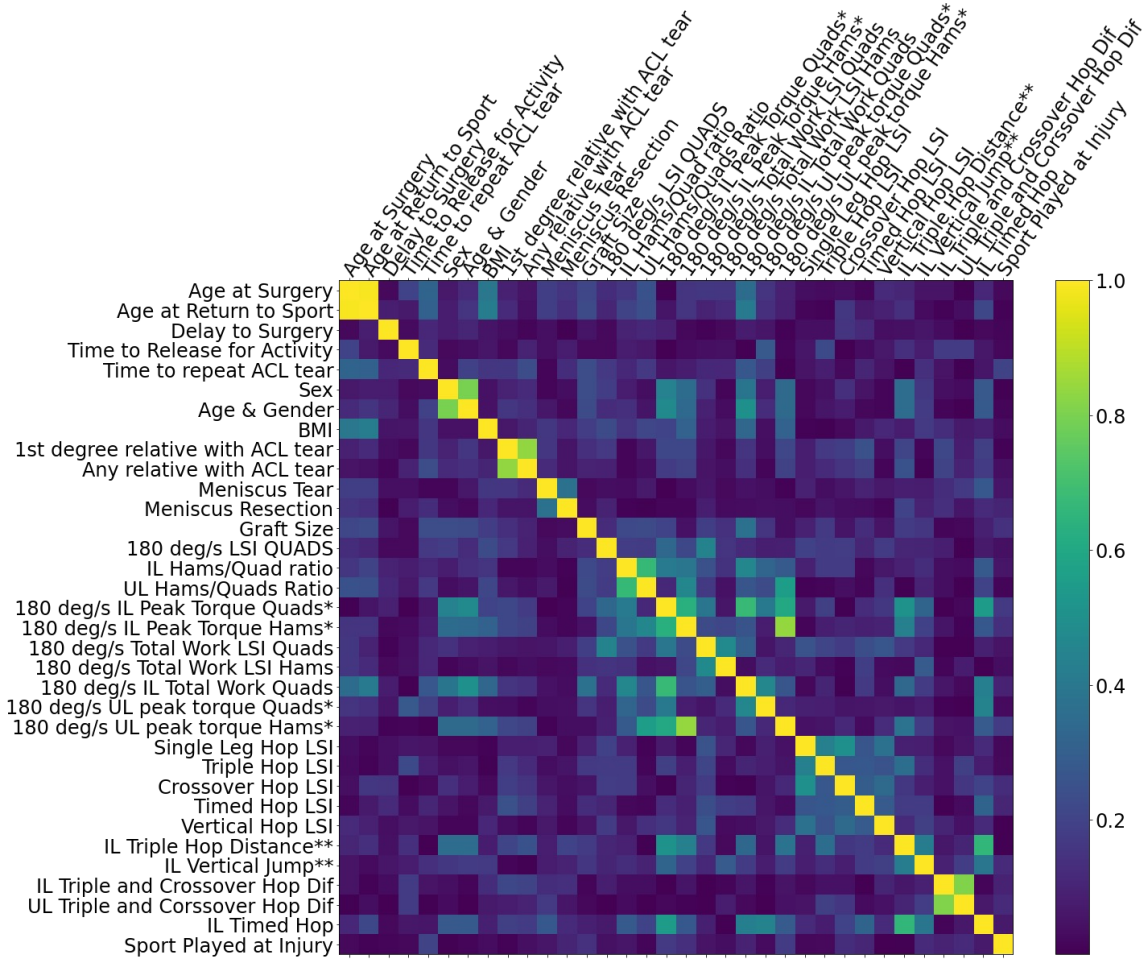
System Architecture

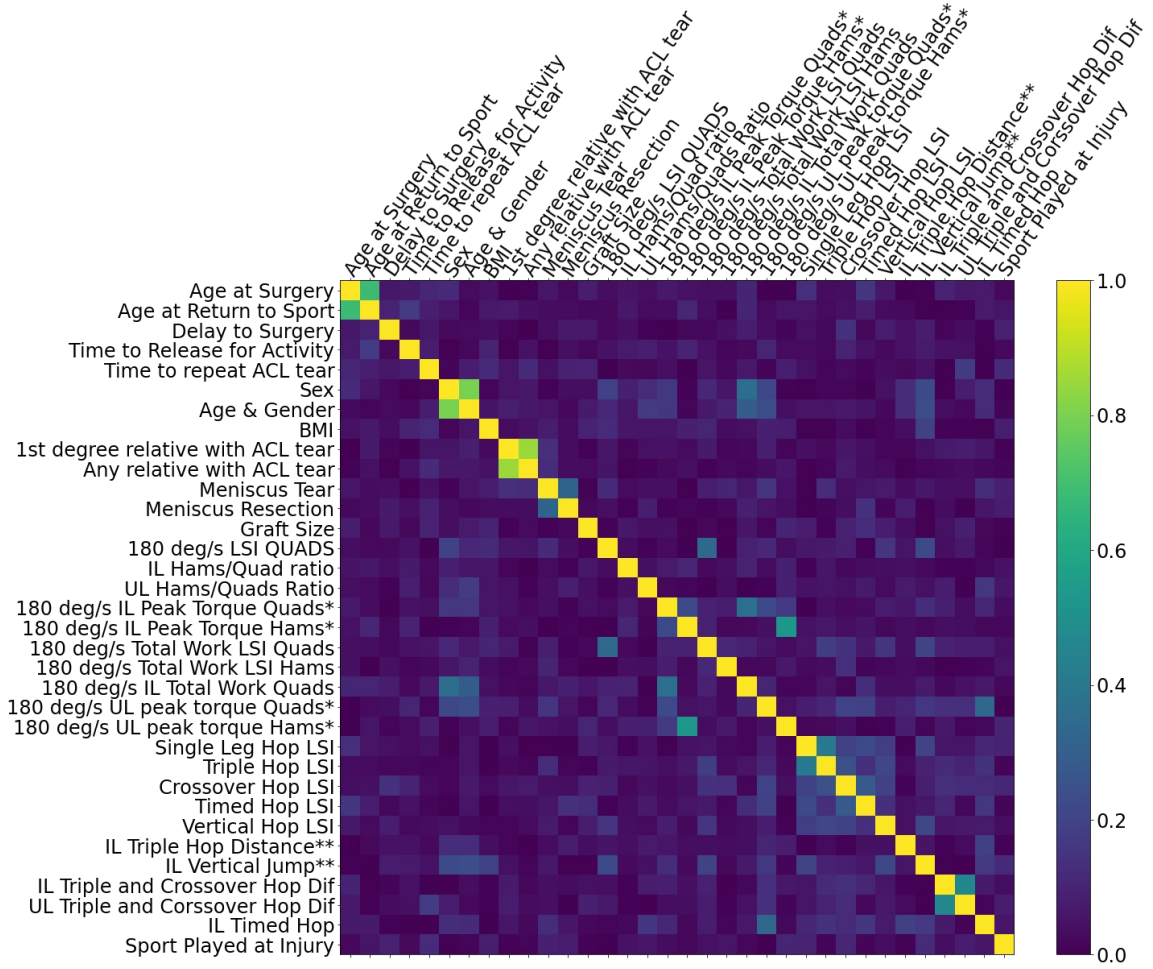


Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

Removing Highly Correlated Risk Factors

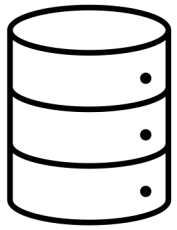




Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

Risk Factor Evaluation



Training Dataset

441 Patients

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

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

Risk Factor	High Risk		Low Risk		Unlabeled
	W	#	W	#	#
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

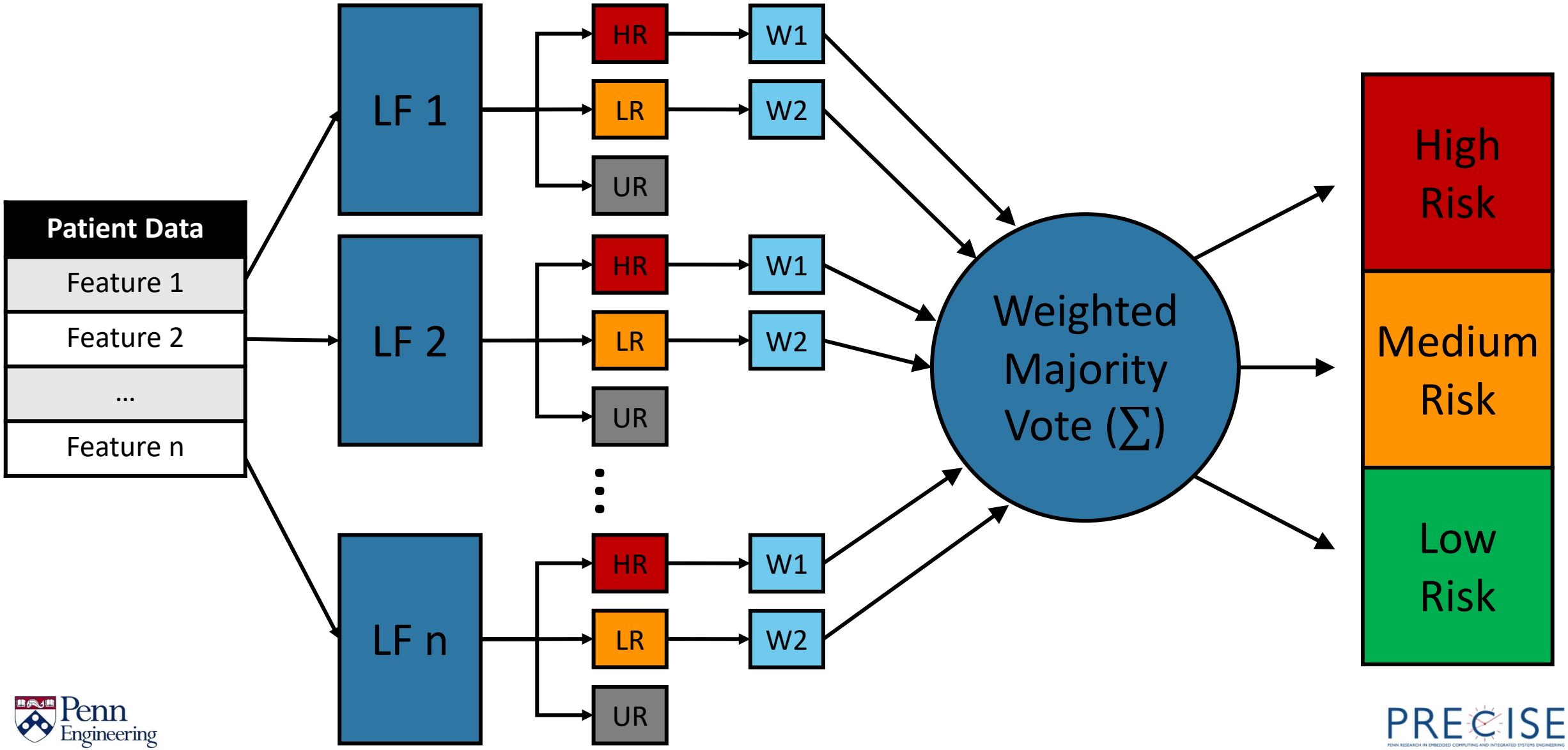
Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

Weighting and Hyperparameter Tuning

Weighting	Hyperparameter	High Risk #	High Risk %	Mid Risk #	Mid Risk %	Low Risk #	Low Risk %
Equal	$c_h = 1, c_l = -1$	26	11.54	102	32.30	101	37.62
Equal	$c_h = c_l = 1$	103	50.49	230	25.33	21	14.28
Risk Factor	$c_h = 1, c_l = -1$	37	13.89	233	31.76	84	41.67
Risk Factor	$c_h = c_l = 1$	85	56.47	195	28.35	74	12.51
Labeling Function	$c_h = 1, c_l = -1$	17.50	31.22	237	31.22	76	43.42
Labeling Function	$c_h = c_l = 1$	**83**	**59.04**	**184**	**29.51**	**87**	**11.49**
Clinician 1	$c_h = 1, c_l = -1$	52	30.77	252	31.35	49	38.78
Clinician 1	$c_h = c_l = 1$	89	49.44	214	28.50	50	16.00
Clinician 2	$c_h = 1, c_l = -1$	27	25.93	242	31.41	84	36.91
Clinician 2	$c_h = c_l = 1$	115	48.96	219	25.57	19	5.25
Clinician Average	$c_h = 1, c_l = -1$	30	20.00	243	31.82	81	38.27
Clinician Average	$c_h = c_l = 1$	99	50.50	222	27.03	33	12.12
Goal			>64		≈ 32		<16

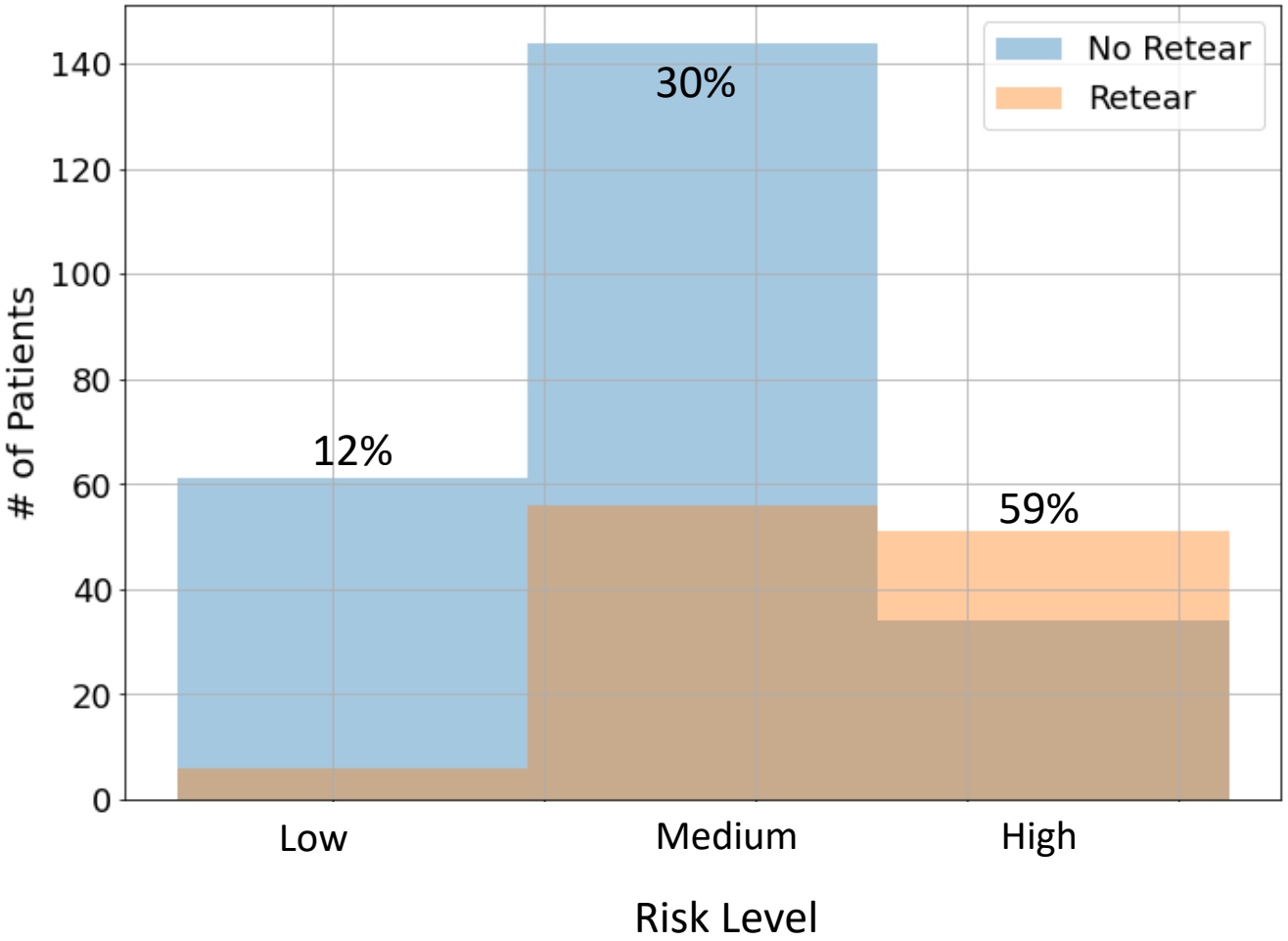
Weighted Majority Voting Ensemble Approach



Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

RT ACL Model



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

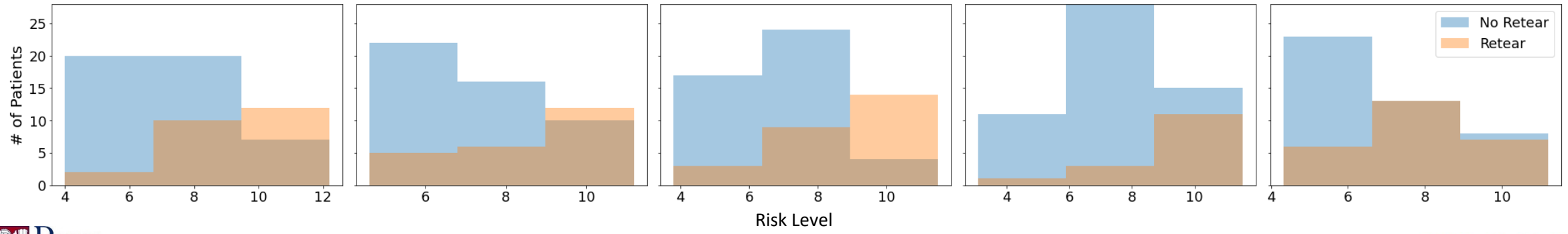
Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

Cross Validation

Evaluation	Dataset	% Re-tear	Age Range	Gender(M/F)
CV1	Train	32	8.3-20.7	145/137
CV1	Test	34	8.5-21.0	32/39
CV2	Train	32	8.3-21.0	139/143
CV2	Test	32	9.8-19.7	38/33
CV3	Train	31	8.3-21.0	143/139
CV3	Test	37	8.7-20.7	34/37
CV4	Train	35	8.5-21.0	139/144
CV4	Test	21	8.3-19.8	38/32
CV5	Train	31	8.3-21.0	143/141
CV5	Test	31	10.6-18.5	35/35
Hold Out	Validation	6	9.8-21.5	46/42

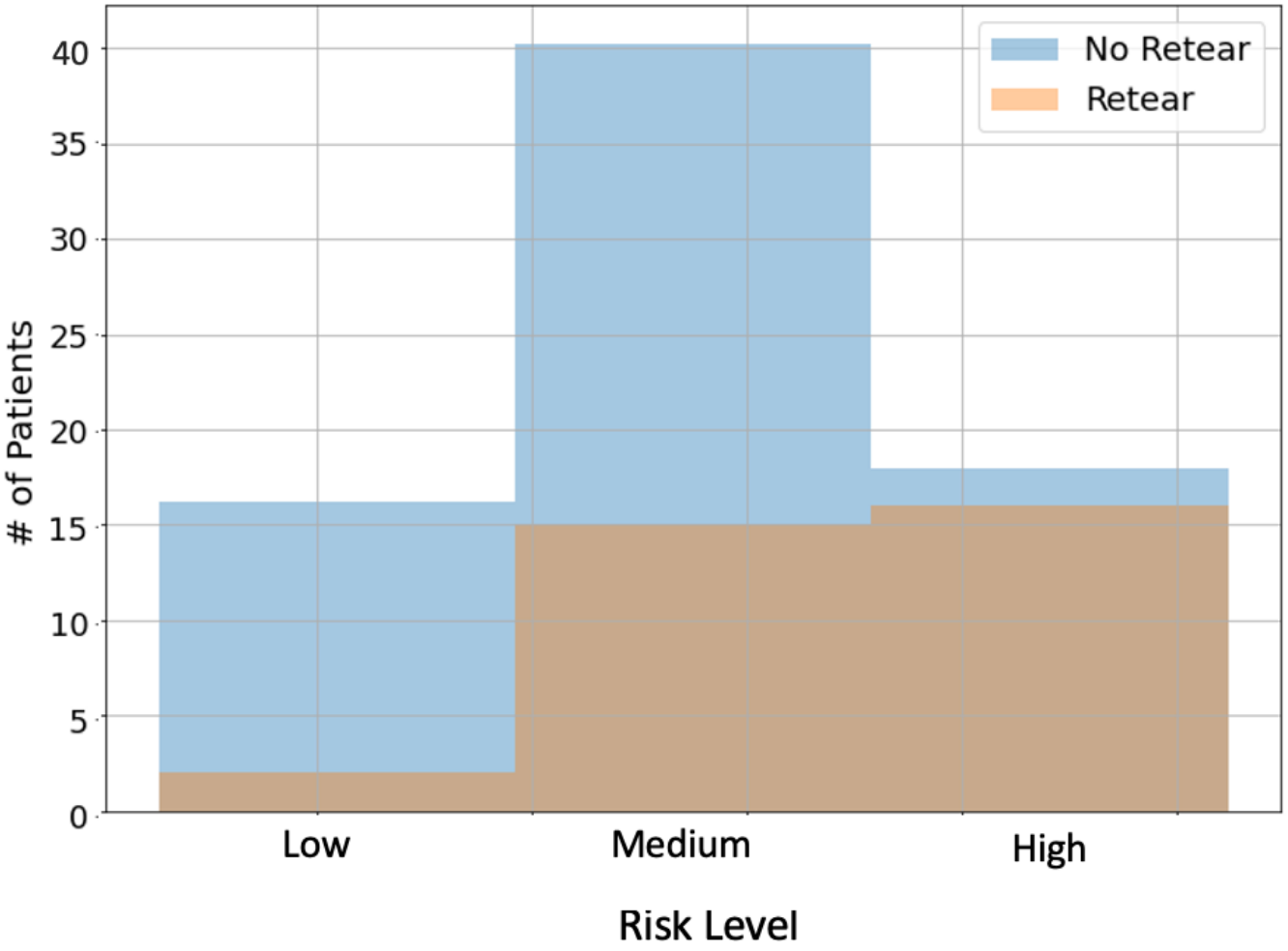
Fold	HR #	HR %	MR #	MR %	LR #	LR %
1	20	55.00	28	18.18	22	18.18
2	22	54.55	31	15.16	18	5.56
3	27	48.14	30	10.00	13	7.69
4	10	80.0	30	33.33	30	10.00
5	15	46.67	26	44.00	29	20.68



Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

Hold Out Evaluation



Identification of Most Significant Risk Factors

Ease of Modification

Optimization of Metrics

$$j^* = \arg \max_{j \in dim(x)} m(x[j]) * (i(x[j]) + e(x[j]))$$

Impact Score

Modifiability	Feature	High Risk %	High Risk #	Low Risk %	Low Risk #
Not Modifiable	Time to repeat ACL tear	92	36	69	22
	Age at Surgery	37	261	19	93
	Sport Played at Injury Codes	37	253	11	34
	Age at Return to Sport	37	188	11	27
	Sex (1=male 2=female)	30	177	34	177
	Age and Sex	29	193	37	161
	Meniscus tear (old)	28	226	37	71
	Any relative with ACL tear 1=Yes 2=No	26	31	30	96
	1st degree relative with ACL tear	23	40	31	87
	Meniscus resection (old)(0=no 1=yes)	23	92	33	205
	Graft Size (mm)	18	11	38	126
Modifiable	Triple & Crossover Hop Uninvolved Difference	54	46	53	78
	Crossover Hop LSI	54	13	53	69
	Triple & Crossover Hop Involved Difference	52	42	54	82
	Involved Limb Timed Hop	49	102	55	45
	Involved Limb Vertical Jump(cm)**	44	18	47	82
	Involved Limb Triple Hop Distance(cm)**	43	101	39	106
	180 deg/s Invovled limb total work Quads	36	110	31	240
	180 deg/s Total Work LSI Hams	34	173	29	80
	Vertical Hop LSI	34	62	40	111
	Time to Release for Activity	33	227	23	51
	180 deg/s uninvolved limb peak torque Hams*	33	109	32	242
	Involvled Limb Hams/Quad ratio	32	307	34	44
	Uninvolvled Limb Hams/Quads Ratio	32	304	36	47

Penn Engineering

PRECISE
PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

Feedback System

```
Patient #:  607.0
Risk Level:  High        Score :  10.532917410200376
Score  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
```

Conclusion

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

THANK YOU!

PRECISE

PENN RESEARCH IN EMBEDDED COMPUTING AND INTEGRATED SYSTEMS ENGINEERING

http://precise.seas.upenn.edu
https://www.seas.upenn.edu/~aawatson/
https://twitter.com/DrWatson_22
https://www.linkedin.com/in/amandawatson22/